Design and Construction of the Super-Frame Structural System in Tabriz World Trade Center Tower

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Abstract

Tabriz World Trade Center Building, a 36-stories structure with only one basement, is considered as one of the major architectural and structural engineering achievements of the experts in Iran. Although, the plan[1] free system in tall buildings and the super frame structure has first developed in Japan, however, its application and technology improvement in Iran using local materials in an advanced system, has been the great achievement of Tabriz World Trade Center project. Plan free, means the use of beam-less roofs and flat floors with the possibility of installation the water and sanitation facilities in floors (embedded at the bottom of the zone), thus four open sides of the building. In the free planning system, the architect has freedom of designing any plan and the building. A super-frame structural system with viscous dampers which is used in high-rise towers with free plan floors consists of a central core wall, super beams located in the upper level of the building, perimeter columns and viscous dampers. In this system, viscous dampers are installed between the tip of super beams and perimeter columns. During earthquake, the super beams and perimeter columns reduce reversal moment in the central core, and viscous dampers mounted in the tip of super beams also reduce structural bending moments and lateral deflection. In this new system even in very high seismic areas all the beams can be replaced by flat floors and the number of internal columns can be reduced to provide a building with the limited number of columns which provide free spaces. Super-frame structural system was applied to the world trade center Tabriz tower in Iran, with improvement in local material which had a great effect on the construction knowledge of experts. In this paper, after the introducing of Super-frame structural system, the implementation details of the structure (World Trade Center Tabriz) will be discussed.

Keywords: Tall buildings, Super-frame structural system, Viscous damper, World Trade Center

1. Introduction

In the past decades, the implementation of most of high-rise buildings were raised with the purpose of presenting the engineers' power in the construction industry. Thus designers often focused on designing of a stable structure. However the architectural elements were generally under the limiting conditions of the structural components. For this reason, the building's exterior protection, which maintain the lighting and the openings to the outside view, was less studied. Today, in harmony with other technological advances made in different sciences, the technology of high-rise buildings has undergone major changes in the architecture, and consequently in the structures. During the recent years, with the development of the technology for construction of towers and skyscrapers, special attention to the architectural design (both in the exterior and interior elements) became more important, and hence, new towers have become increasingly more complicated than previous generations. In Japan, after implementation of the first high-rise building successfully with high-strength materials (Hi RC) in 1970, a large number of buildings of up to 30 stories, have been constructed quickly by taking the advantage of this technology. During the research and studies on high-rise RC construction engineering in Japan, the researchers have realized the construction of buildings with high strength materials as high as 50 stories that has same beam and column cross sections as normally designed for a 30-story high-rise concrete frame. In recent years, the need to provide more flexibility in architectural design of buildings caused, in elements that were responsible to resist lateral loads, and had previously deployed around the building, to be transferred to the central part of the building (elevators and stairs holes), so that a space be created without a column on the floor. However, the studies showed that with this change in design pattern, dimensions of the mentioned elements have reduced and lower lateral stiffness will be created. Then, during the earthquake, the deformation of the higher floors exceeds the expected values. As a result, the idea of implementing shear walls around the elevator holes and stairwell alone is not sufficient to counteract the lateral forces, and fundamental changes in the structural system should be established. A set of analytical, laboratory studies and models which were tested and loaded in full scale, ultimately, it leads to the invention of super-frame structural system. The most important characteristics of a super-frame structural system is that, in addition to ensuring high seismic performance of building, the restrictions raised on the elements of architectural, mechanical and electrical installations, were completely eliminated. In this paper, the super frame technology is introduced and the super-frame structural system and its components are explained then, the performance of the system is compared with other common structural systems. Finally, the features of the Tabriz World Trade Center Tower, which has been constructed using this technology, will be discussed.

2. Concept of super frame system

As illustrated schematically in Figure 1, Super-frame structural system consists of a T-shaped super structure which its components include the central core wall, super beam, perimeter columns, flat slabs and viscous dampers. A central core wall, which is located in the central part of the plan to be made of high strength reinforced concrete materials. The wall can withstand the most adverse external loads. Super beams just are located at the top of the structure and on the central core wall. Perimeter columns that are arranged in the outer parts of a building plan essentially are responsible for the task of carrying the vertical loads. Viscous dampers are installed vertically between the tip of super beams and some of the perimeter columns. These dampers are classified as High performance oil dampers. When applying lateral loads on structures, flexural deformation of the central core causes deformation of the tip of super beams, which dampers act because of that, and through this earthquake-induced vibrational energy is dissipated. This mechanism makes the bending moment in the central core wall and lateral deflection in structure (especially in higher elevation) is reduced. In order to optimize performance of dampers during an earthquake, super beams, usually consists of high-strength steel cables are drawn. This type of structural system where members are located inside the building, are called Outrigger lateral internal structural system. In a super frame, taking into account the considerations related to serviceability caused by floor vibration for residents, post-tensioned concrete flat slab floor system is drawn. In this way, there is no beam between the central core and outer columns, thus allowing free passage of pipes and building facilities is provided. By removing the beams in the floor, the possibility of reducing the floor height is provided which its achievement is a significant saving in construction costs [1].

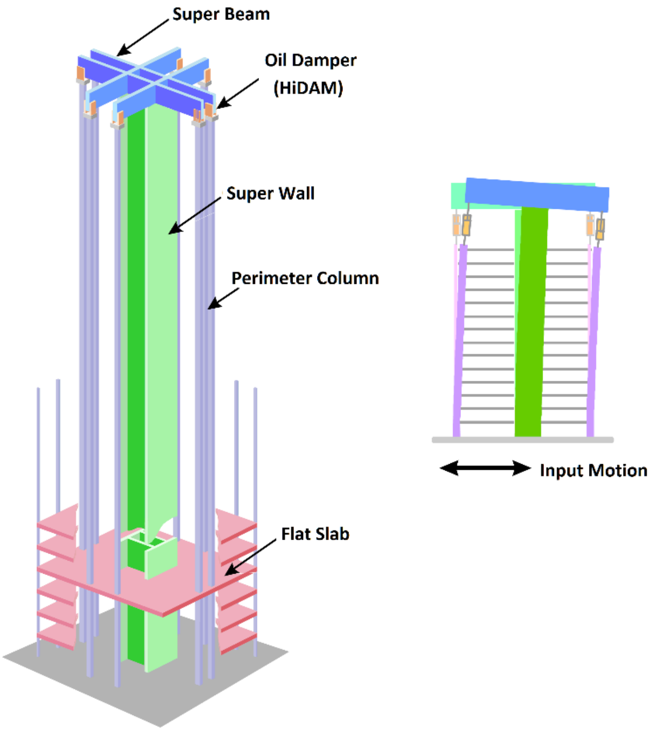
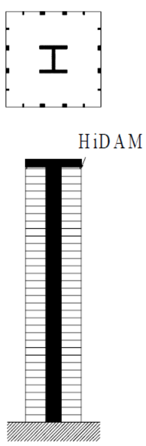
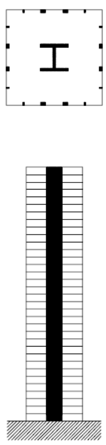
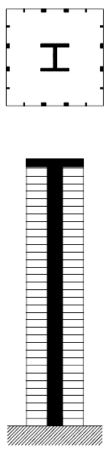
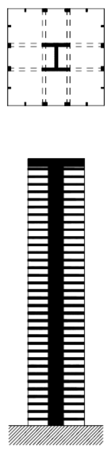
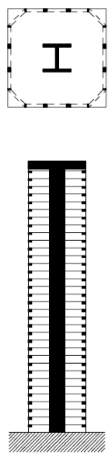


Figure 1- Schematic illustration of the super form structural system (high-strength concrete frame system) [1]

3. Seismic features of Super frame System

In this section, to fully understand the dynamic characteristics of the super-frame system, the results of seismic response analysis conducted in an exemplary model to be compared with other structural systems. The typical model includes a 35-stories building with a height of 122 m with H-shaped central core located in the center of the floor, and 16 peripheral columns. Profile of structural system which has been used to this arrangement for comparative analysis is presented in Table 1. In this table, the super-frame system has been named as Case.1. Case 2 includes a central core system in which only the central core can resist against lateral loads. Case (3) is a core and outrigger system, in which super beams and perimeter columns are rigidly connected. Case (4) is a central beam and core system where central beams are located on each floor between the central core and the outer columns. Case 5 consists of a central core system and tube in which environmental beams are connected to the external columns as cross and form tube frame. In all cases, structural members are designed, reasonably as a member of reinforced concrete. Dynamic response analysis with respect to non-linear features of each member is done under the devastating earthquake which is simulated in a Japanese national project, called New-RC Project. Maximum responses samples obtained from the analysis of the responses are presented in Figure 2. According to the figure, except for the case 2, in other cases, the story drift angles remain at around 1/100. According to the results for case 2, it can be concluded that the core system alone can't prevent the flexure of the upper stories. Case 1, which is the super frame system, shows the lowest response compared to other states. Generally, the story shear force decreases with increasing natural period (due to reduced vibration energy input), but side skips and story drift tends to increase. Super frame system, which, according to Table 1 has the longest natural period, in addition to maintain the advantages of reducing vibrational energy applied, viscous dampers installed absorb vibrational energy and deformation can be prevented. The dynamic design of a super-frame structure, the nonlinear seismic response is done using the equivalent vibration model. For example, in a building with n-story structure, when the total mass of each floor is focused on floor level, a model with n bubbles can be considered. All the walls of the central core, super beams, outer columns, connecting beams, flat slabs and environmental frames are modeled by bending-shear members. Nonlinear properties of these members will be assessed on the basis of experimental data and their analytical study (such as a non-linear static analysis with a fiber flexibility model for the central core walls, a non-linear finite element analysis for flat slabs, a non-linear analysis with progressive loading for perimeter beams, etc.).

Table 1- A comparative study in the structural systems [1]

Case 1	Case 2	Case 3	Case 4	Case 5
Super-RC Frame	Core Wall	Core Wall with super beam	Core wall and boundary beam	Core wall and Tubular frame
				
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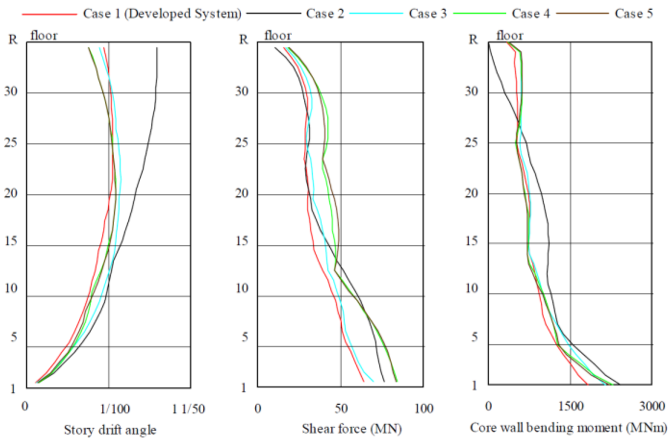

Figure 2- Maximum seismic response in a comparative study [1]

4. World Trade Center Tabriz Building (WTC Tabriz)

The Tabriz world trade center has constructed as the first world trade center building in Iran, with the super frame structural system in 36-stories, with a height of 140 meters (to the top of the dome), with the total area of 41,457 square meters in Kouy Valiasr in Tabriz city, and in a position with landscape overlooking the entire city. The building, in addition to having a unique structural system, has a beautiful architectural design with open outer shell, which is intended to provide lighting and outward vision for its residents. Communicational routes to the building include the western entrance building (exclusive track) of Shariati Street, next to Yas Park, the eastern entrance of the World Trade Square, and south entrances of Lida Street. The main functions defined in this building include office units (2 to 31 stories), and tourism zone (32 to 36 stories). The entire tower tourism complex is located inside the tower dome section. Figure 3 shows an overview of the Tabriz WTC tower. The building has a very important characteristic of plan free in its floors, in which, the internal divisions of plan can be designed and implemented by the immense diversity without any architectural problems, or utilities (that is considered as one of the important design concerns). One floor of the WTC Tabriz tower might include a large, it may be divided to eleven small units for private office users. As previously mentioned, the advantages in architectural designing requires advanced technology in the structure, because the plan free requires that beams in the ceiling to be removed, and water and sanitation facilities are located on the floor. On the other hand, other limiting structural components such as columns and shear walls must be removed or minimized. The super frame structure of the WTC Tabriz tower, also is the result of many years of researching and laboratory model testing on shaking table and also strong wall and floor laboratory by Japanese engineers. The new system is able to insure the structure against the destructive factors such as strong earthquakes in addition to meet the goals of the architecture.

Prerequisites were required to provide the ability to construct the super-frame structural system in the Iran, which a summary of them is presented in Table 2.


Figure 3- Overview of the World Trade Center Tabriz Building

Table 2- The required prerequisites for construction of super frame system

Title	Constructional detailing In Tabriz WTC
Casting of high strength concrete	• Piled raft foundation (f'c=54 Mpa) • Columns (f'c=35-60 Mpa) • Core wall (f'c=35-60 Mpa) • Super beams (f'c=60 Mpa) • Flat slabs (f'c=48 Mpa)
Casting of high strength rebar	• Core wall (fy=700 Mpa) • Super beams (fy=500 Mpa)
Casting of NMB splice sleeves[1]	• Core wall • Super beams • Pre cast columns
Casting of R-PC	• Casting the columns
Installation of viscous dampers	• are installed vertically between the tip of super beams and the perimeter columns.
Prefabricated wall	• The exterior walls of the building
Bonded and unbounded posttensioning tendons	• Flat slabs (unbounded tendons) • Super beams (bonded tendons)

4.1 Cellular Raft Foundation

As indicated in Figure 4, the foundation structure of WTC Tabriz tower is in the form of a cellular raft of 4.5m overall height. The foundation consists of two concrete slabs which are

[1] The NMB SPLICE-SLEEVE is a mechanical coupler for splicing reinforcing bars which uses a cylindrical shaped steel sleeve filled with a Portland cement based non-shrink high early strength grout.

placed at a distance between the deep beams. Deep beams (with different sizes from 80cm to 200 cm thick) are constructed between the two slabs in both directions forming the hollow cellular raft foundation. A cellular raft foundation is a moderate rigid foundation and is more economical compared to raft with the same thickness but highly rigid. The foundation has 35 cast in place concrete piles with a diameter of 220 cm and depth of 30 m, to reduce the amount of settlement. At the junction of the pile to the foundation, pile caps are located. Deep beams and pile caps are connected to each other, by concrete slabs at the top and bottom of the foundation, and generally the entire collection can be seen in the form of a box. The characteristic strength of the foundation concrete is 54 Mpa in compressive strength. Due to the higher density of rebars in some parts of deep beams, the concrete should be placed with high-efficiency. Images related to the implementation of piles and cellular raft foundation of the building can be seen in Figure 4.

Figure 4- Photos of Cellular Raft Foundation constructed in WTC Tabriz.

4.2 The columns of building

In total, 29 columns in the structural design of the World Trade Center Tabriz Building is considered, which as mentioned in the super-frame structural system, they have been distributed in the outer parts of the building plan. Unlike conventional buildings, in which with constant strength of concrete and rebars, the dimensions of the columns at the lowest level has the highest cross section values and the lower sections values at the building top, in super frame the columns just over the foundation has the highest concrete strength, then the columns dimensions are implemented with minimal possible values. Thus, on the higher floors of the building, there is no change in the dimensions of the column, but the strength of concrete and the rebar amounts are reduced (concrete strength varies from 60 MPa on the first floor to 35 MPa on the top floor). In addition to increasing the effective floor areas in the lower stories, and eliminating execute of the difficulty of building in height, this method is effective on structural performance and solves operational problems related to the reduction in size of the column. Type of rebars arrangement of the columns of the WTC Tabriz Super frame building due to the use of high-strength concrete (Hi-RC) is quite different from conventional design practices in the country. In this building, the columns have been implemented in two ways of cast in place and prefabricated concrete. In the cast in place procedure, mechanical couplers are used to connect the longitudinal bars. However, in the prefabricated procedure, R-PC technology with the NMB splice sleeves has been used. Figure 5 shows photographs related to the implementation of the columns.

(a) Cast in place construction

(b) Prefabricated construction

Figure 5- Photographs of cast in placed and prefabricated columns in Tabriz WTC

4.3 Central core wall (Super wall)

Core wall (or the Super Wall), with the H-shaped cross section, has the main responsibility to resist the lateral external loads. It is connected to the foundation at the base, and the super beams at the highest level. Dimensions of the core wall are fixed in all the floors, but rebar arrangement, concrete compression strength and bars tensile strength are reduced from the first floor, to the upper levels. Because of the big size of longitudinal rebars and type of their arrangement in cross-section of the core wall, rebar cages should be made in two parts of prefabricated (for high-strength bars) and in situ. To connect the prefabricated reinforcement cages, which are manufactured in shelves with height of 12 m at the platform next to the building, NMB splice sleeve couplers are used. After installation of prefabricated cages, other details of rebar binding are implemented in situ. This method of reinforcement is completed and concreting is done every step of the core on each floor. Since, a congested reinforcement is used in the central core wall, the type of its concrete has been developed and implemented as a self-compacting concrete (SCC). Figure 6 shows the photographs related to the implementation of the central core wall on the WTC Tabriz.

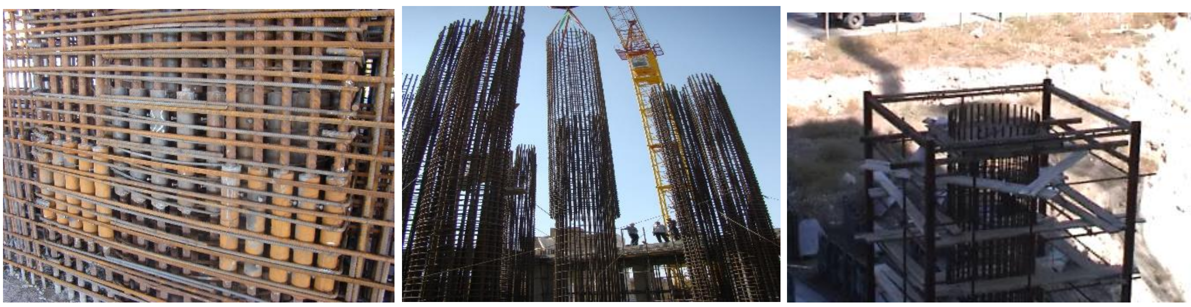

Figure 6- Photos of super wall implementation in Tabriz WTC building

4.4 Flat slab of the floors

In the structural system of the WTC Tabriz building, floors were designed as a flat diaphragms with a thickness of 30 cm, and only an internal beam with height of 60 cm is located on the floor, in which, the floor level difference is formed in two sides of the central columns and perimeter parts of buildings. In other word, on each floor, the outer part of each floor is constructed 30 cm above the central part of floor. This design is intended to facilitate the sewerage and pipe lines installation in the floor. It should be noted that, after this stage and completion of pipe lines, floor will be leveling to the same elevation in both central and outer sides. This type of floor connection has also structural properties. The central part of the roof slab is attached to the outer portion, is separated by a plastic hinge performance in earthquake occurrence. Figure 7 shows photos related to the construction of flat slabs of the floors. The result is the column spacing relatively high, and for most of distances between columns reaches as high as 10 meters. Floor flat slabs are post tensioned by unbounded single-cable tendons.

Figure 7- Photos of flat roof construction in WTC Tabriz building

4.5 Super beams and viscous dampers

As mentioned above, the super beams are located just at the top of the structure with rigid connection to the central core wall. In the structural system of the WTC Tabriz building, four super beams with width of one meter and a height of four meters are considered to connect to the wall core. Certainly, the implementation of super beams with these dimensions at an altitude of 120 meters above ground level requires special technique of construction. Accordingly, this part has been constructed in two steps. First step was started by installation of prefabricated beams, and implementation of upper section has been done by in situ method of construction with bridging of prefabricated beams. Each super beams is prestressed by 8 tendons consist of 12 cables. In Figure 8, some photos of various stages of implementation of the super beams are shown. In end of super beam, four viscous dampers (total of 32) have been installed. The dampers are high viscous dampers in which the energy dissipation occurs by passing high pressure silicone oil through the piston orifices causes a pressure difference on either side of the piston cap, and as a result, the damping force is generated. It is known that in viscous damper axial force depends on the speed of moving piston. Therefore, the maximum force of damper creates the phase difference, and it is known that the maximum speed occurs when that displacement is zero in the system. This is the advantage of these dampers. Viscous dampers are installed vertically between the tip of super beams and the top of outside columns. In Figure 8, the installed dampers at the tip of a super beam are shown. The technology related to manufacturing of this type of dampers is very sophisticated, and only very limited countries have paid attention to manufacture high viscous damper. Although, research efforts of specialists have been time consuming, but led to achieve this advanced technology, and the dampers of World Trade Center Tower in Tabriz have manufactured by related experts in Iran. To obtain approval of its performance, the prototype has been tested abroad, and confirmation of its performance and behavior has been achieved.

Figure 8- Photos of super beams construction and viscous dampers installation in WTC Tabriz building

4.6 Prefabricated ceramic panels for facing of building

Scientific and technological progress in the field of materials has allowed the use of beautiful, durable and economical materials in building facing. As the Japan, is one of the leading countries in modern materials research and innovation. They paid more attention to the technology of ceramic tiles in the building facings. The Japanese engineers, in their technical documentations have acknowledged their inspiration from Iranian architecture related to use the tiles on mosques domes, and long-term durability of the materials against climatic factors had important effect on their decision of material using and production. Taking into account various considerations related to building facing, such as beauty, durability, performance against earthquakes, as well as rapid execution, in recent decades, Japanese researchers have developed ceramic prefabricated panels and used in most of their buildings. Today, in construction of Japan's modern buildings facing, the tiles with various colors are used. Prefabricated panels for facades have reinforced concrete structural cross-section, and are connected by joints (often with bolts) and with clear discontinuance to the building structures. In case of an earthquake angular distortion of the building, each panel can move freely. Thus, no damages occur to panel, tiles and windows or doors installed nearby. Installation of prefabricated panels are bolted during building construction in height, thus, its facade is also completed simultaneously with the completion of the building structure. The only sample implemented using this system in Iran is related to the World Trade Center Tabriz Building (Fig. 9) where prefabricated panels attached to the structure are used to implement the main and dome facades of the building.

Figure 9- Photos of prefabricated facing panels in WTC Tabriz building

5. Conclusions

The super frame technology is an effective method of designing and construction of high-raised buildings specially in seismic areas. Although the technique has been developed in Japan, it can be applied to the important and sophisticated buildings in other countries. It should be noted that a super frame structure has important elements such as central core wall, perimeter columns, super beams, high viscous dampers, and high- strength concrete. Construction techniques should be developed in any using country. This development needs to have a research program and testing methods using local materials.

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