FEATURES AND SUPER-TALL BUILDING APPLICATIONS OF NIOBIUM MICROALLOYED 800 MPa HIGH STRENGTH STEEL PLATES

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Abstract

Building height and span are increasing, requiring the application of high performance steels to withstand the increased loads and ensure a high level of safety and durability. HSA800 is a new Nb-microalloyed high strength steel plate for structural use in buildings developed by POSCO and RIST in 2011. It has upper and lower bounds for yield (F_y) and tensile (F_u) strength of 650-770 MPa and 800-950 MPa, respectively, with a yield ratio (F_y/F_u) limit of 0.85 so as to enhance the seismic resistance of structures. Microalloys such as Nb, V and Ti are added to provide grain refinement with thermomechanical control processing (TMCP) to increase the yield and tensile strengths of the base material. As a result of the use of TMCP, which allows a reduced carbon equivalent, good weldability is also attained. The HSA800 grade was first applied in the concrete filled tubular (CFT) columns of a nine story research institute building in Seoul, South Korea. SA800 and HSA800 will also be applied in the Lotte World Tower, the first super-tall building in South Korea with a 555 m height when completed. Through the application of HSA800, the total weight of construction steel is reduced which also contributes to a reduction in CO_2 emissions from the steelmaking production process.

Introduction

A new construction material that can withstand the increased loads resulting from higher elevation and longer span structures is required in order to meet safety and sustainability requirements. In order to meet such performance requirements, efforts have been made to enhance the strength of structural materials. Since these steel structures can carry higher stresses, a reduction in the building's overall weight results compared to reinforced concrete structures. Thus, steel is considered to be better suited for the construction of ultra high buildings with long span structures compared to concrete.

Large-sized members and ultra-thick steel plates are applied at the lower levels of high rise buildings to withstand the extreme loads arising in lateral resistance members such as outriggers and ballast, and large vertical loads on the columns. These types of large-sized structural members are fabricated from steel plate and strip and are required to meet rigorous standards, including increased reliability and improved weldability.

In 2006/2007 NSC and JFE of Japan developed minimum 780 MPa tensile strength steels for building structures [1,2]. They have special regulations to ensure the material's reliability for building construction, including the yield and tensile strength ranges and the upper limit of the yield ratio and other factors. These developed steels have been applied in the construction of high-rise buildings such as Midland Square, Tokyo Skytree and others [3].

In Korea, POSCO and the Research Institute of Industrial Science & Technology (RIST) have developed Nb-microalloyed 800 MPa high strength steel plates for building structures, which have 20 MPa higher strength than that of competitors' steels. The 800 MPa steel is made using TMCP and as such it has a low C level and hence good weldability. It was accepted as a Korean Industrial Standard (KS) in October 2011. The new standard is KS D 5994 "High-performance rolled steel for building structures" and the steel has been designated as HSA800 [4]. This steel was first applied in a nine story research institute, namely the Korean Center for Artificial Photosynthesis (KCAP) in Seoul, Korea, as CFT columns.

The objective of this paper is to introduce the features of HSA800 with material test results and its application in super-tall building structures. The features are described in two main categories – mechanical properties and chemical compositions. The material properties of this steel were evaluated using a suite of tests and analyses including tensile tests, Charpy impact tests, chemical composition analysis, and microstructure analysis.

Mechanical Properties of HSA800

According to KS D 5994 [4], HSA800 shall meet both upper and lower bounds for yield (F_y) and tensile (F_u) strength of 650-770 MPa and 800-950 MPa, respectively. Yield ratio ($YR=F_y/F_u$) limit, an important factor for seismic design, is also regulated to a maximum of 0.85. Figure 1 illustrates the acceptable property area of HSA800 based on these strength limits for 25 mm and 50 mm thick plates.

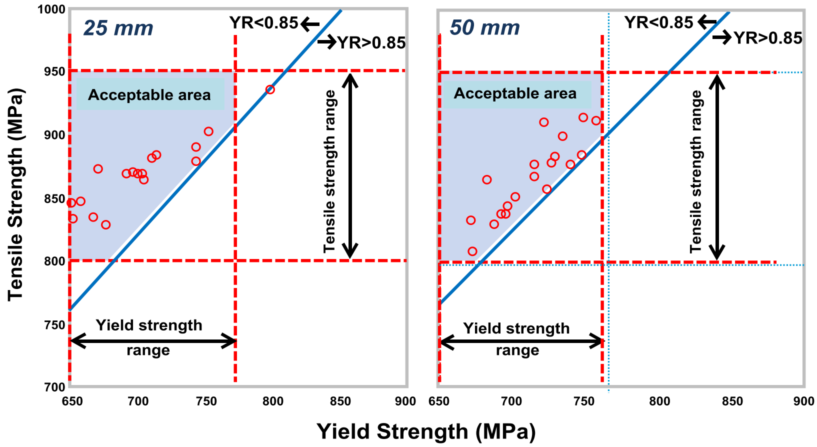


Figure 1. Acceptable property area for HSA800 steel based on the strength ranges and YR limit.

These regulations are one of the very important criteria of the steels to be used for building structures. The yield ratio criterion makes steel quality more reliable and reduces the deviations from the mean value compared to those of general-use steels. Consequently, an enhancement of the seismic resistance of structures and of progressive collapse behavior is attained. Figure 2 plots an example of tensile strength statistical data for HSA800 for a total of 113 samples. The data which is out of bounds has been cropped. The red solid line and black dashed line indicates the probabilistic density function fitted to the data between lower and upper bound of tensile strength and total data including out of bound test results, respectively.

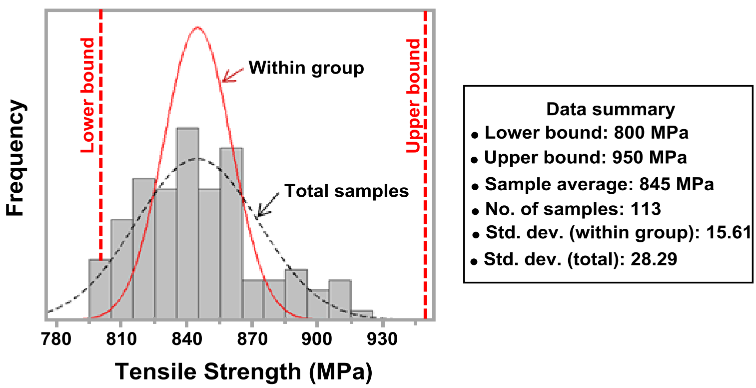


Figure 2. Example of tensile strength histogram of HSA800.

Tensile Test Results

The tensile tests were performed to measure yield strength, tensile strength, yield ratio, elongation, cross-section reduction (contraction) ratio and others in accordance with Korean Standards (KS) [5,6]. The test specimens used were No. 4 test piece (rod type) and No. 5 test piece (plate type). In this study the tests were conducted on specimens of different thicknesses – 15 mm (No. 5, 8 specimens), 25 mm (No. 4, 11 specimens), 50 mm (No. 4, 14 specimens), 60 mm (No. 4, 7 specimens), 80 mm (No. 4, 14 specimens), 100 mm (No. 4, 14 specimens). Specimens over 50 mm thick were obtained at quarter and middle point through the thickness.

The stress-strain curves derived from the uniaxial tensile tests of HSA800 are presented in Figure 3 and compared to the stress-strain curves for SM490 and SM570TMC. Note in Figure 3 that strain hardening occurred up to a strain of 0.05 but without a subsequent yield plateau. Although there is no yield plateau, recent research using built-up H-shape beam test specimens of HSA800 shows that the plastic rotational capacity R meets the minimum level of plastic design required in the Load and Resistance Factor Design (LRFD) provision [7]. As shown in Figure 1 (circle symbol), all test results conform to the Korean Industrial Standards [4].

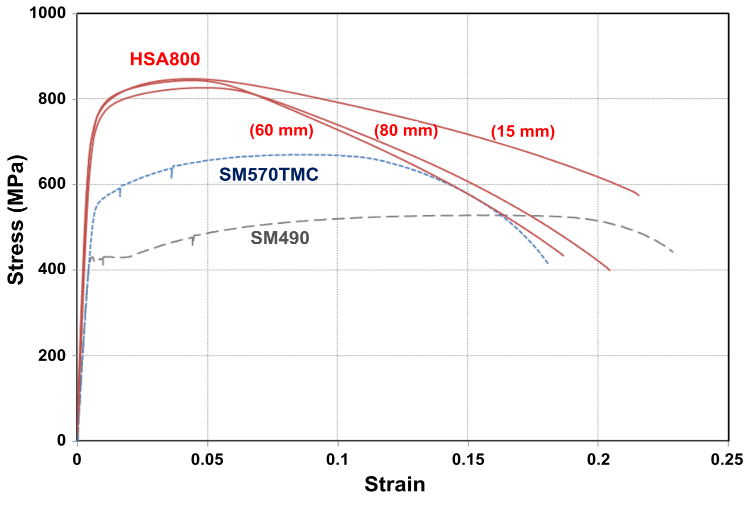


Figure 3. Typical stress-strain curves for HSA800 and lower strength grades.

Charpy Impact Test

Charpy impact testing, also known as the Charpy V-notch test, provides a measure of absorbed impact energy, fracture ratio and transition temperature. The KS requires HSA800 to meet at least a Charpy impact value of 47 J at -5 °C. The Charpy impact test was performed using the standard 10 mm thick V-notch test specimen located at the mid thickness position [8,9]. The HSA800 steel completely satisfied the requirements of the KS standards as shown in Figure 4.

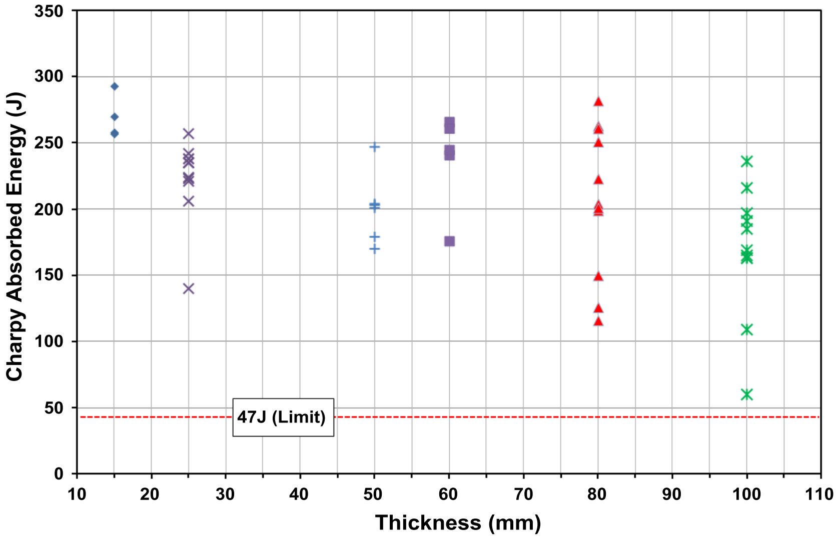


Figure 4. The results of the Charpy impact tests at -5 °C

Chemical Composition of HSA800

The five main chemical elements besides iron (Fe) are carbon (C), silicon (Si), manganese (Mn), phosphorus (P) and sulfur (S). C is the most important element after Fe. Higher C content means higher hardness but lower ductility and weldability. Mn has properties similar to those of C and enhances the hardness and impact properties of the steel for ferrite and pearlite microstructures. Specifically, the effect of Mn is remarkable when the content exceeds 0.5%. Usually, the Mn content in steels used for building structures is approximately 2%. The P and S contents increase the brittleness of the steel and thereby give rise to undesirable properties.

Microalloys such as Nb, V and Ti are usually added to increase the material strength at room and elevated temperature. The roles of these elements include promotion of grain refinement, precipitation and control of recrystallization through the proper application of the thermomechanical control process (TMCP). Moreover, Nb and Ti are the main elements added to American Petroleum Institute (API) linepipe TMCP steels because they promote increased strength through the precipitation of NbC and TiN. However, Ti cannot be added at too high levels because of a propensity to cause surface cracks. The maximum Ti level depends upon the Ti/N ratio.

Chemical Composition Analysis

The chemical composition analytical test is performed to determine the types of element in the steel and the amount (percentage) of element added to the steel [10]. Based on this, the carbon equivalent (C_{eq}) and the weld cracking susceptibility composition parameter (P_{cm}) can be obtained using Equations (1) and (2), respectively.

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14} \quad (1)$$

$$P_{CM} = C + \frac{Mn}{20} + \frac{Si}{30} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (2)$$

The composition was analyzed by collecting specimens with dimensions of 20 × 20 mm from the 1/2 thickness and 1/4 thickness positions in accordance with KS B 0001 [10] for steels of thickness 15 mm, 60 mm, 80 mm, and 100 mm.

Table I summarizes a comparison of the chemical composition of HSA800 and competitors' steels. As shown in Table I, the allowed maximum Mn content in HSA800 is 3.0%, which is approximately two times higher than that of competitors. P and S in HSA800 are limited to 0.015% and 0.006% respectively, and are more rigorously regulated than those of other competitors. Also, similar to those of the competitors, the combined percentages of microalloys Nb, V, Ti are limited to 0.12%.

Table I. Comparison of Chemical Composition of HSA800 vs. Competitors

<table>
<tr><th>Maker</th><th>Steel Type</th><th>C</th><th>Si</th><th>Mn</th><th>P</th><th>S</th></tr>
<tr><td>NSC</td><td>BT-HT630B,C</td><td>≤0.16</td><td>≤0.35</td><td>0.6-1.60</td><td>≤0.030</td><td>≤0.015</td></tr>
<tr><td rowspan="2">JFE</td><td>HITEN780TB</td><td rowspan="2">≤0.18</td><td rowspan="2">≤0.55</td><td rowspan="2">≤1.60</td><td>≤0.030</td><td>≤0.015</td></tr>
<tr><td>HITEN780TC</td><td>≤0.015</td><td>≤0.008</td></tr>
<tr><td>POSCO</td><td>HSA800</td><td>≤0.20</td><td>≤0.55</td><td>≤3.00</td><td>≤0.015</td><td>≤0.006</td></tr>
</table>

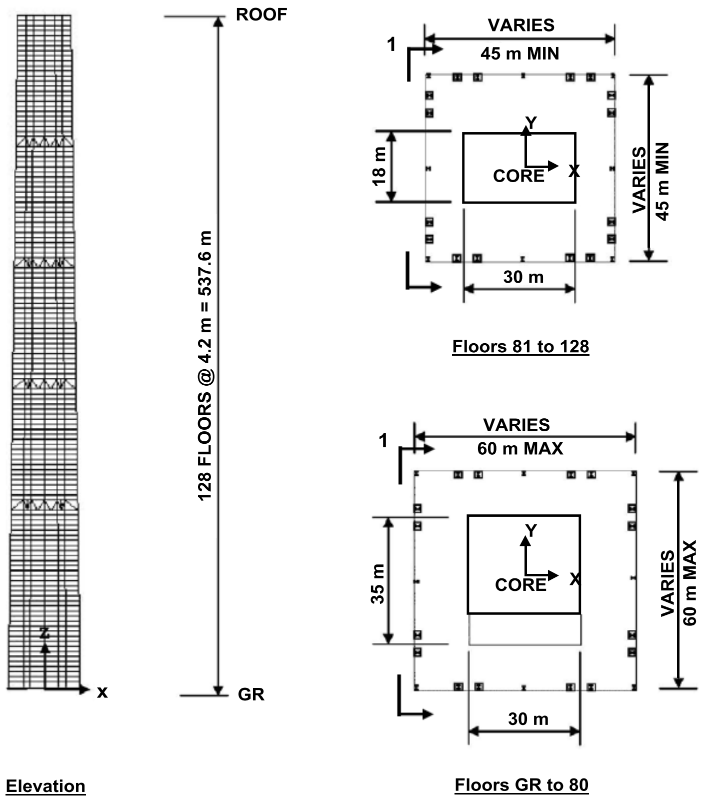
<table>
<tr><th>Maker</th><th>Steel Type</th><th>Cu</th><th>Ni</th><th>Cr</th><th>Mo</th><th>Nb</th><th>V</th><th>Ti</th><th>C_{eq}</th><th>P_{cm}</th></tr>
<tr><td>NSC</td><td>BT-HT630B,C</td><td>≤1.5</td><td>≤2.00</td><td>≤0.80</td><td>≤0.60</td><td>≤0.05</td><td>≤0.6</td><td>N/A*</td><td>≤0.6</td><td>≤0.35</td></tr>
<tr><td>JFE</td><td>HITEN780TB
HITEN780TC</td><td colspan="7">N/A*</td><td>≤0.6</td><td>≤0.30</td></tr>
<tr><td>POSCO</td><td>HSA800</td><td>≤1.5</td><td>≤2.00</td><td>≤0.80</td><td>≤0.60</td><td colspan="3">≤0.12</td><td>≤0.6</td><td>≤0.30</td></tr>
</table>

*Data is not available

Super-tall Building Applications of HSA800

Case 1: 537 m Prototype Building

For the application of HSA800 in a super-tall building, its cost-effectiveness and constructability have been evaluated for a 128 story (537 m) building having a concrete core wall with mega-outrigger and belt truss structural systems as a lateral force resisting system (LFRS). Figure 5 shows the building configurations of this model. Two analytical models – Models E1 and E2 - were developed. Model E1 has been developed and optimized using various combinations of high strength steel (mostly in the gravity load resisting components such as perimeter columns, outer wall columns, belt truss and spandrel girder) and normal strength steel (SM490, SM570TMC), while the other model, E2, has been optimized with only normal strength steel. 70 MPa strength concrete has been assumed for all concrete structural components in both models. Table II summarizes types of materials used in the models.



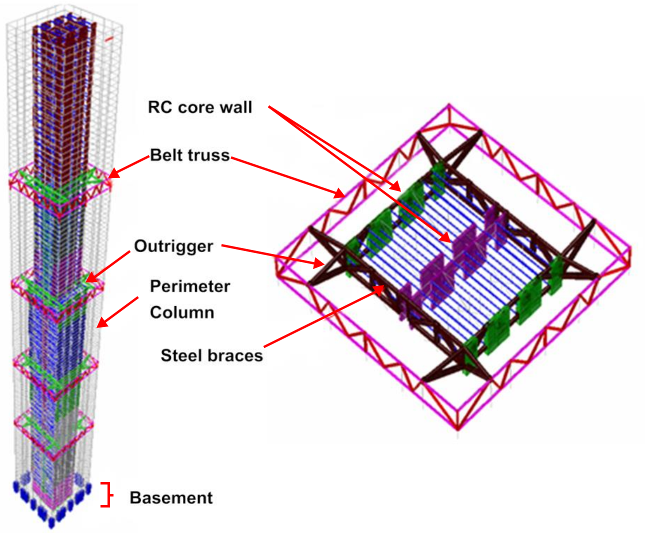


Figure 5. Building configurations and LFRS of the model.

Table II. Types of Materials Used in the Models

Model	Stories	Perimeter Column		Mega Column		Outer Wall Column	Inner Wall Column	Gravity Column
		Steel[1]	Concrete[2]	Steel[1]	Concrete[2]	Steel	Steel	Steel
E1	Basement to L33	HSA800	-	SM570	C70	HSA800	SM570	SM570
	L33 to Roof	HSA800	-	SM570	C70	SM570	SM570	SM570
E2	Basement to Roof	SM570	-	SM570	C70	SM570	SM570	SM570

Model	Stories	Belt Truss	Outrigger Truss	Link Beam	Braced Frame Diagonal	Braced Frame Beam	Spandrel Girder	Floor Beam
		Steel	Steel	Steel	Steel	Steel	Steel	Steel
E1	Basement to L33	HSA800	SM570	SM570	SM570	SM570	HSA800	SM570
	L33 to Roof	HSA800	SM570	SM570	SM570	SM570	HSA800	SM570
E2	Basement to Roof	SM570	SM570	SM570	SM570	SM570	SM570	SM570

Notes: [1] Steel strength is: Fy=650 MPa for HSA800 and Fy=440 MPa for SM570TMC.
[2] Concrete strength used for concrete members is fc=70 MPa (for C70) except slabs that are designed with fc=30 MPa (C30).

The performances of the two models are compared to one another based on five criteria:

i. Wind-induced lateral deflection (H/500) and drift ratio (h/400) (see Figure 6);
ii. Maximum differential column shortening;
iii. Natural periods of vibration/human perception of wind-induced swaying motion;
iv. Distribution of wind-induced overturning moment (see Figure 7);
v. Total amounts of materials.

Table III summarizes the results of the evaluation for the two models in accordance with these criteria. From this table, the structural system of Models E1 and E2 exhibit quite satisfactory global behavior. With the replacement of the gravity force resisting members with HSA800 (9,379 tons), it achieved approximately 32% reduction in gravity members (13,904 tons) and approximately 9% total reduction compared to that of the model using only the normal strength steel.

Table III. Evaluation Results of Model E1 and E2

		Model E1		**Model E2**	
		Material	**Strength (MPa)**	**Material**	**Strength (MPa)**
Structural System	Perimeter Core	Steel Steel Concrete	F_y=650 and 440 F_y=650 and 440 f_c=70	Steel Steel Concrete	F_y=440 F_y=440 f_c=70
Fundamental Period in each direction (sec)	T_x T_y T_z	Mode 1 Mode 2 Mode 3	10.170 9.966 7.258	Mode 1 Mode 2 Mode 3	10.136 9.897 7.130
Max. displ (m)	x-dir y-dir	1.049 (H/512) 1.079 (H/498)		1.029 (H/522) 1.046 (H/512)	
Acceleration (milli-g)	Along wind Across wind	8.49 17.45		8.39 17.03	
Story drift	-	See Figure 6		See Figure 6	
Overturning moment		See Figure 7(a)		See Figure 7(b)	
Building weight (tons)		Steel	Concrete	Steel	Concrete
		SM570 HSA800 36,826 9,379 Total 46,205 (91%)	294,681 294,681	SM570 HSA800 50,730 Nil Total 50,730 (100%)	294,681 294,681

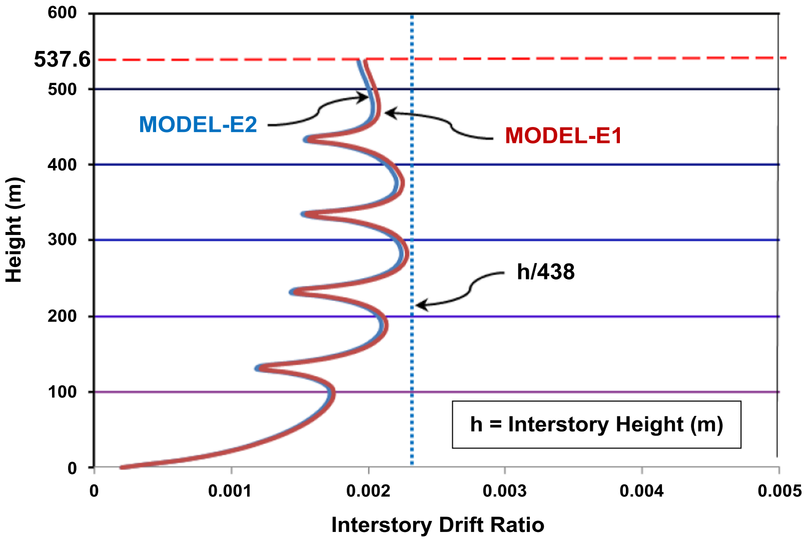
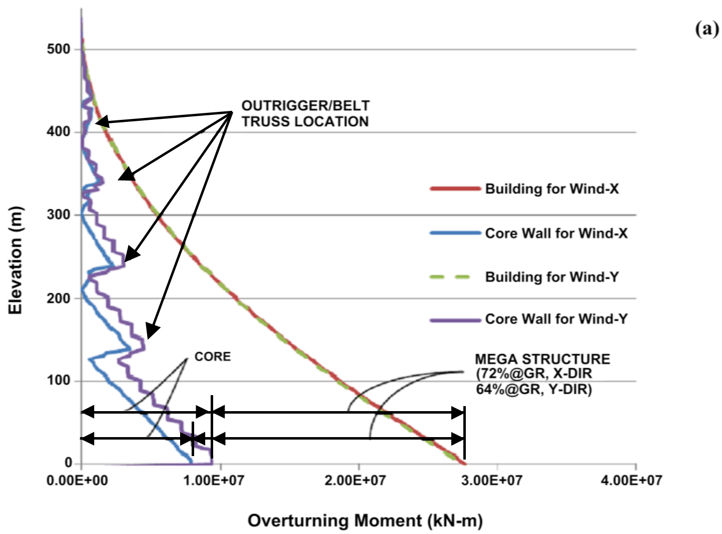


Figure 6. Building/story drift.



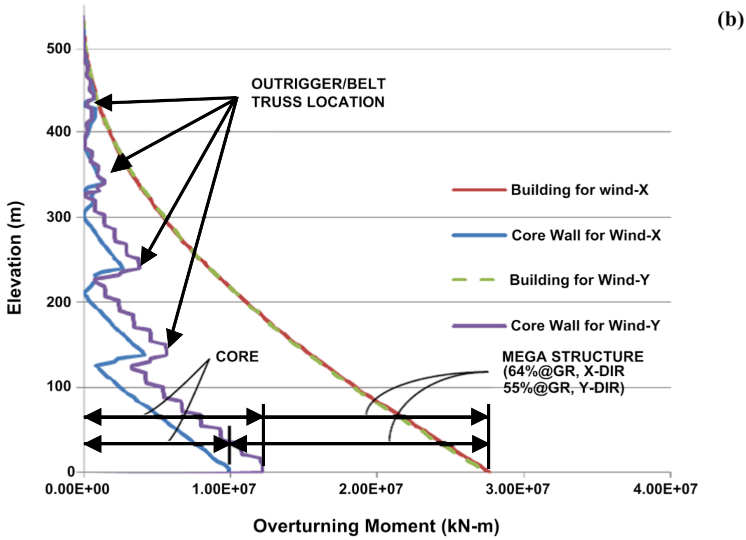


Figure 7. Overturning moment; (a) Model E1, (b) Model E2.

<u>Case 2: Lotte World Tower (123F, 555m), Seoul, Korea</u>

Similar to the previous study, the research to compare and then replace the normal strength steel (NSS) with high strength steel (HSS) was performed for a real project – namely the Lotte World Tower (123 floors, 555 m high), the first super-tall building in Korea. The structural system of this building consists of two sets of steel outrigger truss and belt truss systems with reinforced concrete (RC) core walls as shown in Figure 8. Steel outrigger trusses are located in levels 39 to 44 (5 story height) and levels 72 to 76 (4 story height) with rectangular box-shaped section. Belt trusses are also located in levels 72 to 76 (4 story height) and levels 104 to 107 (3 story height). Two sets of reinforced concrete mega columns (3 x 3 m at base) are located on each side of the building.

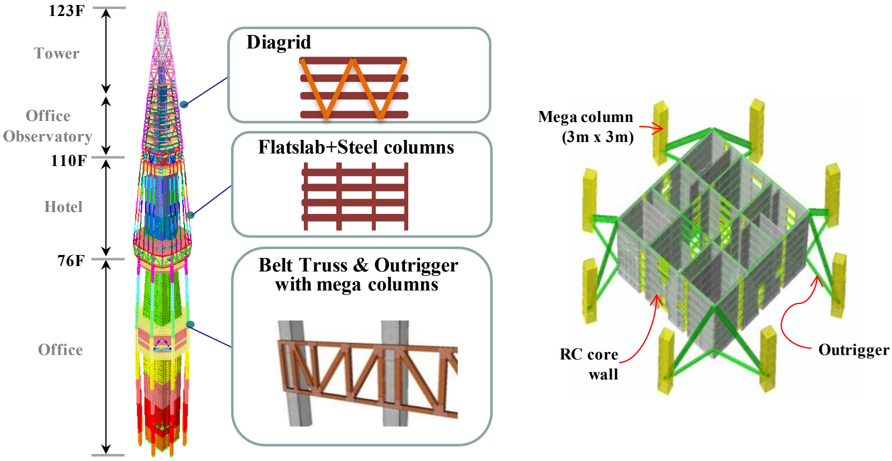


Figure 8. Steel structural system of the Lotte World Tower.

Belt trusses, perimeter columns at hotel floors and outriggers were determined as structural components which could be replaced with HSA800 when considering safety, serviceability and durability. These components were originally designed with SM520 and SM570 steel. In order to optimize the section size with HSA800 and evaluate the effect of each member's contribution to the lateral behavior, modal analyses and demand-to-capacity (D/C) ratio of members were evaluated. The results show that the components which do not affect the overall structural lateral stiffness and do not require additional members to ensure the serviceability (eg. belt trusses, perimeter columns, bottom chords of outriggers) could be replaced with HSA800.

Table IV shows a comparison of steel quantity and section size between NSS and HSA800 for each component. From this table, the total steel quantity before and after applying HSA800 was 4,061 tons and 2,901 tons respectively, which implies that approximately 30% of steel weight could be saved. Also, by reducing the section thickness of the members, several construction parameters such as welding time and cost, as well as crane lift weight, can be reduced. Based on this research, HSA800 will be used in the construction of the Lotte World Tower for the components discussed above.

Table IV. The Comparison of the Evaluation Results

Component		Original Design		Alternative Design	
		Steel Quantity (ton) (Material)	**Section* ($DxWxt_wxt_f$)**	**Steel Quantity (ton) (Material)**	**Section* ($DxWxt_wxt_f$)**
Outrigger	Diagonal Member	757 (SM570)	1600x500x80x20	757 (SM570)	1600x500x80x20
	Bottom Chord	309 (SM570)	950x500x80x20	216 (HSA800)	950x500x55x15
Belt Truss		1,811 (SM520)	800x400x80x50	1,075 (HSA800)	800x400x45x30
Perimeter Column		1,184 (SM520)	400x400x80x40	853 (HSA800)	400x400x55x28
Total		4,061 (100%)		2,901 (71%)	

*Box shape (D: depth, W: width, t_w: web thickness, t_f: flange thickness) (mm)

Conclusions

In this paper the properties and cost-effectiveness of HSA800, the newly developed high strength steel for building structures, were briefly described. HSA800 as produced by POSCO satisfies all performance requirements for building structures in accordance with KS D 5994 [4]. HSA800 brings the added benefit of reducing steelmaking consumption compared to normal strength steels and thus reduces carbon dioxide (CO_2) emissions from the steel and member production processes. Transportation and erection costs are also reduced. These factors are key contributors to mitigating the environmental impact of construction projects which is expected to become a primary driver for the use of steel in the international and the domestic construction industry.

Acknowledgement

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