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Evaluating high performance steel tube-framed diagrid for high-rise buildings

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Abstract. In recent, development of construction and design technology gives taller, larger and heavier steel framed structures. With the tendency of increasing high-rise building, this study is strongly related to structural system, one of significant components in structural design. This study presents an innovative structural system, with high performance steel material, diagrid. Its detail, structural analysis, and structural experiments are all included for the development of new structures.

Keywords: high performance steel; Cyclone Tower; steel-framed diagrid; high-rise buildings; structural experiments

1. Introduction

The shape and form of building structures are varied and materials of construction range from wood to high strength steel. Wood and stone have been historically the most popular building materials, however the use of them has, in recent trends and future prospects used in various buildings, given way to concrete and steel due to their poor availability and difficulty in working. In general steel materials for construction can endure both tensile and compressible resistances which are mainly required to make tapered, tilted and twisted large-scaled forms in buildings due to flexibility of material. It is beyond unified box-type spaces created by concrete for resisting only compressible loads, which have restricted architectural and natural elements to be suitable for human's longing toward aesthetic or free-formed nature.

However it is not easy to define the advantages of steel versus concrete, since these materials depend on so many factors including environmental, social and economic aspects. The ratio of the number of buildings constructed by concrete like R.C is bigger than that of steel framed buildings. According to 2007 report of ministry of land, transport and maritime affairs in Korea steel-framed commercial buildings reached only 27% of all domestic buildings in Korea in comparison with R.C-framed buildings of 73%. This is because concrete material is as about nine times cheap as steel and with respect to stiffness concrete is strong enough to make structures like steel, and therefore relatively concrete material has answered classical demands of consumers that buildings

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must take safety, function and most of all economical efficiency. In gradual consumers as an owner of buildings has a tendency to seek safe, functional and economical components, focusing most of all aesthetic and landmarked components on large-scaled and free-formed high-rise buildings. According to the viewpoint of experts based on 2007 report of ministry of land, transport and maritime affairs, the number of steel-framed buildings is expected to increasingly reach 40% of total domestic buildings in 2011, while R.C-framed buildings decreasingly reach 60% of them.

In the advent of science and technology like the free-formed high-rise buildings using steel, advanced materials emerge from time to time and amongst them, the high functional steel, i.e., in general with yield strength ranging from 460 MPa to 690 MPa, has been extensively and successfully used for decades on the other side of the world.

In recent increasing requirements of consumers for structural steel materials are classified as firstly a high strength for material savings and structural safety, secondly a high performance for a weldability, a fire resistance, a ductility, a low yield point, a lamellar tearing resistance, a corrosion resistance and so on, thirdly a pro-environment like reduction of CO_2 and recycling of steel, and fourthly a minimum of a rise in steel prices. These are also the four basic pre-requisites for the structural use of steel materials. Here the steel including all the requirements is briefly termed a "high performance steel".

High performance steels can easily be identified in fields whereby the weight of structural elements is required as optimal. Such materials are not only renowned for its very high yield strength, but also on its toughness properties, sufficient ductility with elongation of over 15%, and lastly the weldability. Very often, structural engineers or architects would like to design peculiar tension structures with slim and slender profiles and in some occasions, conventional steels are unable to achieve their goals. Further, steels satisfying the requirements can significantly increase the design capacity, therefore reducing the amount of steel to be used.

This study is built up as follows: in Section 2 characteristics of high performance steel which are introduced in this study are presented with respect to structural use. Section 3 presents its practical application to high-rise buildings, here a Cyclone tower project with a steel-framed diagrid system under construction in Korea, introducing high-rise buildings using diagrid frames in Section 3.1 and measuring structural and economical efficiency of a specific diagrid system using steel materials in Section 3.2. Section 3.3 shows in turn development of diagrid detail, analysis and experiment results of the developed steel-framed diagrid detail. Section 4 presents conclusions and remarks of this study.

2. Characteristics of high-performance steel

One of the more recent developments of steels for construction is really a trend of developments given the term high performance. High performance steel materials provide far greater strength, ductility, durability, and resistance to external elements than traditional construction steels, and can significantly increase the longevity of structures in the built environment and can also reduce maintenance costs for these structures considerably.

High performance does not mean merely higher strength, but rather the improved performance of a number of varied factors of steels. For example, welding is used in most construction fabrication and therefore weldability is a significant factor. Many of the new construction steels ease the need for these precautions by producing high quality welds faster with less effort, with less consideration for pre-heat and post-heat and with less concern about internal cracking like lamellar tearing. Ductility is an ability that permits steel to elongate without fracture. Most of all strength is one of the key factors of high performance steels. Increased strength equates to reduced quantities of steel within limits of a given deformation, which may lead to reduced construction cost.

The high performance steels appeal to an optimal combination of improved features that more than make up for their higher specific cost. They provide opportunities to reduce the finished construction cost by lowering fabrication cost and, by reducing steel weight, the costs of shipping and erection. Much of the early research in these products was done for military use, which requires more functions rather than cost. Adapting this technology to building construction applications, along with essentially reducing material costs, gives an impulse to further develop steels.

In this study high performance steel, i.e., TMCP steel with tensile strength of 600 MPa, with high strength and improved weldability is introduced, which is developed by POSCO steel company in Korea.

2.1 High strength steel

High strength steel among the many high performance steels developed has continuously been available for many types of industrial applications such as ships, towers, buildings, bridges, pipelines and machinery. Only recently high strength steel has been utilized as a structural material of buildings, bridges, and offshore platforms, since it gives outstanding advantages such as in constructions of high-rise buildings, buildings with fewer column and longer spans for increased rentable or lettable area, buildings more resistant to seismic and wind loads, increased architectural options with lighter and stronger elements and frames, simplification of handling, fabrication and erection, and development of new construction methods. In general high strength steel produces the more economic construction of buildings and bridges.

2.2 TMCP steel

This steel is manufactured by a thermo-mechanical control process, i.e., TMCP, introduced by Shiro (2002) and Lee *et al*. (2012) and feature excellent weldability and strength stability. They were used first in the ship-building industry. In conventional steels when thickness of plates is greater than for example 40 mm, yield or tensile strength of steel has a tendency to be instable and it would decrease. However TMCP steel has qualities of uniformed strength regardless of thickness. Today, plates with thickness greater than 40 mm are almost all made from building structural TMCP steels.

3. High performance steel application for high-rise buildings

3.1 Steel-framed diagrid system

In origin, there are two possibilities to develop structures due to the limited space on earth. First is to develop something for using horizontal spaces, for example long span (Ernest *et al*. 1978) structures like bridges, space frames, and membrane structures. Second is to develop it for using vertical spaces, for example high-rise buildings with varied structural systems introduced by

Iyengar (1984). Although the development for using horizontal spaces is limited, engineers have been strived to optimally utilize the given spaces. Especially there is no limit for employing vertical spaces, however appropriate facilities or equipments like fast lifts or efficient air-conditioner systems have to additionally be considered since the high region differs from the ground space with respect to environmental conditions. In this section, some application of specific high performance steel-framed high-rise buildings to the letter, i.e., vertical factor for improving spaces is discussed.

Since the first steel-framed multi-story building (Smith and Coull 1991) in Shrewsbury in England has been built in 1797, high-rise buildings have posed design challenges for structural engineers to efficiently utilize the space, especially, if located in a seismically active region or if affected by wind load. Therefore a high-rise building is systematically designed as any vertical construction for which lateral loading conditions like wind or seismic loads are a more significant factor than weight. As the height of the building increases, the lateral loads gradually dominate the structural design.

Structural systems for high-rise buildings in structural engineering denote load-resisting sub-systems, and transfers loads into internally connected structural members referred by Schueller (1990). Varied structural systems like a bearing wall, a core, a frame, and a tube system have been introduced by engineers for high-rise building design. A bearing wall system consists of planar vertical elements forming the exterior walls and it resists both vertical and horizontal loads. A core system is composed of a closed box where the vertical transportation systems are concentrated. This provides flexibility in the building space usage outside the core. The core can resist both vertical and horizontal loads. A frame system consists of columns, beams, and floor slabs to resist both horizontal and vertical loads. A tube system is made up of closed and spaced exterior structural components, which resist lateral load rather than as separate components. Another form for the tube is braced tubes and framed tubes. These structures offer for more flexibility in the use of interior space due to the lack of columns.

Alternative to the structural braced tube system is the so-called “diagrid (diagonal grid)”, which has been officially introduced by Subramanian and Subramanian (1970), for developing structural flexibility of both vertical and horizontal space for high-rise buildings. The diagrid system can be framed by concrete or composite including steel material and its application issue to buildings in Korea is treated in this study. Diagrid is not a new braced tube system and it has been already used for interconnected members among trusses consisting of airplanes or ships. In recent years the structural diagrid system for steel-framed high-rise buildings has been introduced by some engineers and co-workers such as Genduso (2004) and Moon *et al*. (2007). Some well-known tall buildings (Rahimian and Eilon 2006, Zhang and Wang 2012, Leonard 2007) by using diagrid have been already completed or are now under construction.

The steel-framed diagrid structural system consists of diagrid perimeter which is made up of a network of multi-story tall triangulated truss system. Diagrid is formed by intersecting the diagonal and horizontal components. This innovation transfers both gravity loads and lateral loads by redirecting member forces, and eliminates the need for vertical columns on the exterior of the building. Architecturally the absence of columns in the corners of the building provides great panoramic views from the interior. This system was first introduced in the John Hancock Center (Moon *et al*. 2007) in Chicago in USA which was completed in 1969. In recent years in Korea, Cyclone Tower located in Asan city in Chungnam Province, Jam-sil Super Tower in Jam-sil in Seoul, and Future-X Tower in Daejun have been planned for construction as shown in Fig. 1. These are the first trial in Korea, however in the world there are already a few high-rise building using diagrids such as Swiss Re building in London in UK, Hearst Tower in New York in USA, and CCTV building in Beijing in China, which is currently under construction, as shown in Fig. 2 (Subramanian and Subramanian 1970, Rahimian and Eilon 2006) using diagrid systems.

The diagrid is a simple and a systematic structure for constructing large and tall buildings with mainly steel by using straight, curved, or horizontal rings and triangulated beams which together make up a complete structural system. In general buildings, columns are utilized for providing vertical load carrying capacity, diagonals or braces offers stability and resistance to large horizontal forces such as wind and seismic loads. However diagrid members take several advantages in addition to eliminating perimeter columns. At most diagrid system optimizes each structural element. In other words the diagonals and braces try to join in the vertical load transfer, and the columns participate in the lateral load. The two functions are combined into a diagrid and then diagonals, braces, and columns become finally all one system. In general diagrid can be made

(a) Cyclone Tower

(b) Jam-sil Super Tower

(c) Future-X Tower

Fig. 1 Examples of construction plans of steel-framed diagrid high-rise buildings in Korea

(a) Swiss Re Building

(b) Hearst Tower

(c) CCTV Headquarters

Fig. 2 Examples of steel-framed diagrid high-rise buildings in the world

from wood, concrete, and steel or their composite. However steel is the most common material of choice due to its high abilities to resist both tensile and compressive forces. Therefore for example, in Hearst tower steel diagrid has resulted in a highly efficient structural system that consumed 20% less steel material in comparison to conventional moment frame structures (Subramanian and Subramanian 1970).

3.2 Cyclone tower with a high performance steel-framed diagrid system

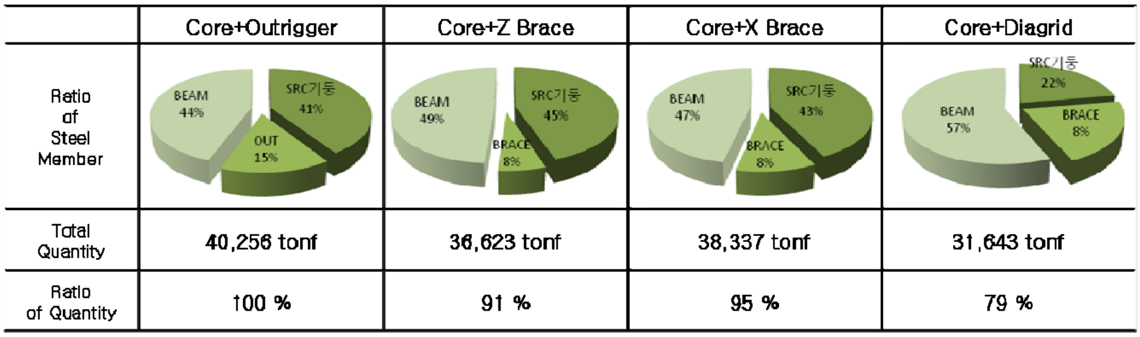
3.2.1 Overview

Cyclone tower was planned to be completed in the year 2012 and contained 3,900 m^2 near KTX, i.e., Korea Train eXpress, station in Asan City in Chungnam Province in Korea as shown in Fig. 3. However it is not a processing construction project now. This project can be reflected to engineers and designers for diagrid system. This building is designed by Kunwon Architects Planners Engineers, structural engineered by CS Structural Engineering Inc., and constructed by a consortium of SK E&C, Daelim, Doosan Heavy I&C, and Kyeryong Construction - is 51 stories tall and 7 stories below, standing 251 m with office and resident spaces. The uncommon triangular framing pattern (also known as a diagrid) required about 4,000 ton (total steel quantity is about 10,000 ton) of structural high strength steel with the tensile strength of 600 MPa and the yielding strength of 440 MPa.

3.2.2 Systematic and economical efficiency of high performance steel-framed diagrid system in Cyclone tower

Steel-framed diagrid systems can evaluate various free-formed, like tilted, tapered, and twisted buildings, including a recent landmarked element due to flexibility of spaces and needlessness of box volumes of beam-to-column types. The total quantity of steel-framed diagrid system with core is reportedly about 21% less than conventional steel frames, here a core + outrigger, a core + Z brace, and a core + X brace system as shown in Fig. 4.

Fig. 3 An air view around Cyclone tower



	Core+Outrigger	Core+Z Brace	Core+X Brace	Core+Diagrid
Ratio of Steel Member	BEAM 44%, SRC기둥 41%, OUT 15%	BEAM 49%, SRC기둥 45%, BRACE 8%	BEAM 47%, SRC기둥 43%, BRACE 8%	BEAM 57%, SRC기둥 22%, BRACE 8%
Total Quantity	40,256 tonf	36,623 tonf	38,337 tonf	31,643 tonf
Ratio of Quantity	100 %	91 %	95 %	79 %

Fig. 4 Quantity comparisons of steel-framed systems

In addition, under the same behaviors as shown in Table 1, the use of high performance steel with almost 600 MPa TMCP reportedly reduces about 23~27% of total steel quantity in comparison with the use of conventional steel material like SM490 as shown in Table 2. Here this high performance steel with the tensile strength of 600 MPa TMCP satisfies demands of consumers like higher tensile and yield strengths, better weldability, lower yield point, and lamellar tearing resistance.

Therefore the use of the diagrid structure as well as the high performance steel can be recommended for structural and economical efficiency of the construction of steel-framed high-rise buildings.

Table 1 Comparisons of structural behaviors between 600 MPa TMCP and SM490 steel-framed diagrid systems

	SM490 steel		TMCP steel with tensile strength of 600 MPa	
	X-direction	Y-direction	X-direction	Y-direction
Period (sec)	4.74	4.59	4.90	4.75
Ratio of displacement between each story	0.0018 (OK)	0.0018 (OK)	0.0053 (OK)	0.0019 (OK)
Displacement of top story	46.0 cm (H/530)	42.4 cm (H/560)	50.0 cm (H/485)	46.0 cm (H/530)

Table 2 Quantity comparisons between 600 MPa TMCP and SM490 steel-framed diagrid systems

	SM490	600 MPa TMCP steel	Quantity
Diagrid	100%	73%	Decreasing 27%
Edge column	100%	77%	Decreasing 23%

3.3 Analyses and experiments of steel-framed diagrid structure

3.3.1 Development of steel-framed diagrid detail

At first, in order to apply a diagrid system to Cyclone tower, Research institute of Industrial Science and Technology (RIST) needed newly an appropriate diagrid detail for high-rise buildings. Possible details are investigated through the benchmarking of foreign such as a tube diagrid type at Guangzhou west tower in China, a plate beam and tube diagrid type at Swiss Re in England, and a H-beam diagrid type at Hearst tower in USA. RIST, SK E&C, and domestic steel manufacturers developed a specific diagrid detail through comparisons among other Alts as shown in Fig. 5.

As can be seen in Fig. 5, Alt 1 and Alt 2 are bolting connections, but the difficulty of the construction of bolting by using an impact universal joint occurs due to narrow width between a H-beam and a corner cap plate, and especially it may be more difficult to make holes due to the use of high strength steel with tensile strength 600 MPa. Alt 4 and Alt 5 use continuous tubes, thus structural stiffness of Alt 4~5 is superior to that of other Alts. However field or shop constructions for diagrid are difficult because of large amounts of welding. Alt 3 is the same detail of Alt 1~2. However it proposes not a bolting but a welding connection due to difficulty of bolting construction at field or shop.

Fig. 6 shows a finally chosen diagrid detail, i.e., Alt 3 in Fig. 5, with a tube and cap plate type connected by all welding. For clear loading path, in and out-stiffeners are used. In advance all alts on diagrid details were synthetically criticized with respect to structural safety, function, productivity, transport, and construction. For example, the diagrid can be divided into four cap plate + tube members and a H-beam, which are partially made in factory and then connections of each member are finally completed by welding in construction site for productivity and transport.

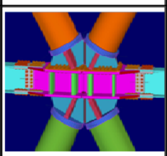
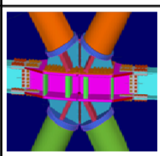
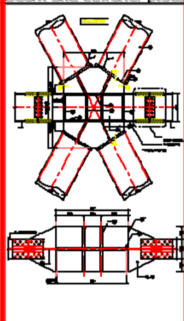
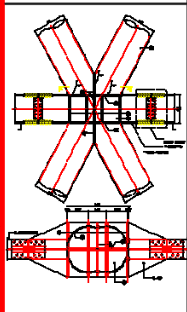
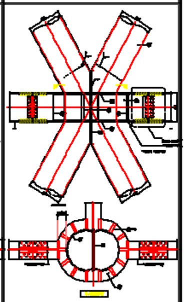
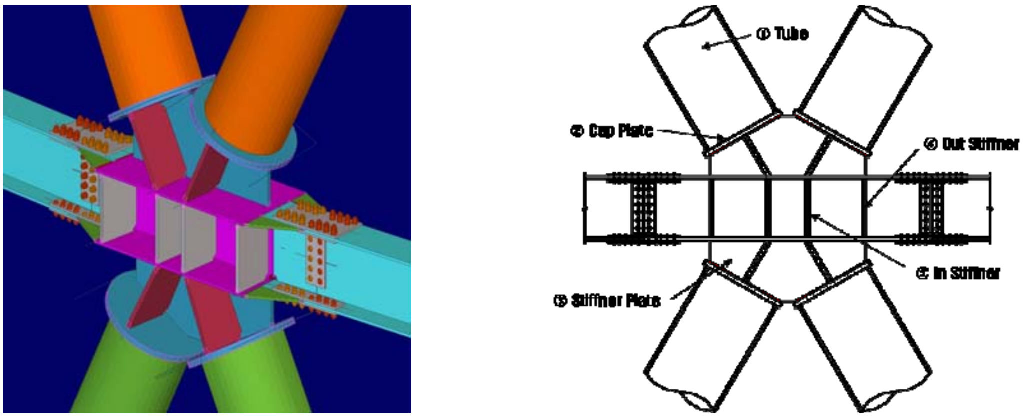
	Bolting Connection		Welding Connection		
Type	ALT1	ALT2	ALT3	ALT4	ALT5
Feature	-Bolting	-Bolting -Move the stiffener to outside	-on site: welding of tube and stiffener plate -in shop: welding of H-beam and stiffener plate	-Directly welding H-flange and tube	-Tube welding
Concept	 ※ Ranch Operation for Bolting: by "Impact universal joint", in case M24 it is possible up to height of 100mm				
Node	H-beam	H-beam	H-beam	H-beam	Tube connection
			Final Detail		

Fig. 5 Alts for diagrid detail



(a) 3D diagrid detail (b) Constitutive elements of diagrid detail

Fig. 6 Details of tube-type diagrid

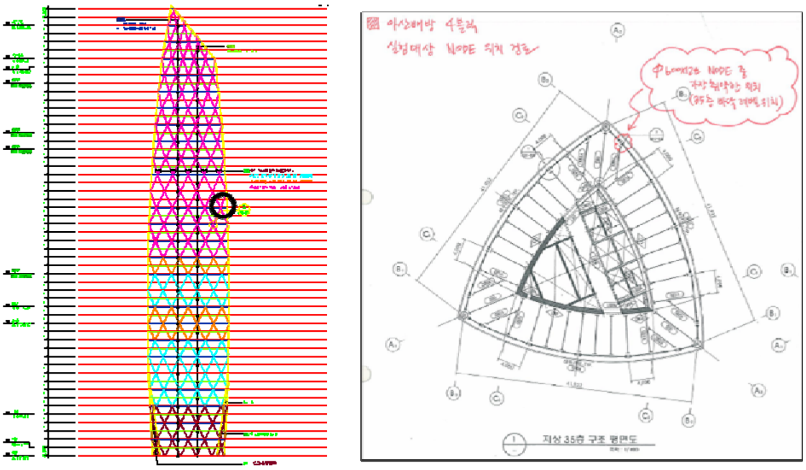
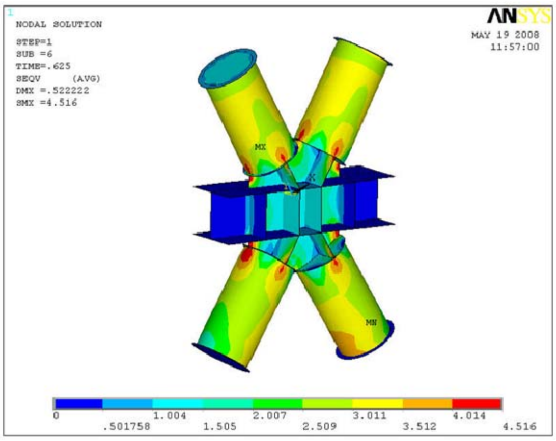


Fig. 7 Location of a selected diagrid member in Cyclone tower for executing analyses and experiments (35 stories)

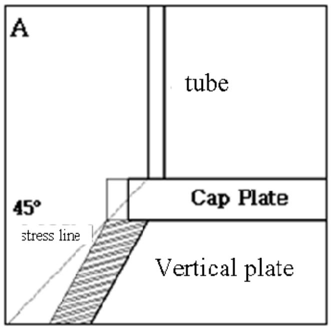
Location of the developed diagrid member in Cyclone tower for analyses and experiments is the 35th floor as shown in Fig. 7 and it is planned to be suitable for maximum load capacity of 1,000 ton of UTM which RIST possesses.

3.2.2 FEM analyses of steel-framed diagrid

In order to verify structural reliability of the chosen steel-framed diagrid (Moon 2012, Nguyen and Altan 2012), as sketched in Fig. 6, an intensive investigation of connection parts of diagrid is needed due to its structural weakness. The tool for the investigation is divided into an analysis method and an experimental method. In order to make experimental test plan, firstly it is required to select proper experimental parameters from FEM analysis results like structural deflections.

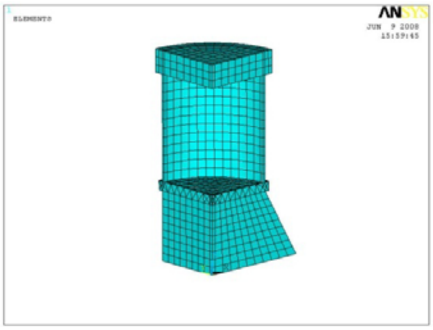


(a) Analysis result

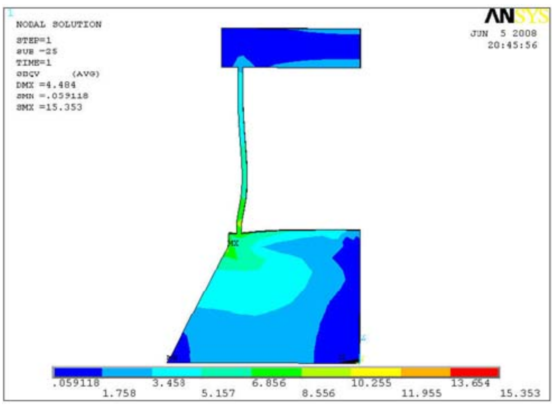


(b) Reduction of stress concentrations

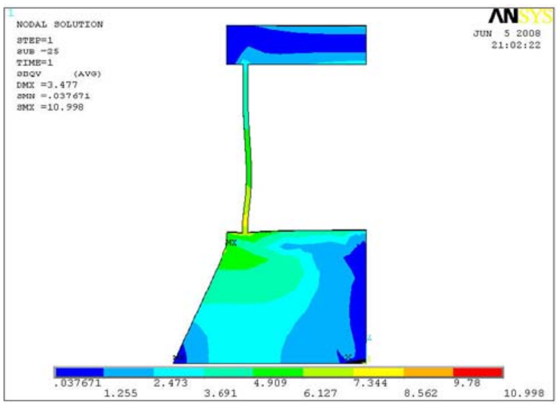
Fig. 8 FEM analysis and a reinforcement method of diagrid



(a) 1/4 analysis model



(b) Analysis result of original model



(c) Analysis result of modified model

Fig. 9 Stress distributions of analysis model of 1/4 diagrid

A typical structural FEM analysis result is shown in Fig. 8(a), when compressible loads are applied onto X-direction of each tube. The FEM analysis was executed by commercial ANSYS (Lawrence 2012) and ABAQUS (Hamid *et al*. 2012) programs. As can be seen stress concentrations intensively occur between cap plate and end of tube and then some reinforcement is required there. Therefore an extension of a cap plate and a vertical plate is an alternative to the reinforcement such as shown in Fig. 8(b) in order to relieve the stress concentration. In addition, a control of cap plate thickness can be considered as an experimental parameter.

Figs. 9(b) and (c), respectively, shows an analysis result by cap plate thickness of 40 mm and cap plate or vertical plate extension of 20 mm, and an analysis result by the same thickness and cap plate extension of 40 mm in comparison. As can be seen the stress concentration as shown in Fig. 9(b) is relieved like as shown in Fig. 9(c) by using structural reinforcements in Fig. 8(b). These results are governed on plasticity analysis. For the purpose of FEM analyses a 1/4 analysis model shown in Fig. 9(a) of diagrid was used due to numerical efficiency.

3.3.3 Experiments of steel-framed diagrid

According to FEM analysis results of Section 3.3.2, experimental parameters were chosen as follows: A cap plate thickness and a cap plate extension length, including a steel type like SS400, SM490, a high performance steel of 600 MPa (here denoted as SM570TMCP), and pre-tensioned axial forces of 0% and 30% describing critical load combinations.

Table 3 shows chosen test specimens according to these considerations. Here DC denotes diagrid connection. G, H, and N are, respectively, SS400 steel, SM490 Steel, and SM570TMCP steel which is a high performance steel developed and produced by POSCO for construction of high-rise buildings. Numbers in specimen name denote thickness and extension length of cap plates. Radius and thickness of tubes are fixed to 600 mm and 12 mm, respectively, to be suitable for load capacity of 1000 ton UTM which is retained in RIST.

Installation and equipment for experiments are sketched in Fig. 10. 1,000 ton UTM is used to apply a compressible load on one tube direction. Axial force of 0% or 30% is applied to another tube direction and it is pre-tensioned by 10 steel round bars. In order to give constant pre-tension forces to tube, road cell is used. The ends of the tube enforced by compression are reinforced by ribs in order to prevent fracture at tube parts not directly related to the center of nodes.

Table 3 Test specimens

Specimen	Steel type	Cap thickness (mm)	Cap extend (mm)	Axial force (%)
DC 462G001	SS400 (F_y = 240 MPa)	40	+60	0
DC 420G002			+20	about 30 (1,756 kN)
DC 440G003			+40	
DC 462G004			+60	
DC 562G005		50		
DC 462H306	SM490 (F_y = 330 MPa)	40	60	about 30 (2,414 kN)
DC 420N307	SM570 (F_y = 440 MPa)	40	+20	about 30 (3,219 kN)
DC 460N309			+60	

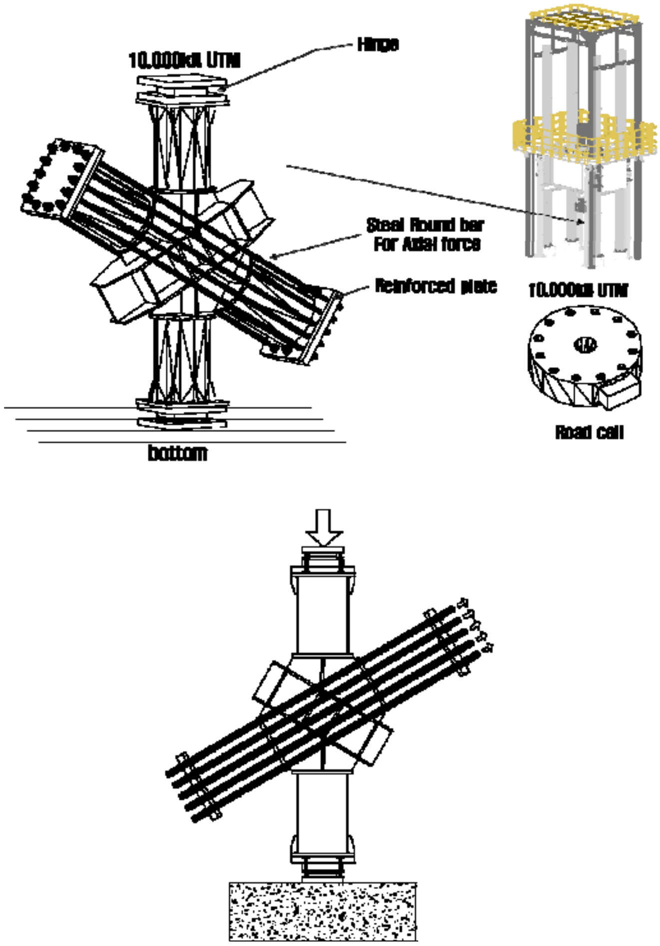


Fig. 10 Installation and equipment for experiment

Fig. 11 shows installation procedures of test specimens in RIST laboratory as the following (1) attachment of strain gages; (2) installation of steel round bars; (3) attachment of hinges; (4) transport and fixation of test specimen; (5) installation of displacement machine and connection of strain gages; (6) pre-tension of steel round bars; and (7) completeness of experiment setting.

Fig. 12 presents experimental results of test specimens of 462G001 using SS400 steel, 462G304 using SS400 steel and 462H306 using SM490. As can en seen compressible deflection occurs between a cap plate and an end of tube and it is almost equal to analysis results in Section 3.3.2. Specimens using high performance steel with tensile strength of 600 MPa (here, SM570TMC) which is not described in this study were not deformed at there, when loaded until almost 1000 ton by 1000 ton UTM. From this result, it can be inferred that member thickness and size can be additionally decreased by the use of high performance steel (here, both TMCP and high strength steel), and therefore material quantity will be reduced and thus economical efficiency is achieved.

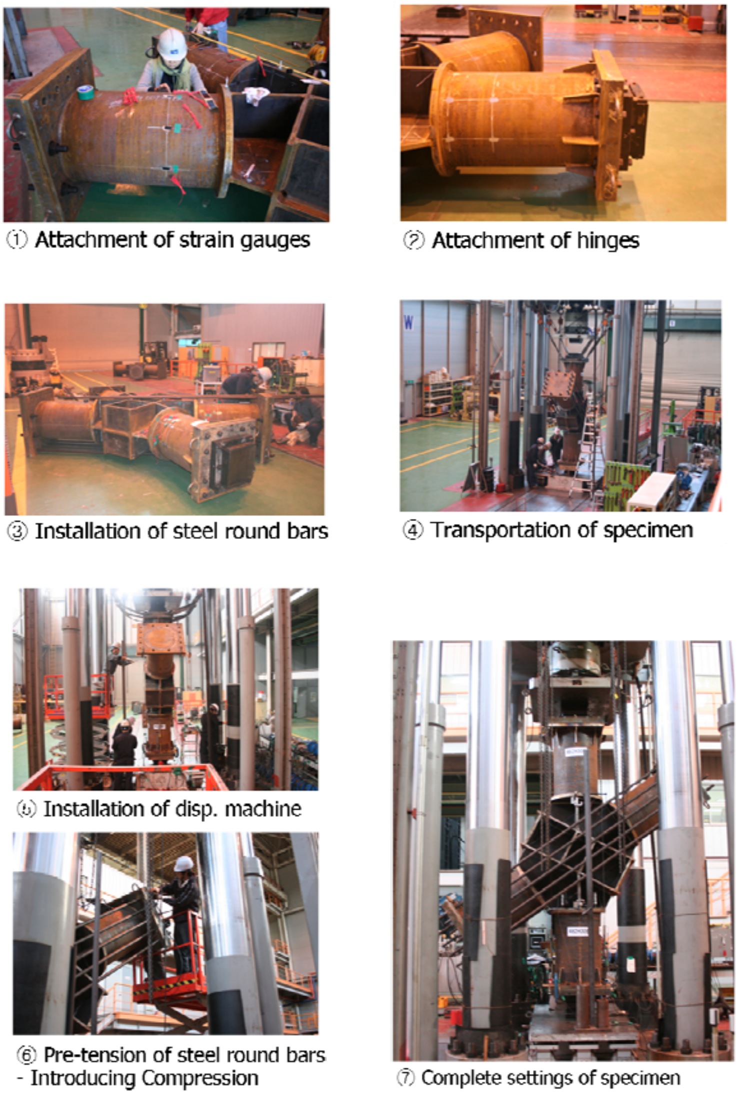
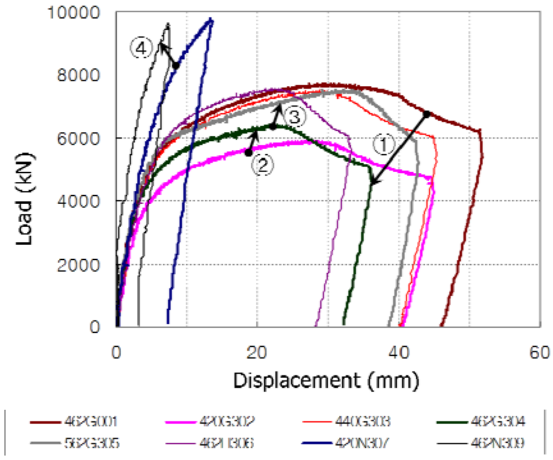


Fig. 11 Procedures setting test specimen in RIST laboratory

Fig. 12 Experimental results of some test specimen



	Specimen	Steel	Cap Thk.	Cap Ext.	Axial Froce
①	462G001	SS400	40	60	0%
	462G304	SS400	40	60	30%
②	420G002	SS400	40	20	30%
	462G304	SS400	40	60	30%
③	462G304	SS400	40	60	30%
	562G305	SS400	50	60	30%
④	420N307	SM570	40	20	30%
	460N309	SM570	40	60	30%

Fig. 13 Curves of displacement and load of each test specimen

Fig. 13 shows curves of displacement and load of test specimens. As can be seen G types of SS400 steel reaches more 45% than standardized tensile strength of 400 MPa. In addition a H type of SM490 also reaches more 50% than the standardized tensile strength of 490 MPa. The structural behaviors depend on cap plate thickness and extension length.

Experiment ① shows structural behavior effects relying on axial forces. Surely stiffness decreases when axial force is loaded. Experiment ② and ④ show the effect of extension length of cap plate. It can be found that structural stiffness of diagrid also increases when extension length increases. Load-displacement curve of experiment ④ stops near loading 10,000 kN due to the limit capacity of 1000 ton UTM. Result of experiment of ③ indicates how the thickness of cap plate has an effect on structural behavior. Naturally increasing cap plate thickness leads to increasing stiffness of diagrid.

4. Conclusions

The design system under the new building standards law with performance-based requirements will call on design engineers to achieve rational and economical building steel structures by adequately employing the characteristics and performance of building structural steels and using the right steels in the right applications. It will also call on steel manufacturers to develop and supply steels to meet a variety of service performance requirements. Steel makers appropriately must cope with the situation of increasing demand of consumers. Moreover the development of new structural system like diagrid also needs in order to extend the demand of the high performance steel.

Cyclone tower project verifies efficiency and compatibility using high performance steel, i.e., 600 MPa TMCP-framed tube diagrid system firstly in Korea. It is an exemplar with the harmony between high performance steel material and structural diagrid system in case high-rise building constructions.

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