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SEISMIC STRUCTURAL DESIGN WITH LARGE SIZE SQUARE HOLLOW STRUCTURAL SECTION COLUMN AND SAFEGUARD TOWER (TSUNAMI EVACUATION TOWER)

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Abstract

It is said that 10% of the earthquakes in the world occur in the vicinity of Japan. As a result, Japan has been accumulating much knowledge and technology with regard to earthquake-resistant building structures. Among various high-technologies, one of the most conventional and economical idea is the "Box column – H-beam moment frame steel structure".

It is one of the two-way moment frame structural system design in which we can reduce the size and weight of the structure compared to the concrete structure (RC in the following) or other steel structures. We can also design with the longer span and, if necessary, we can eliminate the brace to provide larger open space and more designing flexibility for the building. Because of those values, this structural design has been one of the standards for multiple-story commercial buildings in earthquake-prone Japan for more than three decades.

Although immense damages were brought by the Great East Japan Earthquake on March 2011, no major damage to the main structural parts of "Box column – H-beam moment frame structure" caused by the earthquake and tsunami was found as a result of a survey. This structural system had supported whole structures not only against the earthquake load but also against the tsunami load such as the hydraulic pressure or those from being hit by drifting debris.

"Box column – H-beam structure", in addition to its high earthquake-resistant performance, has the following features.

1. It is possible to reduce the size and weight of the whole structure so that it may result in expanding the

available inner space of the buildings as well as reducing the cost of construction, including foundation work, compared to the RC structure.

2. The period of construction will be shortened compared to the RC structure.

3. There is a higher degree of designing flexibility such as long span compared to the RC structure.

4. The period of fabrication will be also shortened in case using the Roll Formed HSS compared to other box or H shape steel structure which require many fabrication processes to form those shape.

Although construction firms, designers, fabricators and especially clients tend to pay attention only to the initial construction costs and material costs, it is becoming prevalent in advanced construction markets to pay attention not only to the initial construction costs but also to the value of the building, that is, to the ROI (return on investment) and the LCC (life cycle cost) from the long-term point of view.

In this way, the Jumbo size square "Roll Formed HSS" and the "Box column-H-beam structure" enhance the long-term value of a building. This value includes not only the commercial value but also the value of protecting human life from disasters may occur in the future.

Keywords: HSS, seismic steel design

Introduction

2:46 PM on March 11, 2011. The earthquake which occurred near the northeast coast of Japan, together with the great tsunami which hit various locations starting approximately forty minutes later, brought great damage to the coastal area of North-eastern Japan, with approximately 19,000 dead or missing. It was M9.0 in terms of the magnitude of the seismic energy. This magnitude was fourth largest in the past century, after the Chile Earthquake (M9.4) in 1960, the Alaska Earthquake (M9.2) in 1964 and the earthquake off the coast of Sumatra, Indonesia (M9.1) in 2004.

On the other hand, a characteristic of this earthquake was that the damage from the tsunami was greater than the damage from the earthquake as it was not an urban near-field earthquake like the Great Hanshin Earthquake of 1995. (M7.3)

Fig. 1: Tsunami

From immediately after this earthquake disaster, many missions have travelled to the site to survey the damage, and structural engineers joined also from our company to investigate the damages to structures.

As damages by earthquake to both RC and steel-structure buildings, although many cases were found such as of outer walls and suspended ceilings that had collapsed in multi-story buildings and of buckled light-gauge bracings, there was no major damage to the main structural parts of “Steel Box column – H beam structures”.

Fig. 2: Major Structural Damages on RC Structure

In the areas tsunami had swept almost everything away, those scenes in which can be seen that nothing but some foundation of the buildings or residences were broadcasted in the world, there were actually some steel structures still on the ground. The core part of those steel structures were not damaged even they have lost roofs and walls. Most of them were "Box column – H-beam structure". There was no major damages at the core part of "Box column – H-beam structure". Some of them have been re-paneled with new roof and wall to be used once again within a few months.

Fig. 3: Steel Frame Structure Intact

Fig. 4: No Damage with Steel Box Column to H-Beam Rigid Frame Connection

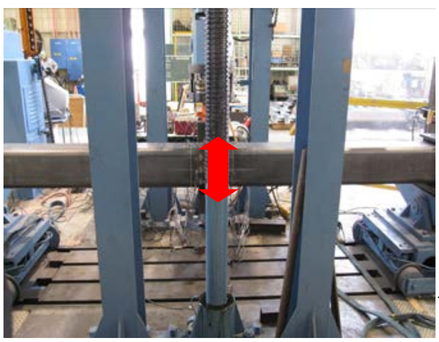
Seismic Design Concept of Steel Structure in Japan and the Performance of HSS and "Box column – H-beam structure"

The general approach to the seismic design of steel structures in Japan is a two-step approach. The primary design is an elastic design to prevent damage by medium scale earthquake. And a secondary design is a plastic design which permits partial damage by large scale earthquakes but does not allow collapse.

That is, the point of the primary design is to keep to a minimum the damage to the structure, and in the secondary design, the seismic energy is made to be absorbed by the viscosity of plastic deformation even though there are also some elements that collapse. In other words, in the secondary design, the deformability, which absorbs the seismic energy, is important.

(Fig.5) is the performance test of the HSS column, and the result shown in the graph is a bilinear loop to indicate the stable yield strength and the high capacity to absorb the seismic energy.

(Fig.6) is the performance test of a rigid frame connection via a through diaphragm, standard connection in Japan, and the result shown in the graph is also a bilinear loop to indicate the same as HSS column. Many such experiments have been conducted in Japan, and these data have indeed been proven in the disaster two years ago.



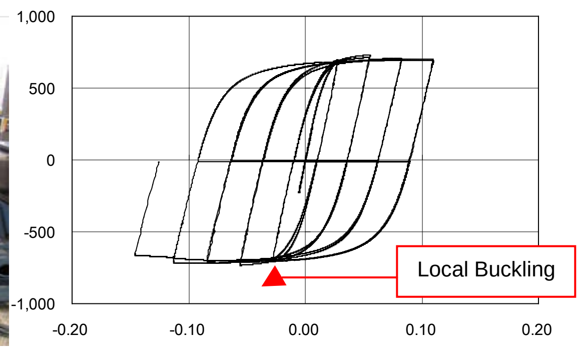


Fig.5: Performance Test of HSS Column

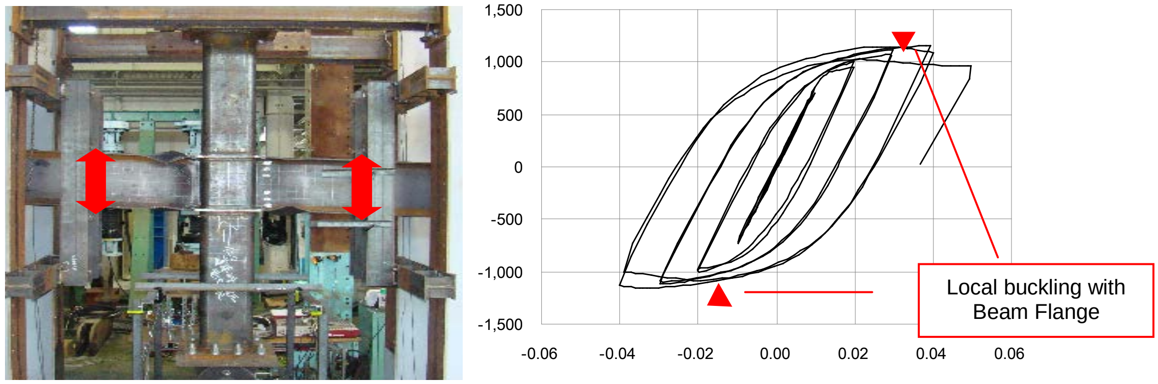


Fig.6: Performance Test of Connection Part (Rigid Frame)

Japanese building structure

From the viewpoint of earthquake-resistant performance, it is also possible to enhance that of the RC structure, by making the sectional areas of the elements larger and placing a large number of earthquake-resistant walls. At present, approximately 70% of the building architectures in Japan are steel structures, and buildings of steel structures and of RC structures exist together even in metropolitan areas such as Tokyo. This is because the required characteristics differ according to such factors as the use the building and, roughly speaking, there are relatively many RC structures of residences and hospitals whereas many single-story factories have one-way rah men, other-way braced structures in which both the columns and beams are of H-section steel. On the other hand, the greater part of the commercial architecture such as offices, shopping malls, multi-level parking lots and warehouses are “HSS column-H beam structure”.

This is because the “HSS column-H beam structure” makes possible structures of large spaces without bracing, which enlarges the effective area and results in greater flexibilities in the positioning of openings and in the internal layout. These are very significant advantages and values of the buildings for the owners. These are linked directly to the income from the buildings and have impact on the ROI.

History of Architectural Structures of Commercial Buildings in Japan

From RC Structure to Steel Structure (1960s)

It was during the so-called era of high economic growth of the 1960s that the architecture of steel structures became prevalent in Japan. During that time, rapid modernization of cities took place and, in parallel to the increase in floor areas of construction starts, there were an increasing proportion of steel structure constructions. (Tab.1)

The main reasons for this were the following four points.

1. The steel structure, compared to the RC structure, allows the structure (columns, beams, etc.) to be smaller and lighter, reducing the load on the frame.
2. The steel structure, compared to the RC structure, allows the effective internal space to be larger since the size of structure can be smaller.
3. The steel structure, compared to the RC structure which requires almost all the work to be on-site,

has a greater component of production and working in the factory, which results in stability of the qualities of the products and workings.

4. With the steel structure, curing periods are not required for the columns and beams, which enable construction periods to be shortened and construction costs to be reduced.

Table 1: History of Architectural Structures of Commercial Buildings in Japan

		1957	⇒	1970	⇒	1990
Building (mil.m^2)	:	44 (100%)	⇒	200 (450%)	⇒	280 (636%)
RC (%)	:	17 (100%)	⇒	22 (129%)	⇒	21 (120%)
Steel (%)	:	6 (100%)	⇒	29 (480%)	⇒	38 (641%)

From H-column/H-beam Structure to HSS-column/H-beam Structure (1980s)

However, during the approximately two decades beginning with the 1960s, which was described in the foregoing, the main role in steel structures was played by H-shape in terms of both columns and beams. In this case, reinforcement by bracing was required in the direction of weak axis (direction of the flange), which had been a major restriction in the architectural design.

It had already been understood at that time that it is possible to make an extended-space earthquake-resistant structure which does not require bracing over a large span by using non-directional box-structured columns which make two-way moment frame structures possible, but at that time it was not yet possible to produce box structures of large dimensions, and thus, even though four-face welded boxes and H-shape to which cover plates were welded had also been used, they did not become very prevalent, as there were also defects in quality upon manual welding by the fabricator.

In 1978, our company began to produce large size HSS by cold roll forming. And, in that year, a great earthquake occurred off the coast of the Tohoku region, which is the same location as the earthquake five years ago. Three years later, in 1981, the standards of earthquake-resistant design were made stricter, and the “HSS column-H beam structure” rapidly became the *de facto* standard.

Column to Beam Connection

In the connection part of "Box column – H-beam structure", the diaphragm plate has the important role to receive and transfer the horizontal seismic force from the beam to the column. There are many types of connection details and the most prevalent in Japan is the type to use “Through Diaphragm” as in Fig.7 .

This type of connection with “Through Diaphragm” has many fabrication steps.

1st : Cut the HSS into three parts, top, middle (Panel Zone) and bottom.

2nd: Weld two “Through Diaphragm” plates on both side of the panel zone.

3rd: Weld top HSS and bottom HSS on each side diaphragm.

Because there are many steps to do, most of the fabricators in Japan use automatic welding robot for this operation, especially for welding. It takes longer time if it was done by manual. (Fig.8)

As there is no automatic welding robot in most of the overseas market right now, there are some other solutions, such as “Inner Diaphragm” or “Outer Diaphragm” (Fig.9). Those fabrications can be done even by manual. Either by the robot or by manual, one of the important parts in those fabrications is the quality control of welding operation.

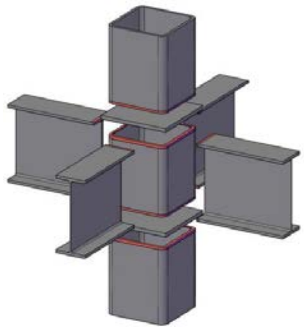


Fig. 7: Through Diaphragm

Fig. 8: Automatic Welding Robot

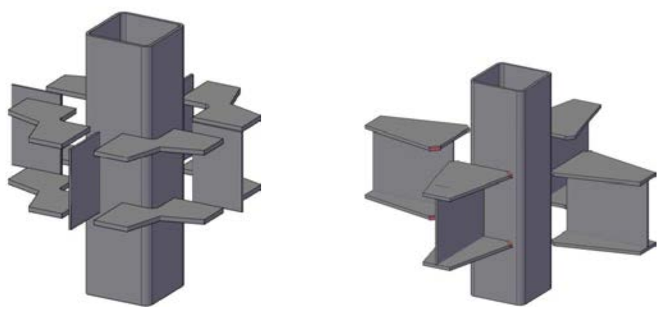


Fig. 9: Outer Diaphragm

Factory Fabrication vs On-site Fabrication

It was stated that with the steel structure, curing periods are not required for the columns and beams, which allows construction periods to be shortened and construction costs to be reduced. It was also stated that the steel structure, compared to the RC structure which requires almost all the work to be on site, has a greater extent of production in the factory, which results in stability of the quality.

In Japan, in most cases columns for up to a maximum of three stories are fabricated in the factory and those are transported by trailers to the construction site.

For connections of columns and beams also, rather than welding directly to HSS, brackets are welded to them in advance in the factory which are then connected by bolting to the beams on site. In this way, it is possible to realize the stability of the quality of the entire structure with a short construction period.

Welding Technology and Quality

In many regions, there are issues of low reliability of the quality of welding, especially of full penetration welding. For example, in some Asian countries, there are not a few fabricators who explain that they are using the welding standards of the AWS (American Welding Society), but the actual condition is that there are not many reliable proficient welding workers. (It may be same even in America.)

It is difficult to incorporate the "HSS column – H-beam structure", which has been discussed, into a design without the reliability of the welding quality since much use is made of full penetration welding such as in connections between column and beam and between column and columns or diaphragm.

In Japan, there is high reliability of the welding quality of fabricators as a result of having prepared an original standard which is more stringent than the AWS standard, the “Japanese Architectural Standard Specification JASS-6” as well as the “Design/Construction Manual for Cold-formed Square Steel Tubes” incorporating this standard, and of having been engaged over many years in the improvement of the skills of welding workers.

There are several key points in managing welding quality, and just the three main points are introduced here.

1. Choice of welding material

   The higher grade welding material must be used than for the main body of HSS and the diaphragms.

   For example, if the steel grade of HSS and diaphragm was 400N/mm2 class, 490N/mm2 class must be used for the welding material. Because of the concentration of forces at the welded part, from which development of cracks frequently occur, it is important to use higher grades than for the main body.

2. Management of heat input and interpass temperature

   The heat input and the interpass temperature are held below a certain level in order to prevent thermal degradation of the welded part and the surrounding material microstructure.

   In most of the case, heat input must be 40 KJ/cm2 or less and interpass temperature must be 350 or less degrees Celsius.

   In case high grade material is used such as 490N/mm2 class for HSS and diaphragm and 540N/mm2 class for welding material, the heat input must be 30 KJ/cm2 or less and interpass temperature must be 250 or less degrees Celsius when welding the corner part of HSS.

3. Management of tolerances and other parameters

   There are several types of standard range or tolerances in which the gap is managed in various forms of welding in order to prevent the generation of cracks from the welded parts and to have horizontal forces transmitted from the beam to the diaphragm without any problem.

Applications of Large HSS in the world

There are a variety of uses of HSS in the world. Although material of relatively small section is also used in such items as steel furniture, handrails and fence posts, with sizes over 250-300mm square, the main use is for large-scale structures such as large truss roofs such as in an airport or of a stadium, columns and braces of large-scale logistics warehouses and pipe rack in petro-chemical industory, and places where there are many constructions of such large-scale structures constitute the major markets for Large size HSS. These may, in other words, be said to be the “architecturally advanced cities”, so to speak, such as in North America, Europe, Oceania, some parts of the Near and Middle East, as well as in the Asian Zone, Singapore, Hong Kong.

Fig. 10: Airport

Fig. 11: Warehouse

Fig. 12: Pipe Rack

These areas are leading the world also in terms of the penetration of all steel structures including those other than HSS, and the background to this is that they are areas with, first of all, ease of procurement of materials, as well as not only integrated technical capabilities from design to construction which goes without saying, but also advantages in comparison to the RC structure such as the 1. Reduced size and weight of materials, 2. Shortened construction period and 3. Effective utilization of space, which have greater value since, as a market, land prices and labour costs are relatively high. Furthermore, although not common to all the markets, there is also the aspect that such matter as the 4. High recyclability of steel is highly evaluated from the heightened interest in global environmental issues.

Applications of Jumbo HSS in Japan

On the other hand, the majority of the uses of Jumbo HSS in Japan are for columns of multi-story commercial buildings such as offices, shopping malls and multi-level parking lots. The background to this includes, in addition to the one environmental and three economic advantages, which were described in the foregoing, the fact that "Box column – H-beam structure" has the excellent seismic performance.

Applications of Jumbo HSS in Chile

During the last two years the Jumbo HSS was introduced in Chile. The “Box column – H-beam structure concept was introduced in commercial buildings and warehouse projects, as well as a “box beam – box column” concept used in food processing plants, were the owner needed the minimum surface were dust could accumulate.

Fig. 13: Warehouse in Chile with HSS Columns and H Beams

Fig. 14: Food processing plant in Chile with HSS Columns and Beams

Application of Jumbo HSS as Tsunami Evacuation Tower (SG Tower)

As mentioned before, there was no big damage on HSS column to beam rigid frame connection even though stroke by earthquake and tsunami during Great East Japan Earthquake of March 2011. Based on this research, NSMP developed a tsunami evacuation tower, called Safeguard Tower (SG Tower) that uses HSS as columns. Other than HSS as columns, it uses composite slab as floor and piloti style that let through water pressure. It can also be equipped with solar-powered post light and slope for further evacuation process. With using steel structure, this makes the construction shorter than structure with reinforcing concrete, and also the parts are reusable if the building is torn down.

The pictures below show some of the mid-size Safeguard tower built in Japan. They are designed for estimated tsunami height of 6-8m from ground level and they can hold about 200 people. (0.7m2/person)

The scale and capacity are depended on the requirement.

Fig. 15: Safeguard Tower in Japan

Fig. 16: Safeguard Tower in Japan

Conclusions

Below is the “Circum-Pan-Pacific Earthquake Belt” which is referred to as the Ring of Fire.

Because of having suffered great earthquake disasters in the past, Japan has been accumulating an array of technology and know-how in the aspects of both hardware and software in order to endure and overcome them.

"**Jumbo Size Cold Formed Hollow Structural Section Column”** and **“Rigid frame connection between HSS column and H-beam”** in this paper are just one or two among this array.

Those of us who live in the present must cooperate with each other in the future for the sake of both our homelands and descendants.

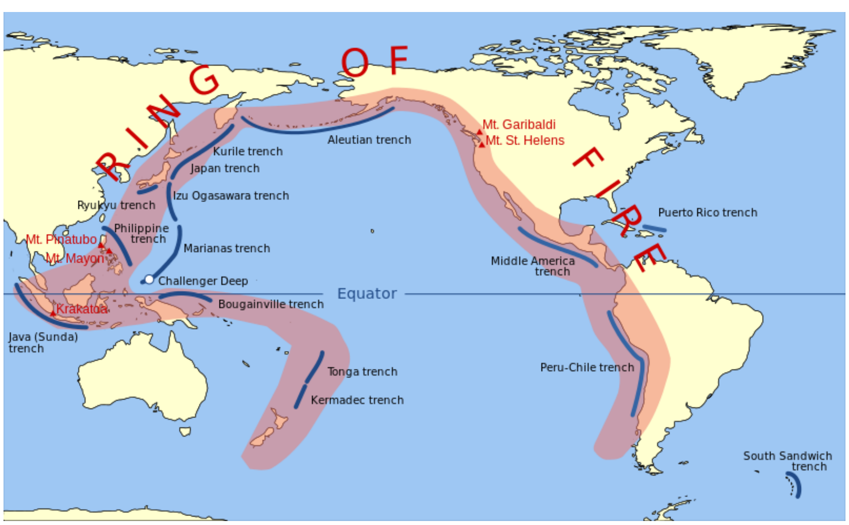


Fig.17: Ring of Fire

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