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HIGH STRENGTH REINFORCEMENT (HSR) - THE SMART SOLUTION FOR A SUSTAINABLE FUTURE

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Abstract: In Canada and in Germany the recent limitation of yield stress for reinforcement bars is f_{yk} = 500 N/mm². In the USA the code limit is 550 N/mm² and in some European countries reinforcement steel with higher yield strain (up to 600 N/mm²) is permitted. In the last decade many higher strength rebars were developed and the trend is towards this new reinforcement grades. The advantages of HSR are cost reduction (due to lower steel weight), size reduction of structural members (e.g. effective floor space increase as columns with high strength reinforcement have a cross section area compared to columns built with a common reinforcement), Increased flexibility for architects (due to higher load capacity with the same column dimensions or smaller dimensions with the same capacity) and reduced congestion issues result in in higher quality construction. A smart construction solution does not only give the designer one advantage (higher strength) but allows further enhancement: Changing the rib pattern in a way that the bar can be used as a threaded bar, there is no further manufacturing done to use the bar in a coupling system. This rebar-system allows further reduction of splice congestion, reduces development lengths and makes modular construction easy. In several countries (USA, Germany, Poland, South Korea, ...) high strength thread bars up to 670 N/mm² yield strength are used already. This paper will lay out the properties of HSR, describes the code compliance and will show several applications around the globe.

1 INTRODUCTION

Concrete is one of the oldest composite building materials. The Romans developed the "opus caementitium". The biggest deficiency ever was that concrete can only transfer very small tension loads. This was the reason why for old structures geometrical forms were chosen that the structure was mainly under compression (e.g. arches or vaults). The first person who used iron to increase the durability of concrete construction was Joseph Monier in the late 19th century. He used florist wire as he was a gardener. For the first applications, any kind of iron or steel was used to increase the tension strength of concrete. In the 1930s the first reinforcing steels were developed in the United States. (Russwurm, 1993)

In the 1950's, national codes for reinforcement were introduced in many countries. Since then, the steel quality was kept almost at the same level. In the German code (DIN 488, 2010) two steel grades are mentioned: reinforcing steel BSt 420 (f_y = 420 N/mm²) and BSt 500 (f_y = 500 N/mm²). The Canadian standards limit the yield strength also to 500 N/mm². According to ACI 318-08 (ACI 318, 2014) reinforcing steel with a yield strength exceeding grade 60, "the yield strength shall be taken as the stress corresponding to a strain of 0.35 %" but the maximum yield strength used in design calculations according to (ACI 318,

2014) is limited to 550 N/mm². The only code which permits higher maximum yield strength is the European Code (EC 2, 2011) (f_y < 600 N/mm²).

Meanwhile the concrete strength was consequently increased from normal strength concrete (NSC, f_c < 60 N/mm²) to high strength concrete (HSC, f_c < 100 N/mm²) and further to ultra high performance concrete (UHPC, f_c > 100 N/mm²). Although these changes allowed for increased concrete strengths, the strength of reinforcing steel was not increased for many decades. For this reason, it is argued in the literature that UHPC should be reinforced with high strength reinforcing bars (HSR) (see also (Reichel, 2010) and (Jungwirth, 2006)). One of the alternatives for reinforcing steel bar (a weldable rebar with a thread rib pattern and a yield strength f_y = 670 N/mm², further called "HSR" or "670W") is described below.

Furthermore, HSR allows for reduction in the quantity of reinforcement. This can be advantageous in different scenarios:

- Constant cross section: reduced reinforcement ratio leads to reduced congestion and saves installation time.
- Constant reinforcement ratio: reduced cross section leads to lower dead load and higher available floor space, which increases the sellable footprint.
- Change of construction method: composite construction can often be avoided by using HSR.

Another advantage of the 670W is the threadability of the bars. The ribs are in such a shape, that the bar is continuously threadable (see Fig. 1). Therefore, the bars can be used for preassembled rebar-cages (modules).

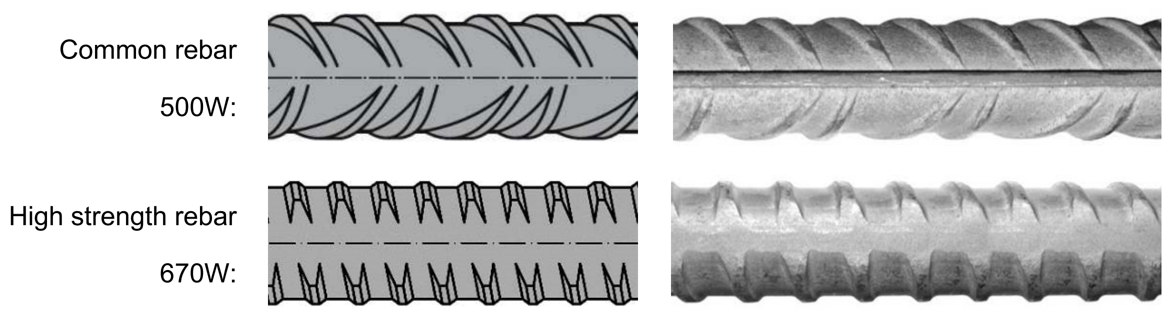


Fig. 1: Comparison of common and high strength reinforcement

2 HIGH STRENGTH REINFORCEMENT (HSR)

High strength reinforcement 670W was initially developed in Europe (SAH, 2018) to be used for geotechnical applications such as micro piles, soil nails and ground anchors. The idea was to use a high strength steel bar to decrease the necessary bar diameter and further to reduce the borehole diameter in deep foundation elements. A smaller borehole increases the drilling speed and reduces costs. Mainly there are two ways to increase the strength of steel: micro alloying or water tempering. The advantage of micro alloyed steel is a high ultimate strength to yield-strength ratio. Water tempcorised steel is much cheaper and has a sufficient ductility to be used as reinforcement for concrete structures.

The high strength thread bars are hot rolled and tempcorised. The bar is continuously threadable because of the shape and the geometry of the ribs. The bar diameters were chosen such that common reinforcement bar diameters used in Europe can be easily substituted. High strength reinforcement is available in a range of diameter $Ø_s$ = 18 to 75 mm (see Fig. 2).

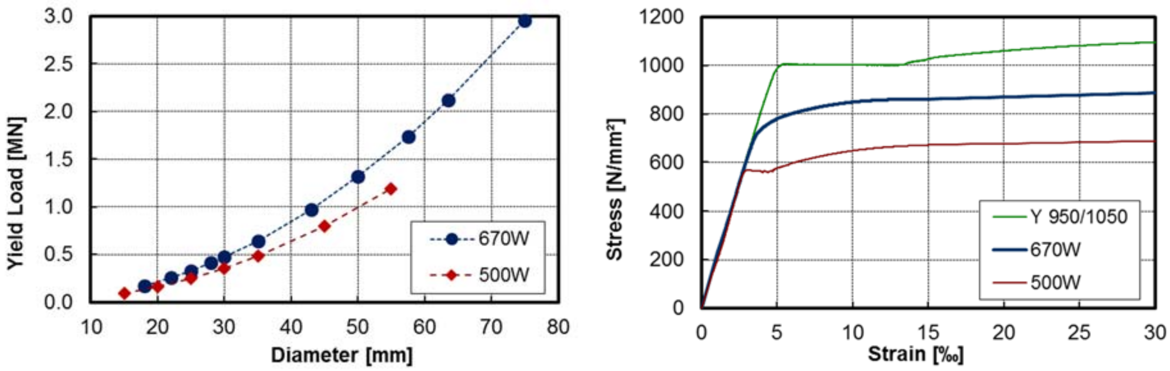


Fig. 2: Comparison 500W and 670W, Stress-strain-diagram for different steel grades

2.1 Material Parameters

HSR has similar mechanical properties as common reinforcement but provide additional advantages. The main mechanical properties are:

- nominal yield strength f_y = 670 N/mm²
- nominal ultimate strength f_u = 800 N/mm²
- high ductility (uniform elongation > 5%, elongation at fracture > 10%)
- no well defined yield point
- low relaxation
- low stress corrosion risk

HSR steel does not have a well defined yield point. For this reason, the yield strength is defined either as the 0.2 % proof-stress (see Fig. 2) or the 0.35 % offset method. The Young's modulus is slightly higher compared to common reinforcement (E = 200.000 N/mm²). The rib height is in comparison to common reinforcement bars is bigger, which leads to a higher relative rib area too. 670W was developed to be used with threaded accessories such as nuts and mechanical couplers in all available bar sizes.

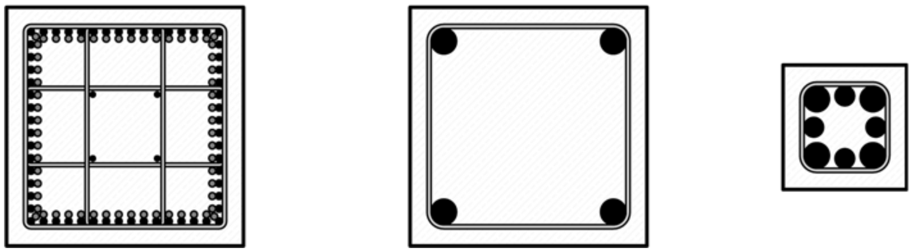
2.2 Accessories

For HSR, there are several accessories and special parts available. These range from different nut types, mechanical couplers, transitional couplers for bar size reduction and end anchorages capable of developing the ultimate force of the bars (see (SAH, 2018) and Fig. 3).

Fig. 3: Thread bar and accessories (plate end anchorage, coupler, end anchorage with anchor piece)

Lap splices can be avoided by using mechanical couplers. Development length can be reduced by using end anchorages. This helps to reduce reinforcement concentrations, discontinuity problems as well as bond loading in lap splice areas and avoid additional stirrups to strengthen the development length.

Using accessories is facultative though it is advisable as mentioned before. It helps to support the advantages of high strength reinforcement. Fig. 4 shows an example how reinforcement ratio or cross section can be reduced significantly. All three columns have the same load capacity.



a) 500W, (ρ=8% at laps)

b) 670W with the same bearing capacity and the same cross section area

c) 670W with the same bearing capacity and ρ=20%

Fig. 4: Possible cross sections:

3 HSR AND CODE REGULATIONS

3.1 Eurocode

The range of yield strength in Eurocode 2 (EC 2, 2011) is between 400 N/mm² and 600 N/mm². High strength reinforcement exceeds this range by about 10 %. There is no upper limit for the bar diameter in the code. The rib geometry of continuously threaded bars is not covered by the EN 10080 but the relative rib area is larger than specified in the code.

In consideration of these divergences, some structural regulations need to be discussed. At first, due to the higher yield strength, it is not possible to keep the same limits of span to depth ratio to limit deflection. Higher stresses cause higher strains and higher strains cause higher deflections. Therefore, either stresses are limited or deflection needs to be calculated and if necessary constructional depth is increased. At second, the calculation of crack width and further the bond properties have to be considered. For a survey of differences in structural behaviour between 500W and 670W three beam tests with each grade were done. According to these tests, the higher relative rib area of 670W cause the same crack width but a lower crack spacing (Wechtitsch, 2006). A detailed research project confirmed these first results (Scheibe et al, 2013). Special points will be raised in the following paragraphs for the particular possible applications of HSR.

3.1.1 Columns, general

Serviceability limit state plays secondary role for columns. That is why columns are to be considered to be ideal for a first application for high strength reinforcement.

Following constraints for columns are given by (EC 2, 2011):

- Maximum reinforcement ratio: $\rho \le 4\%$ ($\rho \le 8\%$ at laps)
- Maximum concrete strain for concentric loading: $\varepsilon_c \le -2.0‰$ (see Fig. 6a)

The aim for columns with high strength reinforcement is to provide a high bearing capacity and a maximum utilisation of the materials. For this reason, both constraints shall be opened.

3.1.2 Maximum reinforcement ratio

The restriction of reinforcement ratio is given by the possibility of casting. With small diameters it is not possible to place the concrete and provide a high quality for reinforcement ratios exceeding 8%. This is why (EC 2, 2011) limits the ratio. Columns armed with large diameters (up to 75 mm) can be casted even with reinforcement ratios up to 20% (see Fig. 4). For high strength columns the maximum ratio will therefore be set to $\rho = 20\%$ which is proven by experience (see also (Falkner et al, 2008)).

3.1.3 Maximum concrete strain

The maximum concrete strain for concentric loading (normal forces) is limited in (EC 2, 2011) with $\varepsilon_c \leq -2.0$ ‰. DIN 1045-1 which was the German equivalent code to (EC 2, 2011) allows $\varepsilon_c \leq -2.2$ due to effects concerning creep and shrinkage without calculation. This would cause a steel stress of $\sigma_s = 2‰ \cdot 200{,}000$ N/mm² = 400 N/mm² which is much lower than the design yield strength of $f_{yd} = 670 / 1.15 = 582$ N/mm². For an economical design it is important to increase concrete strain up to about $\varepsilon_c = \varepsilon_{yd} = 582 / 205{,}000 = 2.84$ ‰. This can be provided by calculating the effects due to creep and shrinkage (see Fig. 5, (EC 2, 2011) and (Falkner et al, 2008)).

Columns in high rise buildings are not loaded abruptly. They are loaded step by step. Months or years are needed to finish the building construction and for application of the full characteristic load. During this time, concrete redistributes the load to the steel (see Fig. 5).

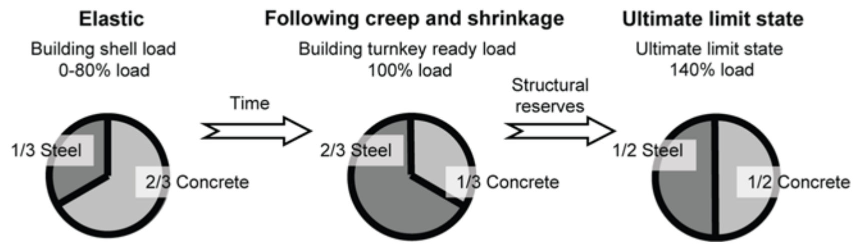


Fig. 5: Load redistribution of a column (Falkner et al, 2008)

Due to these effects concrete is unloaded and can be reloaded for ultimate limit state. The stress-strain-curve is modified and steel can be loaded to yield strength (see Fig. 6a). The strain difference $\Delta\varepsilon_{cs}$ includes effects due to load transfer from concrete to steel and unloading of the concrete.

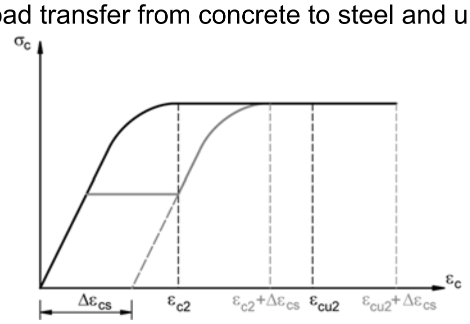


Fig. 6: a) Stress-strain relation for concrete with and without creep and shrinkage (Falkner et al, 2008)

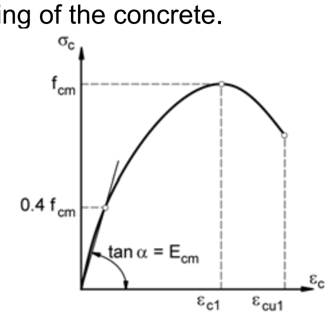


Fig. 6: b) nonlinear strength-stress relation for concrete according to (EC 2, 2011)

3.1.4 Further considerations

In addition to the consideration of creep and shrinkage, a nonlinear calculation of the bearing load of a cross section can be performed. The nonlinear stress-strain-relation is given in (EC 2, 2011) (see Fig. 6b).

It is obvious that the peak of the curve is at ε_{c1} (for example: C 30/37: $\varepsilon_{c1} = 2.2‰$, $\varepsilon_{cu1} = 3.50‰$). In Fig. 7b, the bearing capacity for different reinforcement ratios are shown. For low ratios ($\rho \approx 4$ %) the concrete carries more than 50%, for high ratios concrete carries only 10% to 20% of the ultimate load. Therefore, depending on the concrete strength, the bearing capacity will increase up to yield strain ($\varepsilon_{yd} = 2.84‰$) of the steel even without any effects concerning creep and shrinkage (see Fig. 7a).

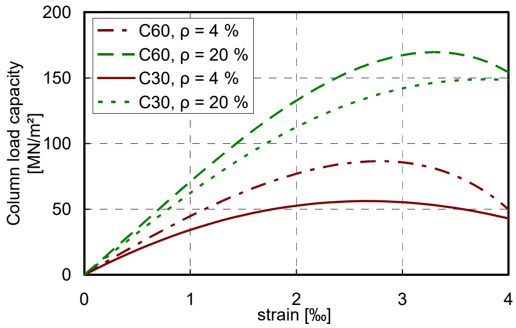


Fig. 7: a) Bearing capacity of 1m² column depending on the reinforcement ratio and concrete strength

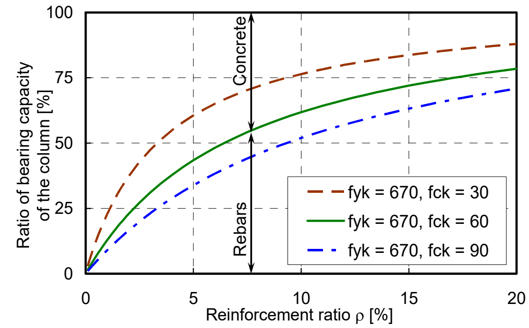


Fig. 6: b) ratio of bearing capacity of concrete and reinforcement of a column

This shows the advantage of using high strength reinforcement. For columns the absence of a well defined yield point does not provide any disadvantage. Only in the use of compression controlled flexural members a realistic stress strain curve has to be used for calculations as otherwise a brittle failure mode might occur.

3.2 ACI 318

ACI 318-14 (ACI 318, 2014) gives different restrictions depending on the field of application for the rebar (see Fig. 8). For longitudinal reinforcement, the maximum yield strength for design is f_y = 550 N/mm² (80 ksi). A further limitation is the maximum compression strain of concrete of ε_{cu} = 0.003. A main rule of design is the strain-compatibility of concrete and reinforcement. The yield strength of reinforcement can be found either by the 0.35% strain method or the 0.2% offset method. The theoretical maximum yield strength with the 0.35% strain method would be $f_{y,max.}$ = 0.0035 × 200.000 = 700 N/mm² (= 101 ksi). Using the strain limit of concrete, the maximal possible yield strength would be
$f_{y,max.}$ = 0.0030 × 200.000 = 600 N/mm² (= 87 ksi).

HSR is approved in the US by ICC-ES (ESR 1163, 2015) to be used for columns and shear walls with the full capacity. Different other approvals for similar steel grades (Grade 100 (ESR 3367, 2016)) would allow the use of fy = 690 N/mm² (= 100 ksi) for lateral support reinforcement. The limitation of f_y = 550 N/mm² (= 80 ksi) was driven by available reinforcement grades in the USA. ACI 318-14 (ACI 318, 2014) limits the concrete strain with 0.003. The commentary states that the actual test results “vary from 0.003 to higher than 0.008 under special conditions” (ACI 318, 2014).

Table 20.2.2.4a—Nonprestressed deformed reinforcement

Usage	Application	Maximum value of f_y or f_{yt} permitted for design calculations, psi	Applicable ASTM specification: Deformed bars	Deformed wires	Welded wire reinforcement	Welded deformed bar mats
Flexure; axial force; and shrinkage and temperature	Special seismic systems	60,000	Refer to 20.2.2.5	Not permitted	Not permitted	Not permitted
	Other	80,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	A184[1]
Lateral support of longitudinal bars; or concrete confinement	Special seismic systems	100,000	A615, A706, A955, A996, A1035	A1064, A1022	A1064[2], A1022[2]	Not permitted
	Spirals	100,000	A615, A706, A955, A996, A1035	A1064, A1022	Not permitted	Not permitted
	Other	80,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted
Shear	Special seismic systems	60,000	A615, A706, A955, A996	A1064, A1022	A1064[2], A1022[2]	Not permitted
	Spirals	60,000	A615, A706, A955, A996	A1064, A1022	Not permitted	Not permitted
	Shear friction	60,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted
	Stirrups, ties, hoops	60,000	A615, A706, A955, A996	A1064, A1022	A1064 and A1022 welded plain wire	Not permitted
		80,000	Not permitted	Not permitted	A1064 and A1022 welded deformed wire	Not permitted
Torsion	Longitudinal and transverse	60,000	A615, A706, A955, A996	A1064, A1022	A1064, A1022	Not permitted

[1] Welded deformed bar mats shall be permitted to be assembled using A615 or A706 deformed bars.

[2] ASTM A1064 and A1022 are not permitted in special seismic systems where the weld is required to resist stresses in response to confinement, lateral support of longitudinal bars, shear, or other actions.

Fig. 8: Maximum yield strength for reinforcement according to (ACI 318, 2014)

Also for the ACI based design, the same considerations as shown in chapter 3.1 for long term effects are valid. Again a higher strain than 0.003 can be achieved in calculating the stress-redistribution.

3.3 CSA A23.3

The regulations in CSA A23.3 are similar to ACI – especially the safety concept. But the deviation between CSA and ACI is, that CSA would allow a maximum compressive strain for concrete of ε_{cu} = 0.0035 (similar to Eurocode 2) and does define the limit for f_y to 400 N/mm² or the stress corresponding to a strain of 0.0035. The maximum yield strength of a bar could be $f_{y,max.}$ = 0.0035 × 200.000 = 700 N/mm² (= 101 ksi). This regulation is to some degree contrary to CSA A23.3 Clause 8.5.1. According to this clause, the yield strength shall not exceed 500 N/mm².

A general limitation of yield strength for reinforcement might be based on test data and empiric derived design formulas. In any event, for compression members neither deflection nor crack width limitation are important and hence there is no reason to limit the yield strength of the reinforcement lower than the stress corresponding to the crushing strain of concrete.

HSR further allows a less brittle failure mode for columns and give additional “hidden” safety as it can take additional load and allows a load redistribution close to failure from concrete to steel (see Hude, 2013; Mueller et al., 2012).

4 EXAMPLES OF USE

670W has been used successfully in multiple construction projects, changing the skyline landscape throughout major cities around the world. High rise buildings in Kuala Lumpur (Malaysia), Warsaw (Poland), Frankfurt (Germany), Miami and New York City (USA) among others were successfully built with HSR. In this paper only a few examples can be shown.

These systems are now present in multiple applications ranging from foundation to superstructure work. When combined with currently available methods of Building Information Management (BIM), using the threadability of HSR a modular system called “High Strength Reinforcement System” (HSRS®) was developed. This provides maximum efficiency in the construction process. The versatility and relative ease of installation of an HSRS® allows for the optimization of the reinforcement inside the section of structural concrete members. This provides advantages such as material savings, reduced labor times and improved quality of construction among others. 670W can also provide this advantages using stick building method as it will reduce the total steel quantity up to 40% compared to 400W.

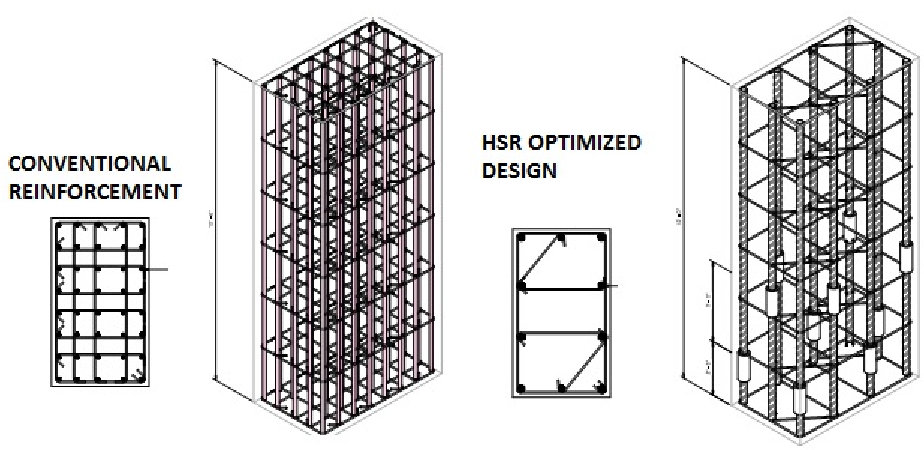


Fig. 9: Reinforcement conversion and layout optimization

4.1 Foundation Applications

Large bar diameters of high strength reinforcement can be a very cost effective option in foundation work. It can be used as the main reinforcing system or as an alternative to embedded steel members in concrete sections for deep foundations.

The use of threaded bars and mechanically coupled connections can eliminate complicated welded splices. Also, the bar threading has been proven to yield a high level of bond strength with the surrounding concrete. This application presents benefits in multiple aspects such as required labor, assembly times and inspection work for welding.

Very high reinforcement ratios can be accommodated and even two layers of reinforcement can be coupled (see Fig. 10).

Fig. 10: a) Multi-ring Caisson splice concept

Fig. 10: b) 55 Hudson Yards_ Caisson splicing

4.2 Super structures

670W is proving to be a cost efficient alternative on projects with a wide range of applications. From decongesting heavily reinforced sections, to allowing for fabrication off site on constricted jobsites using cages, the system aims to provide a feasible alternative for concrete construction. The combination of high strength concrete, HSR and innovative design tools has helped to bring this concept as an alternative to structural steel construction.

Fig. 11 shows the application of HSR in modules in New York City. One of this 63.5mm bars 670W (#20, Gr. 97) does replace 5 bars 35mm 400W (#11, Gr 60). It is obvious that common reinforcement would be impossible to be assembled in the same cross sectional area.

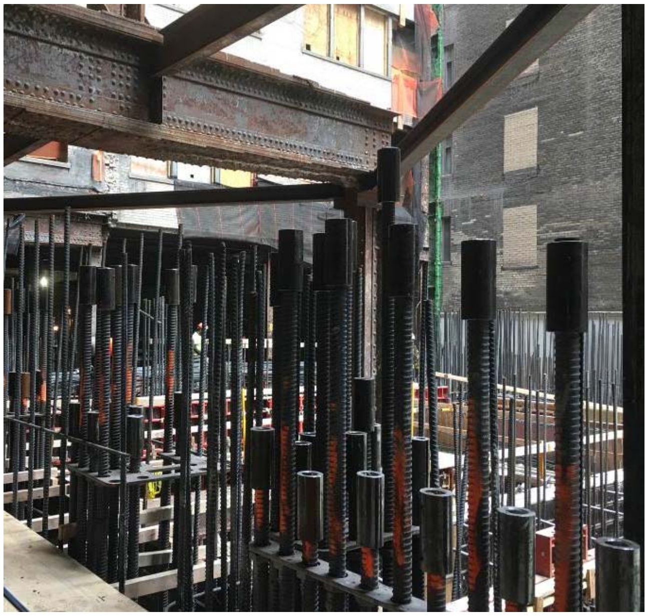


Fig. 11: a) HSR clusters and modular system

Fig. 11: b) Module pick up

A new high rise structure being built on 53 W53rd Street is a great example of the use of high strength systems. Commonly known as the MoMA Tower building, this structure is manly comprised of high strength concrete in combination with HSR. The complex geometry of the building and the challenge of reinforcing common framing joints identified as nodes, were best addressed by the use of HSR. Working together with the design team, a steel node concept using load bearing gusset plates, threaded bars and accessories was developed and implemented in critical joint connections. This approach reduced fabrication and erection times significantly. By using accessories designed for the HSR and threaded connections, the welding operations of the gusset plates within these joints were optimized and simplified benefiting the project significantly. (see Fig. 12)

In addition to the placement of reinforcement, coordination was also critical for the erection and installation of the big gusset plates at the core of the joints. Once all reinforcing steel entering the joints was modelled, the reinforcement layout dictated the shape of the plates and the size of the nodes.

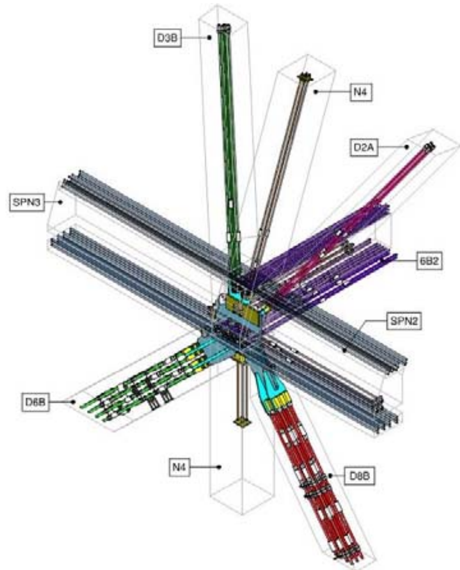


Fig. 12: a) Joint details at Node location

Fig. 12: b) Node erection and installation

5 CONCLUSION

Thread bars 670W have been used in geotechnical applications for over 10 years. Their versatility and improved mechanical properties led the way for use of the bars as concrete reinforcement in several other applications. High strength reinforcement fulfils all requirements to be used as reinforcement (high ductility, good bond behavior, low relaxation and low stress corrosion risk) and surpass the strength parameters of common reinforcement. Bond strength of high strength reinforcement is significantly higher compared to common reinforcement in normal strength concrete and it is slightly higher with UHPC.

The main advantage of using high strength reinforcement is high ductility and a remaining post failure load capacity.

In recent years, Architects and owners have increased their requirements for new buildings. These requirements concern structural safety, visually attractive design, high sustainability and a small ecological foot print. To fulfil all these requirements, it is important to use high performance products along with innovative methods aiming to optimize building members. Benefits related to production process, cross section decongestion and durability are achieved by the use of HSRS®.

As demonstrated by recently completed high rise structures and currently ongoing projects, the use of High strength reinforcement in combination with UHPC will help optimize the performance and construction of heavily reinforced concrete sections in new structures

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