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NIOBIUM-BEARING CONSTRUCTION STEELS AND GLOBAL APPLICATION TRENDS

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Abstract

The technological development of value-added applications for niobium (Nb) microalloyed construction steels continues globally for both low and high yield strength applications. The civil engineering and end user community demands structural bars, shapes, beams and plates with improved properties. Properties such as toughness, better fire and seismic resistance, yield-to-tensile ratio consistency and improved weldability are end user desires for both low and high yield strength construction applications. Nb-bearing construction steels have been and will continue to be developed to address these more demanding applications in both the low and high yield strength construction sector. Various Nb structural steel technologies are applied dependent upon the specification requirements, cost benefit considerations and competitive market conditions. These technologies and market dynamics are described. For example, several mills within the construction beam sector have adopted the application of 0.02 to 0.04%Nb and reduced the carbon content for lower strength (S355 and S420) steels with improved mechanical property performance and weldability compared to traditional peritectic construction steel grades. Operational cost reductions are experienced by the steel producer as well when the Nb low carbon low alloy concept is adopted. Advanced Nb-bearing high strength structural steels have also been developed. Another evolving Nb product segment involves the high carbon long product pre-stressed concrete wire rod market. Micro additions of .005 to .020%Nb exhibit improved wire drawability during manufacturing as well as improved mechanical properties compared to traditional non-Nb bearing high carbon steels. Finally within the low carbon construction sector, the shift from the high volume heavier gauge S235 and S275 construction grades to lower carbon Nb-bearing S355 lighter gauge steels offer potential to reduce construction cost with a favorable environmental impact on the carbon footprint.

Introduction

Value-added niobium (Nb) bearing microalloyed plate steels continue to be researched, developed and commercially implemented throughout the world. These steels successfully meet the ever-increasing material demands for improved mechanical properties and in-service performance for demanding 21st century structural applications. Such material and civil engineering design demands require Nb-bearing steels that deliver higher strength at thinner cross sections, improved toughness, fracture and fire resistance, reduced yield-to-tensile variation and improved weldability. Applications span diverse global construction market segments such as buildings, skyscrapers and industrial complexes, wind towers, reinforcing bars, pre-stressed concrete wire rods and several other uses in which niobium continues to provide an important role in steel because of the enhanced properties that can be attained over conventional construction steels.

Another key consideration is the ever-growing concern about the environment and resources. Structural design in the 21st century must take these environmental responsibilities into consideration. The application of these new, advanced high-strength Nb-bearing steels for structural applications contributes to a reduction in the carbon footprint and material resource sustainability. In addition to the steelmaking impact, construction activity can cause significant emissions of CO_2 gas. The structural designers will endeavor to reduce emissions of greenhouse gases through the selection of green materials as structural components, including steel.

The unique metallurgical attributes that Nb provides in structural steels create the opportunity to not only meet future environmental challenges and demands, but also successfully meet stringent mechanical, corrosion and elevated temperature construction demands. Historically, Nb-based structural steels were in limited production during the 1980’s. Over the last two decades, through the numerous Nb-bearing structural steel global research and development project activities conducted by steel mills, universities, research institutions and CBMM, significant progress has been achieved in the develop of more environmentally friendly construction steels. Nb-bearing structural products are now specified in a variety of applications and markets. The diverse array of structural steel markets, future potential and application trends is discussed herein. Application of microalloyed steel designs to fundamental steel construction projects will make a significant positive contribution to the long term carbon footprint. Applications of value-added Nb-bearing steels can reduce the overall material and construction costs for many advanced high strength structural and civil engineering applications.

Background

Increasing the longevity of structures is a very effective means of reducing the carbon footprint and long-term infrastructure cost. Usually the lifetime of the buildings terminate as a result of deterioration and out-of-date facilities. The deterioration of structural components is not always the reason for demolition in many cases, but rather the structural framework that becomes inadequate for users.

Approximately 350 million tonnes of construction steels are simple heavy thickness carbon manganese (C-Mn) steels that do not contain microalloy and hence, are not defined as High Strength Low Alloy (HSLA). These C-Mn steels involve structural sections, angle and channel long products and plates. Replacement of these thick section C-Mn steels provide an enormous opportunity to reduce weight and cross sectional thickness of structural components through the adoption of HSLA and hence, the reduction of greenhouse gases and carbon footprint.

Although there are different civil engineering designs and many diverse product applications in the structural market, the Nb metallurgy and production strategy to manufacture these steels often remain the same. Cross-application of similar Nb microalloy steel grade systems are specified for different end user requirements. Today's structural steels demand properties such as: 1) improved toughness at lower temperature, 2) higher yield strengths for lower cross sectional area of structure, 3) higher elongations, 4) improved weldability to reduce construction time, 5) improved elevated temperature properties, 6) improved fracture toughness, 7) seismic-resistance and 8) improved fatigue resistance.

Considering the requirements in structural design previously discussed, steel is the preferred structural material. Steel can be produced in large quantities and usually in relatively consistent quantity, although there are areas of improvement concerning residual and impurity contents in the commodity S235 and S275 C-Mn grades and in some cases, even the HSLA S355 low strength construction grades depending upon the steel producer. Of course, steel members are recycled. However, further improvements aiming at producing anti-corrosion steel, fire resistant steel and also steel provided with high fracture toughness. High fracture toughness demands of common structural materials such as S355 structural components led to the comprehensive windtower development project.

The cross-application of microalloy-bearing HSLA steels has been applied for many years in steel mills throughout the world. This practice has resulted in limited structural design enhancements with improved properties for some construction products when the steel cannot be applied to offshore platforms or oil and gas pipelines.

Niobium-Bearing Construction Steel Structural Application Overview

The carbon steel construction segment is one of the largest product segments within the global structural steel segment. In 2011, nearly 500 million metric tons of construction steel bar, beam, plate, section and wire rod production supply the global construction industry needs. This specification covers carbon manganese steel shapes, plates and bars of structural quality applied on riveted, bolted, or welded construction of buildings and for general structural purposes. Nucor applications specifically include both bar and narrow plate (maximum width of 355mm) for construction frames, metal building systems, structural steel shapes, trusses and weldable construction systems. The major construction steel product segment distribution for 2011 is shown in Figure 1.

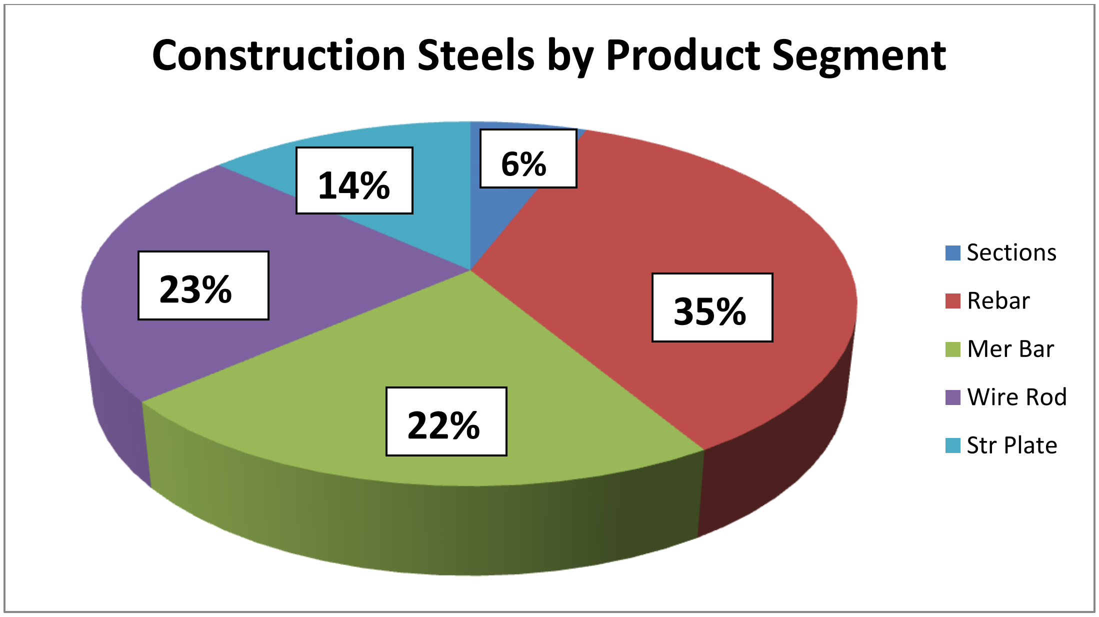


Figure 1. 2011 Construction Steel Distribution by Product Sector

Within the construction steel segment, approximately 70 percent of the steel currently produced is still non-alloyed carbon manganese (C-Mn) steel grades. The highest Nb usage is currently with the structural sections segment (beams, angles and channels) in grade S355 and S420 structural plate for windtower and construction plate for both industrial and non-industrial buildings. Advanced high strength microalloyed construction grades from S460 to S890 represent the balance.

Niobium usage in the rebar market is an evolving recently developed market. Traditional lower strength grades are taking advantage of Nb to reduce rebar weight on projects as well as improve the nesting in concrete structures. A recent development is the commercialization of value-added S500 and S600 seismic and fire resistant rebar.

Within the merchant bar and wire rod sector, Nb usage has been quite limited to date. Within the long products sector, the addition of Nb in high carbon and alloy long products has been limited to date, but is increasing in popularity and application.

Low Strength and Advanced High Strength Construction Steel Differentiation

Different from the automotive or pipeline segment where carbon levels are typically less than 0.10%, many of the plate structural products exceed 0.15%C approaching allowable specification maximum carbon levels of 0.22% on many S355 grades and some S420 grades due to perceived lower cost. Consequently, there is a still a preponderance of structural plates and beams produced throughout the world with carbon levels greater than 0.18%C. There are various reasons for this as it relates to miscalculated cost, process metallurgy, mill configuration and furnace reheating efficiency and performance. Some mills choose the higher carbon level approach to achieve strength, but sacrifice toughness, weldability and product performance. [1] Some mills decided against the adaptation of a more efficient heating and rolling operation to accommodate low carbon microalloy mechanical metallurgy practices. Similar situations also exist in several plate mills rolling construction plate. Hence they have not taken full advantage of the Nb solution to lower carbon levels which increases yield strength, ductility, toughness and weldability.

Within the higher strength or advanced higher strength construction grades, defined as S500, S550, S690 and S890, low carbon and traditional microalloyed TMCP practices have been adopted. In these cases, the application of higher Nb-bearing steel influences the grain refinement and toughness since rolling takes place at higher temperatures. Furthermore, high strength structural steel grades with yield strengths up to 960MPa have been produced with different levels of Nb. [2]

Some sectors of the construction design and steelmaking sector perceive that Nb only applies to higher strength construction steels exceeding approximately 420MPa. This relationship is quite evident within the end user and civil engineering community. However, recent Nb technological innovations have developed beam and plate applications with enhanced fatigue and fracture toughness in low carbon low alloy (LCLA) S355 grades of steel for construction applications. Some case examples of these lower strength Nb-bearing structural grades are presented.

The adoption of the as-rolled Nb-LCLA technology is replacing the traditional higher carbon Nb or V normalize heat treated grades for lower strength construction beam applications for skyscrapers and structural plates for windtowers. The distribution of the family of structural steel grades is illustrated below in Table 1.

Table 1. Construction Segment Strength Grade Distribution

Commodity C-Mn	**Low Strength HSLA**	**Advanced High Strength**
S235/S275	**S355/S420**	**S460 to S890**
70%	**25%**	**5%**

A significant tonnage of approximately 100 mm tonnes of construction steels that receive a normalize heat treatment because it is a peritectic medium carbon steel chemistry. Elimination of this heat treatment step realizes a massive reduction in the carbon footprint, reduced energy consumption and a reduction in the production cost per tonne. The Nb windtower structural support case example is later discussed.

Microalloy Design Considerations for Low Strength Low Carbon Construction Steel Sections and Plates Applications

In view of the recent demand for alternative high strength structural beam chemistries and associated economic and processing cost factors, the niobium microalloying approach has been adopted and considered for the production of large structural beams with improved mechanical properties. Structural S355 beams with the desired strength-toughness combination can be successfully obtained by the effective use of niobium-microalloying design approach and TMCP rolling practices. The niobium-microalloyed steels exhibit outstanding notch-toughness at -40^{o}C compared to other traditional V-microalloy design systems. Detailed investigations involved stereological analysis and electron microscopy validating that toughness is strongly influenced by microstructural features.

The impetus for this work was a concerted effort to differentiate the V-bearing S355 structural beams from the Nb-bearing beams product quality performance. The reduction in carbon content from 0.15%C to the 0.08-0.10%C range coupled with the Nb-addition (0.02-0.04%) provide both improved weldability and toughness at reduced cost. The second objective was driven by the civil engineering and design community who demanded beams with improved toughness. The beam chemical composition range shown below is congruent with the ASTM A992 chemistry specification is outlined below in Table 2.

Table 2. Chemical Composition Range of Nb- and V-Microalloyed Construction Steels

Elements	**Nb-microalloyed steel (wt.%)**	**V-microalloyed steel (wt.%)**
C	0.030-0.100	0.030-0.100
Mn	0.500-1.500	0.500-1.500
V	0.001	0.020-0.050
Nb	0.020-0.050	0.001
Si	0.15-0.25	0.15-0.25
P	0.010-0.020	0.010-0.020
S*	0.015-0.025	0.015-0.025
N**	0.009-0.010	0.009-0.010

* ≤0.008% S dependent upon design and beam application
** Electric arc furnace steels

Research and development resulted in the successful commercialization of Nb-bearing beams replacing V-bearing beams with significant toughness improvements. The adoption of this Nb-Low Carbon Low Alloy (LCLA) technology has produced over 20 million tonnes of structural beam production globally to-date. The ASTMA992 beam (S355) study was based on industrial heats which then lead to the commercialization of low carbon Nb-bearing beam in place of a low carbon V-only bearing beam. The incorporation of Nb technology has significantly improved the beam toughness properties through grain refinement and strategic cooling practices during rolling. The Nb addition refines the grain by 2 ASTM sizes, lowers the carbon equivalent by 0.07% and improves the toughness. Near net shape cast structural beams containing only a single Nb microalloy exhibit double the impact strength at room temperature compared to a V-only microalloy system at similar sulfur, phosphorous and nitrogen levels and cooling rates as illustrated in Figure 2. [3]

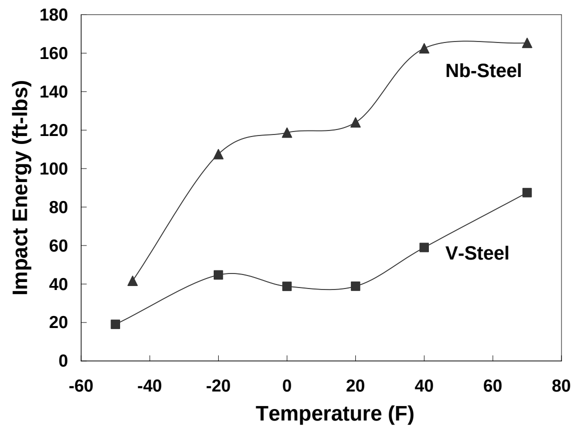


Figure 2. Charpy V-notch impact strength comparison – Nb vs. V

A second part of the study investigated a comparison of different cooling rates. Micrographic analysis revealed that the primary microstructural constituents at a low cooling rate were polygonal ferrite and pearlite. At intermediate and high cooling rates, the microstructure consisted of lath-type/bainitic ferrite and degenerated pearlite together with conventional ferrite-pearlite. With an increase in cooling rate, there was an increased tendency towards formation of lath ferrite/bainitic ferrite with a consequential decrease in the conventional ferrite-pearlite microstructure. [4] Figure 3 illustrates the influence of Nb on the transformation to the formation of degenerated pearlite which contributes to the improved toughness. No degenerated pearlite was observed in the V-bearing steel grade.

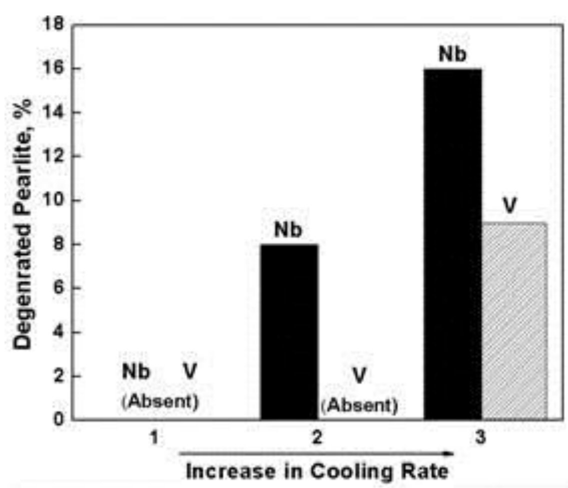


Figure 3. Percent Degenenerated Pearlite versus Cooling Rate – Nb and V Comparison

A combined Nb-V microalloy approach is currently under development for heavy beam S420 sections with industrial trials currently in progress. The application of low sulfur calcium shape control is also being employed to further improve toughness on the low carbon grade.

Nb-Low Carbon Low Alloy Wind Tower Application

Within the windtower sector, the end user requirement to improve power generation efficiency requires construction of towers to higher elevation. However, at that time, fatigue and fracture toughness limitations of the traditional steel structural supports moved designers to consider carbon fiber composites. As a result of this threat of carbon fiber composite substitution for the HSLA S355 structural steel supports, a new steel material design was required to halt the threat. With the proven success of the beam applications, the Nb-Low Carbon Low Alloy (Nb-LCLA) as hot rolled product provided a viable, cost effective solution.

Wind Tower Design Trends and Challenges

This decade will see a further increase in the height of wind towers presenting new materials and civil engineering challenges. In the past 15 years of wind energy growth, the current trends of the industry are 80, 90 and now over 100 meter towers being introduced in Europe and North America. Turbines have increased in size to 2.0MW, 2.5MW, 3.0MW and increasing to 4.5MW. The dead load of these higher elevation structures are surpassing 2600kN (600kips). Consequently, structural dynamics, frequency response, fatigue and fracture toughness properties of materials and soil-structure interactions become increasingly important.

With these industry demands, the designers and fabricators must consider the current market demographics including such issues as budget constraints, alternative materials for these higher towers, the necessity for cost-effective design and materials of construction. The windtower growth trend will continue for the next 10 years in both the mature as well as evolving markets around the world. Many of these countries embrace wind energy as a sustainable, cost effective and environmentally-friendly green solution.

Windtower designs will transcend beyond the traditional pole-tube design into special shapes with improved materials, for both S355 and S420 and, in some cases higher strength steels, that will better accommodate these higher dynamic stresses, complex loading and vibrational fatigue conditions experienced during the operation of these higher structures.

The cost-benefit considerations are higher for structures that translate into higher efficiency, lower cost per MW generated and stronger structural tower capacity. Considering these increased structural steel demands, fatigue and fracture toughness structural steels were examined. A joint research fatigue and fracture toughness study was performed comparing normalized versus as-rolled industrially-produced Grades S355 plate steels for windtower construction. [5] There has been very little recently published on the fatigue and fracture toughness properties of these structural steels. Therefore, such data was created in this research for S355 structural steel plate produced via 21st century steelmaking and hot rolling practices.

Industrial Trial Rolling Comparison

Since the higher 0.015%C plate steels are very popular globally for this application, industrial heats were produced for both the low and medium carbon grades. Medium S355 C grades are produced due to the normalizing heat treatment requirement in some windtower specifications. Figure 4 illustrates the loss in strength due to heat treatment.

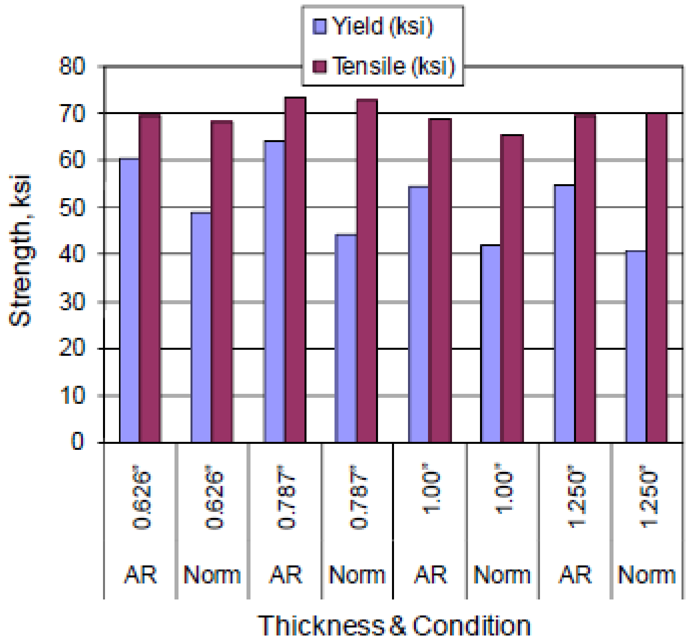


Figure 4. Effective Loss of Yield Strength Due to Normalize Heat Treatment

Industrial heats were produced to compare Low C-Nb with Medium C-Nb as-rolled product versus Medium C-Nb normalize heat treated product. The compositions are listed below in Table 3.

Table 3. Chemical Compositions of Nb-LCLA vs. Medium Carbon [5]

Steel	C	Mn	P	S	Si	Cu	Ni+Cr+Mo	Nb	CE[1]
Low C – Nb	0.06	1.27	0.011	0.001	0.34	0.27	0.41	0.031	0.35
Med C – Nb	0.15	1.39	0.012	0.003	0.22	0.20	0.32	0.019	0.43
Med C – Nb Norm	0.15	1.32	0.011	0.003	0.21	0.22	0.23	0.014	0.42
ASTM A572-50 & A709-50 (max)	0.23	1.35	0.04	0.05	0.40	-	-	-	-
EN 10025-2 S355K2 (max)	0.23	1.70	0.035	0.035	0.60	0.60	-	-	0.45
[1]CE = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15									

The comparison of the impact properties of the three steels exhibits a consistent upper shelf for the Low C-Nb in both the transverse and longitudinal directions and superior impact toughness of 265 ft-lb in the longitudinal direction and 250 ft-lb in the transverse direction at -100°F as shown in Figure 5.

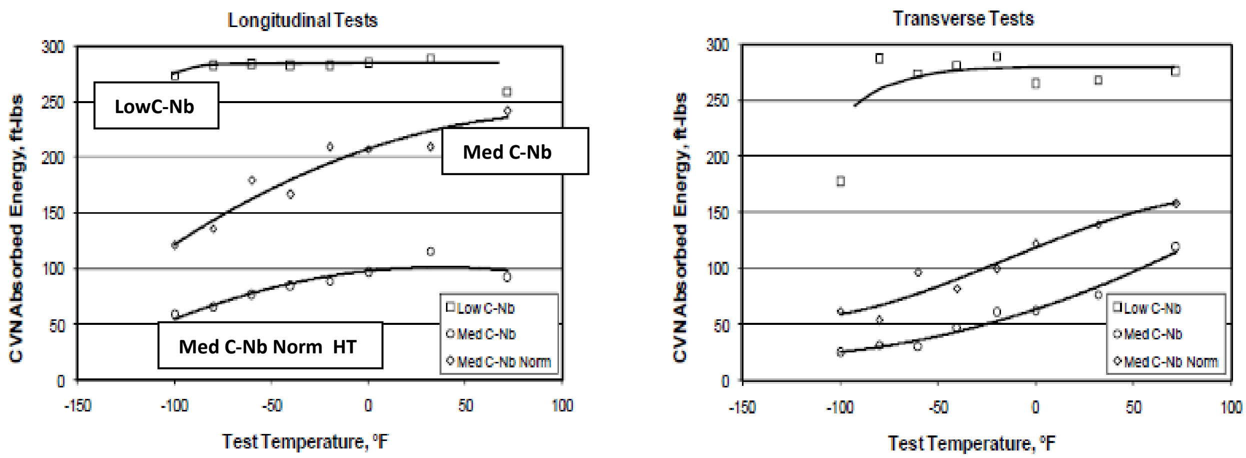


Figure 5. Charpy Vee-Notch Absorbed Energy [5]

<u>Fatigue and Fracture Toughness Implications of As Rolled vs. Normalize Heat Treated</u>

There is very little fatigue and fracture toughness data available in the literature for 21st century produced structural plate steels such as S355. Hence, this research work was performed to determine the fatigue and fracture toughness of these important parameters for designers. Improved fatigue and fracture toughness properties of the as-rolled Low C-Nb compared to the as-rolled Medium C-Nb and Medium C-Nb heat treated are remarkable on these industrially produced heats. Table 4 summarizes the mechanical property results for the industrial heats.

Table 4. Mechanical Property Comparison [5]

Steel	YS (ksi)	UTS (ksi)	-60°F TCVN (ft-lbs)	Upper Shelf TCVN (ft-lbs)	Fracture Toughness, K_{Ic} (ksi/√in)	Fatigue Endurance Limit, S_e (ksi)
Low C – Nb	65	76	270	280	375	44
Medium C – Nb	64	82	30	120	235	39
Medium C – Nb Normalized	57	77	80	160	250	35

The fatigue and fracture toughness performance of the medium carbon normalized rolled and/or normalize-heat treated plate steels deteriorates compared to as-rolled low carbon Nb-bearing windtower plates. In these ferrite-pearlite steels, the damage generally occurs in the ferrite as opposed to the pearlite, which can arrest cracks from propagating. [6] Ferrite which has been more effectively strengthened by Nb(C,N) precipitates (e.g., Low C-Nb steel) will exhibit greater cyclic hardening. [7] This greater cyclic hardening provides more resistance to slip, thereby leading to a higher fatigue endurance limit.

Based on the fatigue and fracture toughness data performance, the implications of specifying the EN 10025 normalized rolling delivery condition which is common by windtower designers are clear. The steel chemical composition constraints imposed by the EN 10025 normalized rolling requirement result in wind turbine tower plates with reduced weldability, toughness and fatigue resistance.

Higher production cost are associated with the Med C normalize heat treatment route. Steelmaking costs are higher compared to the Low C-Nb approach and the normalize heat treatment. Castability and slab surface quality is significantly improved for the Nb-LCLA composition based upon application of this approach in structural products such as beams, windtower supports and other general construction steels. Improved castability is measured through increased casting speed and lower rejects due to surface and internal casting defects because the peritectic issues are eliminated.

There are several implications of this development as it relates to future windtower designs involving specifications, the selected carbon level and steelmaking/rolling practices. Consideration of future civil engineering design challenges and market trends for higher elevation windtower designs, several specification and chemistry issues need to be addressed. The second implication involves cost. The cost of steelmaking and welding in the Low C are less compared to the medium 0.15%C steel. The as rolled product exhibits both cost and metallurgical benefit attributes compared to the traditional higher carbon structural steels.

Nb and/or Nb-Mo Steels for Earthquake Zones & Fire Resistance Requirements

The development of seismic resistant rebar was initiated with the introduction of Nb to existing rebar grades. Increased sizes of reinforcing bars at greater than 40mm in diameter, high yield strength (greater than 450MPa) with improved weldability are required in concrete reinforcing bars for seismic zone construction. Microalloyed steels with vanadium have been traditionally used in rebar, but recently, the strong grain refinement effect of Nb has resulted in the increased development of Nb-bearing steels in concrete reinforcing bars for 450 to 550MPa strength levels improving ductility and toughness. The addition of Mo also offers improved fire resistant properties for an evolving market.

Currently a large quantity of rebar is produced with no microalloys incorporating the Tempcore process, however, ductility is reduced. The cooling scheme achieved through application of the Tempcore process with a Nb-Mo grade may be reduced or eliminated in the lower strength grades as well, resulting in reduced operating cost and increasing mill productivity. The Tempcore process is applied to reinforcing bars to increase the yield strength, but elongation, toughness and fatigue performance may be impaired due to the microstructure.

<u>Fire Resistant Plate Steels</u>

Fire-resistant constructional steels have been commercialized in some parts of the world (China and Japan) and are being examined in the USA. Current activities are focused on development of specifications for testing of elevated temperature properties. Some material specifications and niche applications (e.g. high-rise building columns, structures where friable insulated coatings are undesirable) will follow. Selected metallurgical studies are reviewed, with a focus on Nb-containing steels that are intended to help understand the microstructure/property relationships that control fire-resistant (FR) properties. Specific examples are cited which illustrate the apparent benefit of Mo in suppressing precipitate coarsening rates at elevated temperature, beneficial effects of microstructure refinement, microalloy precipitation, and warm working of ferrite on the FR properties.

Since structural steels usually maintain most of their strength at 350°C (and indeed some steels may be stronger at 350°C than at room temperature due to strain aging effects of interstitials), this requirement is effective and conservative, but quite restrictive that it drove development and implementation of newer steels with improved properties at elevated temperature. The FR steels produced in Japan for the past several years guarantee a minimum yield strength at 600°C that is 2/3 of the room temperature yield strength, i.e. having a minimum yield strength ratio of 2/3, and these developments have already stimulated implementation of FR steels in some niche applications. Some other design codes cite yield strength ratios of 50% at 600°C. [8]

With the evolving demand for fire resistance, it became apparent that a Nb-Mo based structural steel design could also improve fire resistance at the same time. Therefore, it was decided to study various compositions focused upon fire resistance behavior. So, the need for fire resistance in construction steels for high strength at elevated temperatures was defined in the USA. Also, there are very limited commercially available fire resistant plates produced globally. Simultaneously, work is being performed in China at Baoshan Iron and Steel Company as a result of the increasing demand for high performance fire resistant structural steels for use in commercial building-type applications. A low Mo-Nb approach via TMCP has demonstrated acceptable high temperature strength in China. [9]

Based upon the research and development of the USA research as well as other previous developments in Japan, specifically Nippon Steel [10], it was decided to create a task force within ASTM to study the possibility of writing an ASTM specification. An ASTM Fire Resistant Steel specification has been approved.

Experimental Nb-Mo Fire Resistant Steel Comparison

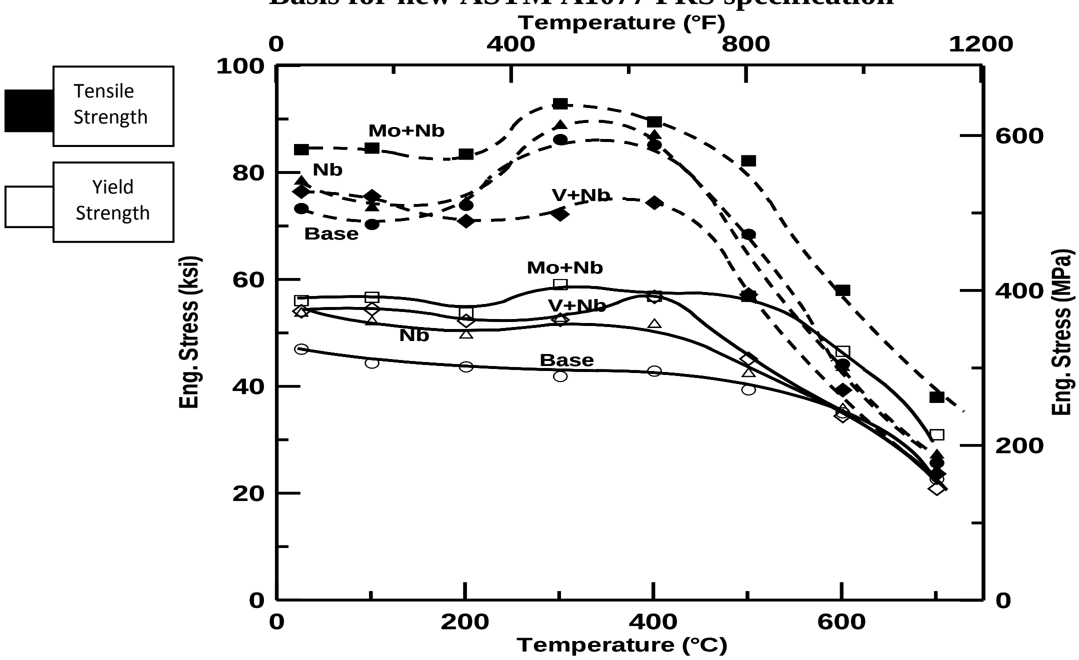
The new ASTM A1077/A1077M specification, “Standard Specification for Structural Steel with Improved Yield Strength at High Temperature for Use in Building,” has been approved by the standards committee and published in March 2012. The specification encompasses a Nb-Mo alloy design that retains two-thirds of its yield strength at 600°C. Table 5 compares the compositions to the commercially available Japanese FRS plate.

Table 5. Compositions of Experimental Fire Resistant Steels [11]

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Al	N
Base	0.11	1.16	0.018	0.013	0.19	0.25	0.08	0.17	0.02	0.004	0.001	0.002	0.010
Nb	0.10	1.06	0.005	0.031	0.27	0.39	0.16	0.09	0.047	0.001	0.021	0.003	0.016
Mo+ Nb	0.10	0.98	0.008	0.028	0.30	0.38	0.15	0.10	0.48	-	0.017	0.004	0.010
V+Nb	0.08	1.13	0.005	0.030	0.27	0.32	0.11	0.13	0.036	0.047	0.021	0.003	-
Nippon I	0.11	1.14	0.009	0.020	0.24	-	-	-	0.52	-	0.03	-	-
Nippon II	0.10	0.64	0.009	0.050	0.10	-	-	-	0.51	-	-	-	-

Figure 6 exhibits the superior elevated temperature properties of Nb-Mo plate steels compared to other ASTM A572 or ASTM A992 type construction steels.

Basis for new ASTM A1077 FRS specification



Nb-Mo retains 2/3 of its R.T yield strength at 600°C → **Basis for new ASTM FRS specification**

Figure 6. Yield and Tensile Strength vs. Temperature (25-700°C) for Base, Nb, Mo+Nb and V+Nb Alloys [11]

The Nb+Mo exhibit the best high temperature performance. The strengthening mechanism involves the co-precipitation of Nb,Mo(C,N) in a fine dispersion of 3 to 5 nanometers within the ferrite matrix. Figure 7 illustrates the co-precipitation of the Nb,Mo(C,N).

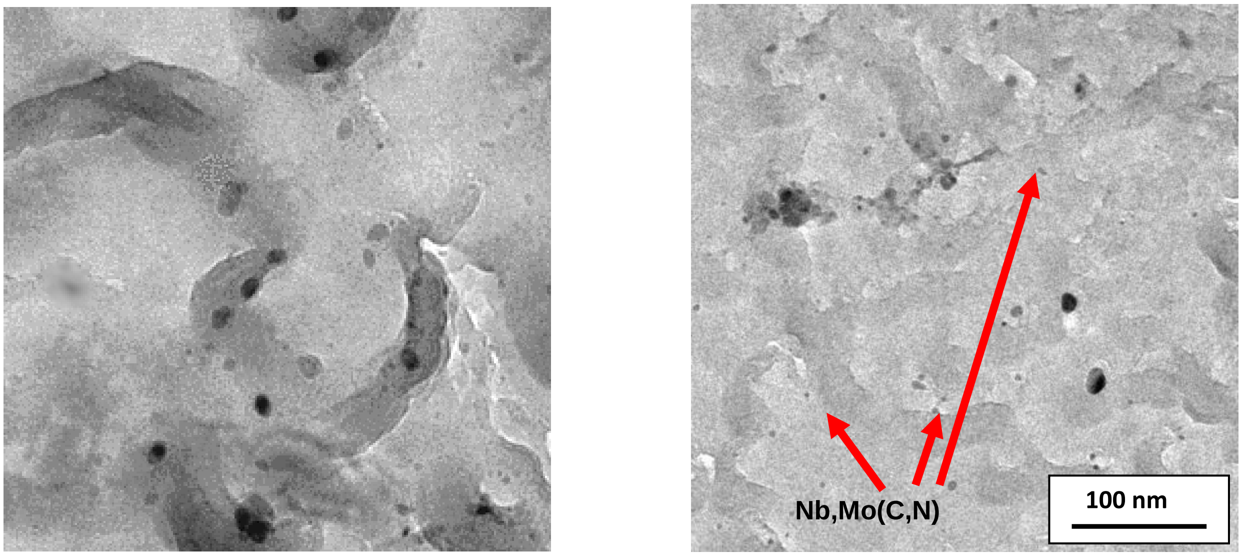


Figure 7. Co-precipitation of duplex Nb,Mo(C,N) precipitates in ferrite matrix

The diffusion of Nb and Mo at different carbon concentrations influences the precipitation kinetics. Initially, solute Nb and Mo will retard dislocation climb motion, dislocation recovery and grain boundary migration. However, as the temperature increases, the dislocations can go mobile at approximately 400 to 500ºC. Consequently, the yield strength reduction as exhibited in Figure 6. Finally as the fire ensues, the secondary precipitation of Nb,Mo(C,N) occurs and traditional Ostwald ripening mechanism is in effect. These metallurgical principles are now being transferred into the rebar product sector.

Nb Microalloy in High Carbon Construction Steels

In most cases, Nb has not been the microalloy of choice or even considered for that matter in most high carbon steels. The reason has typically focused on the lower solubility of Nb in higher carbon steels. Although there is lower solubility, the effectiveness of Nb in the grain refinement and precipitation strengthening mechanism in Nb, Nb-V and Nb-Mo steels has been demonstrated. Within the higher carbon steel segment in the past, research focused on Nb levels that were quite high with less than desirable results. Now, MicroNiobium levels of 0.05-0.020% prove extremely effective in improving product performance. Applications include Nb in eutectoid pre-stressed concrete wire rod and rail, Nb-V for power transmission components in windtower gear boxes and Nb-Mo in fire resistant value added reinforcement bar. [12, 13]

Historically, higher Nb levels (especially exceeding 0.040%) were thought to be necessary in order to obtain proper grain refinement, microstructural control and strength in higher carbon equivalent steels. However, high carbon metallurgical and production research and experience indicate high Nb levels in high carbon steels certainly make the processing more challenging and the resultant properties are not optimized. It is important to consider the synergistic precipitation behavior effect between the Nb and V and, in some cases, Mo which can contribute to the improved mechanical performance. This duplex or triplex microalloy complex precipitation behavior requires further study.

The application of the MicroNiobium high carbon steel technology mechanism, metallurgy and processing parameters has led to an enrichment of the opportunity to more widely introduce Nb into other high carbon steel products. This development has been invaluable for the implementation process to successfully incorporate these micro-levels of Nb (0.005-0.020%Nb) in existing high carbon steels to improve fatigue, fracture toughness, ductility, manufacturability and overall product performance.

MicroNiobium Alloy Approach® on Prestressed High Carbon Concrete Wire Rod

The application of the MicroNiobium Alloy Approach® in carbon steel long product and plate steels enhances both the metallurgical properties and processability and reduces the operational cost per tonne. The process and product metallurgical improvements relate to the Nb-pinning effect of the austenite grain boundaries. The metallurgical mechanism of the MicroNiobium Alloy Approach is related to the retardation of austenite grain coarsening during reheat furnace soaking of the billet, slabs or shapes before rolling. Although the Nb-solubility is limited when higher amounts of Nb are used in higher carbon steels compared to low carbon steels, through empirical evidence and actual operating data, the Micro-Niobium Alloy Approach has demonstrated very positive results on high carbon grades such as steel wire rods and bars, eutectoid steels, and other medium carbon engineering alloy applications.

The developmental chemistries were evaluated to determine the effectiveness of Nb, V or Nb-V concentrations on the pearlite interlameller spacing and mechanical properties in a eutectoid steel. Table 6 shows the chemistries and Table 7 the mechanical properties.

Table 6. Nb and V Eutectoid Chemistries

	C	Mn	Si	Cr	Nb	V
V1	0.80	0.70	0.20	0.15	0.0	0.09
V2	0.80	0.70	0.20	0.15	0.0	0.05
VN	0.80	0.70	0.20	0.15	0.02	0.05
N1	0.80	0.70	0.20	0.15	0.02	0.00
N2	0.80	0.70	0.20	0.15	0.04	0.00
N3	0.80	0.70	0.20	0.15	0.09	0.00
N4	0.80	0.70	0.20	0.15	0.12	0.00

Table 7. Mechanical Properties

Steel	YS 0.2% (N/mm²)	TS (N/mm²)	Reduct. of area (%)
S0	627	1086	30.4
V1	733	1154	26.8
V2	719	1154	22.9
VN	740	1169	38.0
N1	648	1139	45.1
N2	680	1102	41.4
N3	666	1115	38.4
N4	709	1150	35.8

Review of the mechanical property data shows the best elongation with Sample N1 which is the 0.02%Nb MicroNiobium Alloy design at 45.1% reduction of area. The yield strength, tensile strength and reduction of area is met as defined by SO in Table 7. The mechanism of this optimization of the Nb concentration in this high carbon eutectoid steel is the refinement of the lamellar spacing. As exhibited in Figure 8, the refinement of the lamellar spacing is the finest at 75nm with 0.02%Nb directly linking the superior elongation.

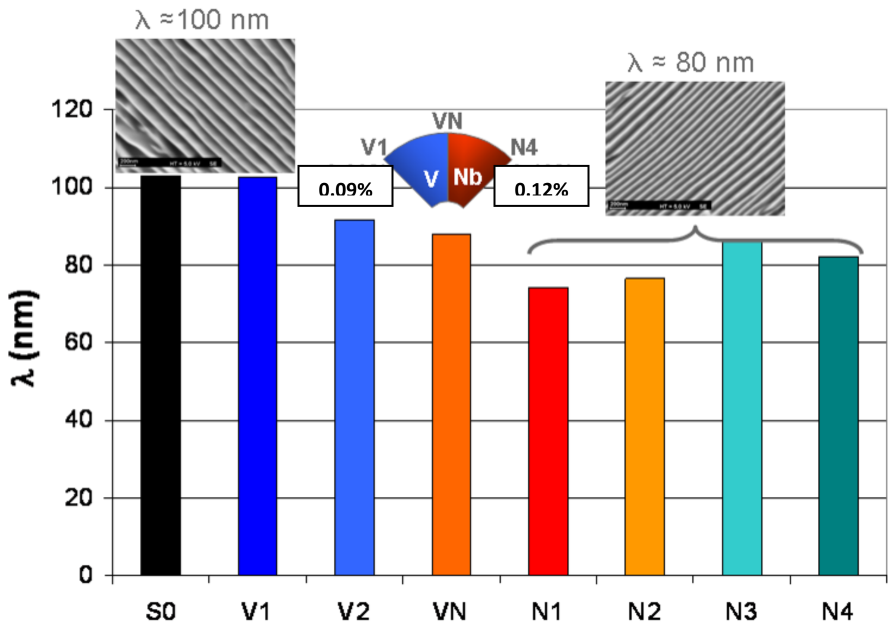


Figure 8. Interlamellar Spacing Refinement with MicroNiobium (μ-Nb) Addition in 1080 Steel

The master rods were then drawn into the final pre-stressed wire rod product. Figure 9 relates the reduction of area to the strain ratio of the initial diameter to the final product diameter. The optimum strain ratio for the industrial wire draw operation is between 1.50-1.80. The consistent 55 percent reduction of area (μ-Nb with the 0.02%Nb eutectoid chemistry) over this strain ratio range is excellent (i.e. flat) and results in increased productivity at the wire rod mill.

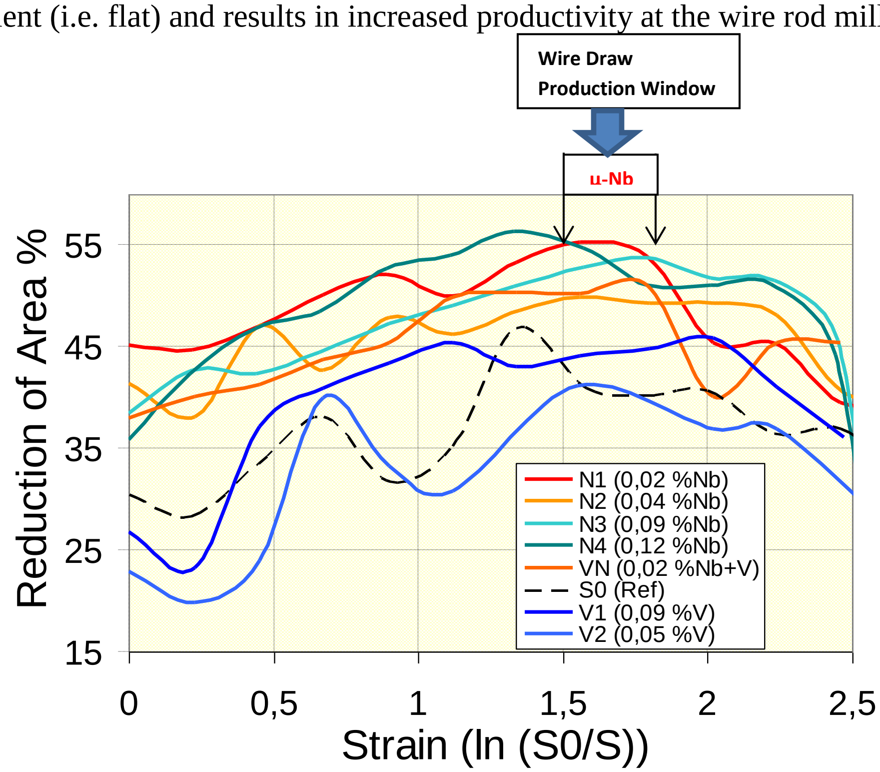


Figure 9. Drawability Performance

C-Mn versus C-Mn-Nb Microalloyed Bridge Steel Sustainability Comparison

The application of Nb-microalloyed structural steels offer the opportunity to reduce the total weight of a given structure, such as a building or bridge structure, compared to non-microalloy steel construction. Generally, one considers the cost savings due to less material and lower construction costs associated with construction which translates into significant cost savings. However, the intangible benefit is the significant reduction in emissions and energy consumption from the fact that less steel is produced as a result of the weight reduction in the structure.

The following comparative study illustrates the significant reduction in emissions (kilograms of CO_2) and energy consumption (gigajoules) comparing a structure constructed from 10,000 tonnes of S235 steel versus 9,000 tonnes of S355 Nb-bearing HSLA steel structure at 0.03%Nb. The 10% weight savings is a conservative estimate considering bridge design stiffness, specification requirements and design considerations. The results of the analysis are shown in Table 8 (CO_2 emission reduction) and Table 9 (GJ savings) compares steel plates and beams melted via the BOF versus the EAF route. [14]

Table 8. CO_2 Emission Savings - BOF versus EAF

Factor	**BOF (kilograms CO_2 per tonne steel**	**Emission Reduction (x10^4 Kilograms CO_2**	**EAF (kilograms CO_2 per tonne steel**	**Emission Reduction (x10^4 Kilograms CO_2**
Coke savings	51.1	5.11	0	-
Blast Furnace	1000	100.0	0	-
BOF	244.7	24.47	0	-
EAF	0	-	506.1	50.61
V Degas/Ladle Met	38.6	3.86	70.5	7.05
Cont Cast	19.8	1.98	19.5	1.95
Hot Rolling	188.5	18.85	141.1	14.11
Pickling	77.2	7.72	42.5	4.25
CO_2 Reduced Emissions	-	**161.99**	-	**77.97**
Reduced CO_2 Emissions 1,620 metric tons @ BOF & 780 metric tons @ EAF				

Table 9. Energy Savings – BOF versus EAF

Factor	BOF (GJ per tonne of steel)	Energy Reduction ($x10^3$ GJ)	EAF (GJ per tonne of steel)	Energy Reduction ($x10^3$ GJ)
Coke savings	3.89	3.89	0	0
Blast Furnace	12.48	12.48	0	0
BOF	1.02	1.02	0	0
EAF	-	-	6.11	6.11
V Degas/Ladle Met	0.72	0.72	1.25	1.25
Cont Cast	0.34	0.34	0.34	0.34
Hot Rolling	2.67	2.67	4.10	4.10
Pickling	1.40	1.40	0.79	0.79
CO_2 Reduced Emissions	-	**22.52**	-	**12.59**
Reduced Energy Consumption 22,520GJ @ BOF & 12,590GJ @ EAF				

The integrated mills' opportunity to reduce carbon emissions and energy usage is nearly two times higher than the EAF operations. However, this analysis does not consider the carbon emissions generated from the generation of power for the electrodes to melt the 100% scrap charge or the production of direct reduced iron pellets for the EAF. With this in mind, it becomes apparent that the potential carbon savings are significant for both operational routes.

The construction case study is just one example of the cost and environmental impact resulting from the simple substitution of S235 with S355. Upgrading some critical member sections of a structure to S460 may result in an additional 3% reduction in emissions and energy consumption. However, there are civil engineering considerations such as the stiffness, slenderness and twist of the sections which must be defined by the designer.

Advanced High Strength Structural Steel Development Trend

The application of advanced high strength structural steels are a further opportunity to reduce weight, but the application is somewhat limited based upon the relationship between the allowable stress load and the structural member slenderness. This relationship and convergence of the allowable stress load for advanced high strength steels compared with lower strength structural steels is illustrated in Figure 10 as the slenderness parameter increases.

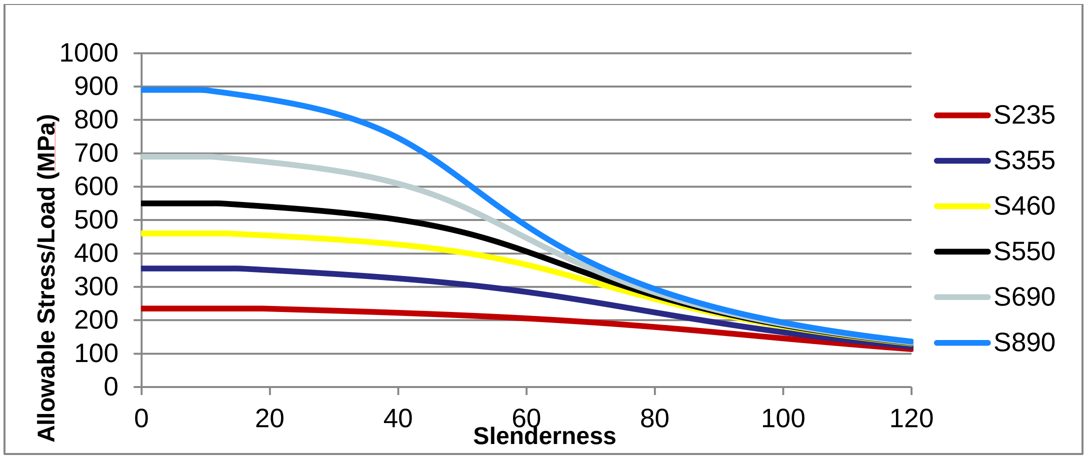


Figure 10. Slenderness of Structural Member versus Allowable Stress Load

The effect of a columns unbraced length and radius of gyration is combined in the slenderness ratio calculation. The slenderness ratio for steel columns is defined as the ratio of a column's length (l) to the radius of gyration (r).

Slenderness ratio = l/r

In general, the greater the slenderness ratio, the greater the tendency for the member to fail under buckling, Therefore, less load can be tolerated since most steel columns are not symmetrical about both axes (wide flange) and the least radius of gyration governs for design purposes because it is about this axis in which the column will fail first. The radii of gyration, r, about both axes are given in the AISC manual. Hence, under certain circumstances, the application of advanced high strength construction steels cannot be cost effectively applied and lower strength Nb-low carbon steels are appropriate. These design decisions are governed by the end user.

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