The Application and Research Progress of High Strength and High Performance Steel in Building Structure

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Abstract: High strength and performance steel with high strength, good ductility and welding property, weather resistance, material-saving and so on, have been popularized and used in high-rise and large-span buildings, as well as roads and bridges. Researchers are suggested to put forth new structural design theories and develop new structural steel and systems to meet the higher and higher requirements towards the properties of structural steel raised by the increasingly diverse, complex, and novel modern building structures. Through discussing the current situation about the studies on and the employment of high strength and performance steel at home and abroad and analyzing some existing problems of the current theories and design methods on steel structure buildings, the paper aims at providing references and conducts for later relevant studies.

1. Introduction
Steel structure is the main structure form used for buildings and bridges at present because of its good anti-seismic property, environmental protection, quick construction, and high utility rate of space, novel images and many other advantages. In the Wenchuan earthquake, the fact steel-structure buildings suffered relatively slighter damages and provided as a safe and efficient solution for poster-disaster temporary housing and reconstruction, has clearly demonstrated the outstanding anti-seismic ability of steel structures[1-3].

After years of study, particularly on the Northbridge earthquake and Kobe earthquake respectively taken place in the U.S.A, 1994 and in Japan, 1995, researchers have found that the properties of steel utilized for buildings are major elements influencing the safety of steel structures under earthquake. Controlling the range of yield strength, with ensuring lower yield ratio, higher tenacity and good welding property plays decisive roles in guaranteeing the ductility and avoiding brittle failure under earthquakes. Therefore, scholars come up with a thought of improving structures’ anti-seismic performance by perfecting the properties of steel and a conception of developing high performance steel for constructions[4-6].

2. The conception of high strength and performance steel
High strength steel refers to the steel well harmonized between its strength and tenacity, which also means the low-alloy steel, gets good comprehensive mechanical properties after tempering. Steel with tensile strength beyond 1200Mpa is called as high-alloy steel, and as ultra-high-strength steel as beyond 1500Mpa. High performance steel is a kind of steel with excellent usability under service.

Usually, high strength steel refers to the one with yield strength beyond 460MPa. This steel has
been successfully employed for the National Stadium, the new CCTV building[7]. Meanwhile, several kinds of structural steel with yield strength at 500Mpa, 590Mpa, 620Mpa, 690Mpa and above have been recommended recently.

America raised the conception of high performance steel at first and primarily applies it to road and bridge structures. This makes stricter demands to steel’s impact ductility, weather and fatigue resistance and welding property. At present, steel of three grades--HP50W (345MPa), HPS70W (485MPa) and HPS100W(690MPa),are mainly used for roads and bridges in the USA. Grade HPS70W steel, universally used as a substitute for the steel with yield strength at 345MPa,not only improves the working capacity of bridges, but also economizes steel at a rate from 15% to 20%.In brief, the age that plenty of high strength and performance steel is utilized for constructions has come.

The widespread application of high strength and performance steel not merely saves massive funds for engineering, but also affords a more advisable solution for large and complex structures. Its advantages are as follows:

1. Comparing to the increase of the strength of material by a large margin, there are more remarkable enhancements in steel’s comprehensive properties, such as fracture toughness, welding property, cold bending property, weather resistance and so on.

2. The use of high strength and performance steel can cut down the size and weight of steel structure. Consequently, corresponding reduction of the workload and materials for welding, as well as the coatings of all stripes and the efforts to construct will facilitate the process of transportation, construction and installation.

3. To weld the high performance steel, workers don’t have to preheat it or can do that at a lower temperature. This helps lower the costs on manufacturing, transportation, construction and installation of steel structures, and thus generates more considerable economic benefits than ordinary steel.

4. Regarding to the service of buildings, the cut-down of components’ size will leave more space to act, especially when the bottoms of structures claim for more free height.

5. The application of high strength and performance steel can effectively decrease the quantity of steel in an unit building area and the consumption of energy, which is significant to the sustainable development and does be an important direction to the future of structural engineering.

3. The development of high strength and performance steel

Recently, many instances about the use of high strength and performance steel in projects have appeared in China, Japan, America, Europe and some other countries and areas, which involve construction structures, bridge structures, power transmission tower structures and so on. American are more likely to employ high strength steel in bridges. For example, the steel’s grades for highway-bridges in America are HPS5W, HPS70W and HPS100W, etc. Instead of controlling the range of yield strength and strength ratio, these types merely limit the minimum yield strength while requiring more representative indexes to impact toughness and welding property.

High performance steel for construction structures features the restrictions on the maximum strength ratio and the range of yield strength. For example, Grade A992 hot rolled section steel, produced by American in 1998, is defined that its strength ratio cannot exceed 0.85 and the yield strength can only changes from 345MPa to 450MPa, thereby ensuring the plastic development of steel frames under strong earthquakes. Japanese Grade SN490B steel and Grade SN490C steel---yield strength are both defined at a range from 325MPa to 445MPa---are very good steel for constructions due to their excellent plasticity, welding property, lamellar tearing resistance and Z-direction property. In China, the steel plates used for constructions-also called as GJ steel-possess high strength, good ductility and welding property. Meanwhile, this steel can guarantee the Z-direction property additionally with weaker thickness effects. It’s a comprehensively predominant steel category like Japanese SN steel and classified for five grades: Q235GJ, Q345GJ, Q390GJ, Q420GJ and Q460GJ.

The development of new structural steel is closely tied to that of new manufacturing technique as the more advanced technique and the stricter technical norms can increase steel’s properties greatly.
Steel Plates For Building Structure (GB/T19879-2005)[8] stipulates the technical standards of high performance steel in detail, ensuring the volume production and application of high performance steel such as the Grade Q345GJ steel and the Grade Q465GJ steel. Low-Alloy High-Tensile Structural Steel (GB/T1591-2008)[9] defines the technical criterion of high strength steel from Grade Q460 to Grade Q690. It points out that the maturity of welding skills and good weld metal with enough strength, tenacity and ductility can meet the requirements raised by the production and installation of structures at all.

Europe has taken high strength steel of Grade S460 to Grade S690 into codes[10]. Australia has triumphantly applied steel with high strength at 690MPa to high-rise and large-span buildings, and begun to research composite structures in which steel’s strength can reach 690MPa. In this way, the consumption and weight of structural steel can be cut down conspicuously and the economic benefits rise sharply. Japan is studying on how to make use of the steel with tensile strength from 600MPa to 1000Mpa for structures to enhance their anti-seismic ability.

Domestic current structure steel design codes only make necessary definitions and specifications to common steel with strength below 420MPa. Similarly, the highest strength touched by American current building steel codes is 450MPa. In conclusion, the structural properties, bearing capacity, ductility, deformation performance and design methods haven’t yet been well studied worldwide. Researchers still rest on a stage that they directly impose the analysis and design theories of common steel on high performance steel, leading to the inadequate employment of high strength and performance. Table 1 shows the corresponding codes between domestic high performance steel and the foreign one.

Table 1 The correspondence of high performance steel plate in the world.

| Steel numbers | China | USA | Japan | Europe | UK | Russia | Australian |
|---------------|-------|-----|-------|--------|----|--------|------------|
| Q235          | Q235  | A36 | SS400,SM400, SN400 | Fe360 | 40 | C235   | 250        |
| Q345          | A242,A441, A572-50, A588 | A242,A441, A572-50, A588 | SM490,SN490 | S335M | 50B,C,D | C345 | 350 |
| Q390          | A550-1 | STKT540 | HS390 | 50F | C390 | 400,Hd400 |
| Q420          | A572-60 | A440B,SA44 0C | S420M | - | C440 | - |
| Q460          | A736 | SM570 | S460M L | 55EE,55F | - | - |

High strength and performance steel has been applied to some domestic and overseas buildings and bridges successfully and effectively. For example, the National Stadium (the Bird Nest) uses over 700-ton Grade Q460E/Z235 high strength and performance steel with thickness over 110mm while the new CCTV building over 2300t, and the Grade Q460 steel has been employed for power transmission towers[11-15]. The application of high strength structural steel to some projects has demonstrated China’s capacity to produce high strength structural steel. However, comparing to developed countries, lag still exists in the field of high performance steel for construction.

4. Fundamental design theories of high strength and performance steel

High performance steel, particularly the thick one, has more superior mechanical and chemical performance indexes than common steel for its high strength, low strength ratio, narrow fluctuation range of yield strength, good tear resistance and welding property. Construction structures with high strength steel, especially welding structures, also have characters of high working stress and large elastic deformation, which observably distinguish their stress performances and failure modes from those of common steel structures. To research high strength steel structures, it’s suggested to exploit better experimental setups with stronger loading capacity rather than conventional facilities to meet
the required load in failure tests to high strength steel. Taking the application demands of high strength and performance steel into account, researchers should primarily study on and deal with following fundamental design theories.

4.1. The stress-strain relationship and mechanical indexes of high strength and performance steel
So far, there are no adequate databases to determine the basic mechanical indexes of high strength and performance steel, and the partial coefficients of materials haven’t been intensively studied on and analyzed. Consequently, for high strength and performance steel from Grade Q460 to Grade Q690, researchers should lever advanced loading facilities to systematically test the properties, determine the stress-strain relationship and characteristic indexes like modulus of strain hardening, ultimate strain and ductility, especially the hysteretic behavior under cycling load, in order to lay the foundation for structural design and data analysis[16].

4.2. The constitutive low of welding and bolted connections of high strength and performance steel
The performance of welding lines under stress and the stress distributions of bolted connections obviously differ with those of common steel when it comes to high strength and performance steel. Because of the high stress of connected plates under design load and the large elastic deformation of joints, researchers should determine the stress distribution of bolts and welding lines, as well as failure modes and deformation characteristics of the former and the stress-strain relationship of the latter, and thereby raise the design strength of joints.

4.3. The fatigue property of joints of high strength and performance steel
While favorable welding helps improve the fatigue of joints of high strength and performance steel, the enhancement of working stress makes the structures under cycling load stay in high-stress circumstance, such as bridges. Due to the deficient reflection to the fatigue characters of high performance steel structures by reinforcing the study on those of common steel, it’s necessary for researchers to re-research the problems about fatigue of high strength and performance steel through experiments to lay the groundwork for the employment of it in bridges.

4.4. Deficiency and residual stress in high strength and performance steel members
Improvements of the welding property and the strength of high strength and performance also change the residual stress distributions of welding lines, as well as the bearing capacity of structural components. According to current perspectives, the ratio between the welding residual stress strength and yield strength of high strength steel is smaller than common steel’s. As a result, the structural properties of the former are less affected. However, researchers should determine the real residual stress distribution of high strength and performance steel components through tests to build a foundation for the analysis and application of components’ bearing capacity.[17-21]

4.5. The mechanical properties of connections in high strength and performance steel structures
Although the application of high performance steel can strikingly improve the mechanical properties, ductility, and anti-seismic property of welding joints, up to now, high strength and performance steel structures haven’t suffered ultra-strong earthquakes and further disclosed the explicit stress states and the failure patterns of joints under high stress. It’s recommended to determine the computing methods of ductility index and bearing capacity through doing experiments to research the failure and energy dissipation mechanisms and the hysteretic characteristics of frame joints under earthquakes. In this way, the foundation for the entire structural anti-seismic design can be laid.

5. High strength and performance steel structure systems
With the continuously spreading application of high strength and performance steel to high-rise and large-span structures, it’s necessary to establish suitable systems to give full play to the advantages of high strength and performance steel and set up its fundamental design theories and methods, along
with studying on the wind, earthquake and fire resistance, for setting norms and standards, as well as directing projects.

(1) Exploit the low mass. To welded steel plate beams in the boilers of large power stations, heavy crane beams, large-span deployable structures and so on, the application of high strength steel will remarkably decrease the thickness of steel plates and the weight of structures, and thus facilitate the processes of manufacturing and installation.

(2) Exploit the high strength. In lattice structures of high-rise buildings, spatial lattice structures and transfer trusses, the components mainly bear axial force, so the usage of high strength steel is helpful to the exercise of steel’s mechanical properties.

(3) Exploit the narrow range of yield strength. In high-rise frame structures, the center pillars use high strength steel while the beams use common one. The reasonable characters of steel for anti-seismic structures shall be that the columns keep elastic under medium earthquakes with high yield strength while the beams with low strength ratio and narrow range of yield strength have good ductility and strain strengthening ability, and thus the whole structures can obey the principle of strong column and weak beam and guarantee the plastic hinges to arise at beams in order to remain stable more easily under strong earthquakes.

(4) Exploit the good welding property and the high impact toughness. To the welding structures under earthquakes, especially the ones with thick plates, the application of high performance steel can clearly enhance the ductility of welding connections and consequently avoid damages in these regions.

6. Conclusions

With the rapid advancement of steel making skills and the increasing augment of steel output and types, high strength and performance steel will be more available and applicable to building structures. The successful employment of the Grade Q460 high strength and performance steel, with the wide use of the Grade Q345 high performance steel for high-rise buildings, has demonstrated the superiority and potential prospects of high strength and performance steel to the whole steel structure industry. At the same time, the prosperity also companies with many issues. The structure design theories and methods based on common steel cannot adapt to the high strength and performance steel structures at all. Researchers have to study on the fundamental mechanical properties of high strength and performance steel, come up with structural analysis and design means and develop suitable structural systems to give the superiority of high strength and performance steel full play. On the basis of concluding the current situation of the application of and the study on high strength and performance steel structures, this paper makes following proposals:

(1) The development of new steel structures and the augment of steel products raise a claim on the rational choice and application of steel. American have systematically researched on the high performance steel for bridges and put forward corresponding design and application guide, as well as completed hundreds of bridges, but clearly overlooked the study on that for buildings. Current building structural norms lack necessary regulations on the rational use of high strength and performance steel. High performance steel, like fire-resistance steel and GJ steel, encounters obstacles to generalize domestically, and important parameters as the design strength values of the steel and its connections are more needed to be analyzed and researched in the long term.

(2) According to current studies and application worldwide, the steel structures welded with thick plates in seismic zones, especially the structures bearing heavy load and over-large deformation and the deployable roof structures demanding light weight, should give preference to high strength and performance steel. It’s suggested to develop new high performance steel structures and composite structures, to advance mixed structures with high performance and common steel, and to innovate making and welding skills to show the superiority of high performance steel.

(3) At present, the steel industry is revising the standards of materials, connections, and design and construction technique. Contents about high strength and performance steel should be gradually absorbed in technical standards and regulations for normalizing and directing engineering practices and promoting the bright development of high strength and performance steel structures. However, the
current studies are not enough to systematically research the fundamental theories and design methods about high strength and performance steel and conclude the experience of welding and constructing. This, to a large extent, restricts the application of high strength and performance steel and urgently demands relevant researches to figure out the imperative problems in projects.

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