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EFFICIENCY OF CONCRETE DIAGRID COMPARED TO CONCRETE FRAMED TUBE AS LATERAL LOAD RESISTING SYSTEM

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ABSTRACT
One of the most recent innovations of high-rise tabular structural system is diagrid structure. Diagrid structural system has been widely applied to high-rise buildings at the last two decades. Diagrid system is predominating other types of tabular structural systems because of its structural efficiency and aesthetic potential. To examine the efficiency of diagrid system as lateral load resisting system, a comparative study on the behavior of diagrid system with framed tube system, has been conducted under earthquake action. Three-dimensional finite element models for a reinforced concrete diagrid building and a concrete framed tube building of 36 stories with similar plan configuration and characteristics were performed. The only variation between the two systems is the exterior lateral load resisting scheme. Dynamic response spectrum analysis was utilized to investigate the dynamic behavior for both diagrid and the framed tube system. Findings which include modal results, lateral story displacements, story drifts, story shears and story moments were presented and discussed. The results revealed that diagrid system is more effective as lateral load resisting structure than the framed tube system with a reduction of 21 % of the consumed materials.

KEYWORDS: Diagrid, Framed Tube, Earthquake, High-rise Buildings, Dynamic Response.

كفاءة نظام الشبكة القطرية الخرساني مقارنة بنظام الإطار الأنبوبي الخرساني كنظام مقاوم للأحمال الجانبية

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الملخص
يعتبر نظام الشبكة القطرية الإنشائي أ حد أحدث الأنظمة الإنشائية للمباني العالية وأكثرها أنشارا. يمتاز نظام الشبكة القطرية عن باقي الأنظمة الأنبوبية المشهورة كفائتة الإنشائية للأحمال الجانبية الناتجة من الزلازل أو أحمال الرياح وأيضا بشكله المعماري المتميز. لاختبار كفاءة نظام الشبكة القطرية في تحمل الأحمال الجانية تم عمل دراسة مقارنة بين هذا النظام ونظام الإطار الأنبوبي. تم عمل نمذجة ثلاثية الأبعاد للنظامين بأبعاد متماثلة وبارتفاع ٣٦ دور لكلا النظامين وتم التأثير بحمل ديناميكي (زلزالي). أوضحت النتائج أن نظام الشبكة القطرية أن كفاءته أعلي لمقاومة الحمل الزلزالي من مقاومة نظام الإطار الأنبوبي.

الكلمات المفتاحية: نظام الشبكة القطرية، الإطار ألأنبوبي، الزلازل، المباني العالية، الاستجابة الديناميكية.

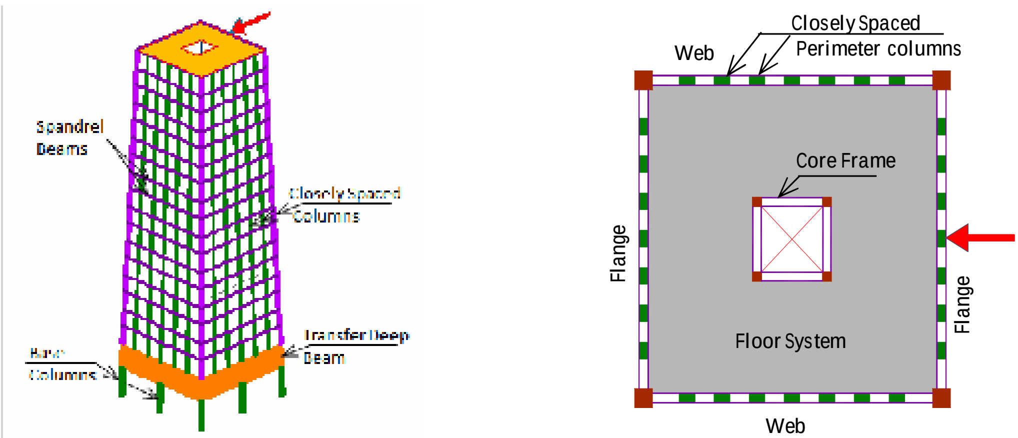
1. INTRODUCTION
Structural systems of tall buildings can be divided into two broad categories: interior structures and exterior structures. This classification is based on the distribution of the components of the primary lateral load resisting system over the building. A system is considered as an interior structure if the major part of the lateral load resisting system is located within the interior of the building. If the major part of the lateral load resisting system

is located at the building perimeter, a system is categorized as an exterior structure [1]. Tabular structural systems, as exterior structures are the most effective systems implemented for high-rise buildings. Tabular structural systems include framed tube, braced framed tube, tube-in-tube and bundle tube structural system. Most of current projects of high-rise buildings around the world have been constructed using tabular structural system. One of the contemporary innovations of high-rise tabular structural system is diagrid. Diagrid system is predominating other types of tabular structural systems because of its structural efficiency and aesthetic potential. To study the efficiency of the diagrid system compared to the framed tube structural system, the basic tabular system, an analytical investigation is performed under earthquake action. An overview of structural arrangement, structural behavior, advantages and disadvantages of the two systems from the literatures are explained in the next subsections. Examples of existing constructions for the two systems are also demonstrated.

1.1 Framed Tube System

A framed tube structure can be defined as a three-dimensional system that engages the entire building perimeter to resist lateral loads. Framed tube structural system was first introduced by Fazlur Rahman Khan [2] in 1960s. Introduction of the tubular structure as lateral load resisting system has brought a revolution in the design of high-rise buildings. Most of current high-rise buildings employ the tubular concept in one form or another. The primary characteristic of a framed tube is the employment of closely spaced exterior columns, usually spaced from 2-4 m, interconnected by deep spandrels so that act like a hollow cylinder, cantilevered perpendicular to the ground. The lateral resistance of framed-tube is provided by very stiff moment-resisting frame that form a tube around the perimeter of the building. Framed tube structures may be in variable floor plan forms, including square, rectangular, circular, and freeform. Figure 1 (a) and (b) depicts the structural system for a typical framed tube structure.

The tubular concept is both structurally and architecturally applicable to concrete, steel, or composite system and have been used in the range of 40 to more than 100 stories [3]. As shown in Figure 1 (b), the strong bending direction of columns is aligned along the face of the building to benefit the most from their local bending action. For the lateral loading, the perimeter frames aligned in the load direction act as "webs" of the tube cantilever and those perpendicular to the load direction act as "flanges", as shown in Figure 1 (b).



a) Isometric view of Framed Tube **b) Plan View of Framed Tube system**

Figure 1. Structural System of Framed Tube

The tube carries all the lateral loading, transferred through the rigid floor system, while the gravity loading is shared between the outer tube and the interior columns or walls [4]. The efficiency of the system is developed from the great number of rigid joints acting along the periphery of the building. Framed tube structure allows fewer interior columns, and so creates more usable floor space. The overturning moment under lateral load is resisted by compression and tension in the columns (flanges) while the shear resisted by bending of columns and beams primarily in the two sides (webs) of the building parallel to the direction of the lateral load.

Tabular structures are more so economical that in most cases the amount of used structural materials almost half of that used for conventionally framed buildings [5]. However, framed tube system has some drawbacks in terms of architecture and structural perspectives. For the aesthetics of the tube structure the enthusiasm is mixed, some praise the logic of the clearly expressed structure while others criticize the grid-like facade as small windowed and repetitious [3]. In framed tube structures, both the outer vertical and the horizontal elements usually are having large dimensions, so this may result in obstructing the interior view of the building. In addition, a weakness of the tube structure is that the system is subjected to shear lag effects, since flange frames are ineffective in distributing the lateral loading stresses uniformly among the flange frame columns. The mid columns are less stressed than the corner columns and therefore not contributing as much as they could [5]. The influence of shear lag is to increase axial stresses in the corner columns while reduce the same in the inner columns of both the flange and the web panels.

For framed tube, window openings usually cover about 50% of exterior wall surface. Larger openings for retail store or garage entries are accommodated by providing deep transfer girders in the entrance level, although disrupting the behavior of the tabular structure locally at that location [6]. The depth of the provided transfer beam depends on the base column spacings at the ground level. It can be of a depth of the entire height of the ground floor as in the Brunswick building in Chicago, Figure 2 (a). The building was completed in 1965, and with its 35 stories became the tallest reinforced concrete structure of its time [7]. The transfer wall beam at the ground floor of the Brunswick building, with a full floor height allowed the gravity force to be divided almost equally among the columns above the transfer wall beam. Another form of transfer beam is that for the Two Shell Plaza building of a 26 story in Huston 7]. For this building, more efficient and refined solution for transferring the loads from the perimeter columns to the widely spaced base columns was using a series of haunched transfer beams in the lower floors so that they can transfer the loads in a more smooth and gradual way, Figure 2(b). For usual column spacing at the ground, the depth of the transfer beam is moderate like in a 50 story One Shell Plaza building, (opened in 1971) in Huston as shown in Figure 2 (c).

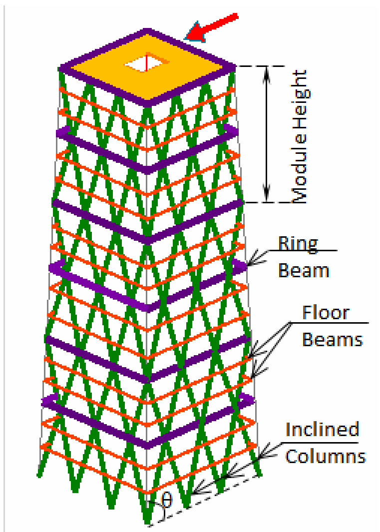
a) Brunswick Building in Chicago **b) Two Shell Plaza** **C) One Shell Plaza in Houston**

Figure 2. Forms of Transfer beams in Constructed Concrete Framed Tube

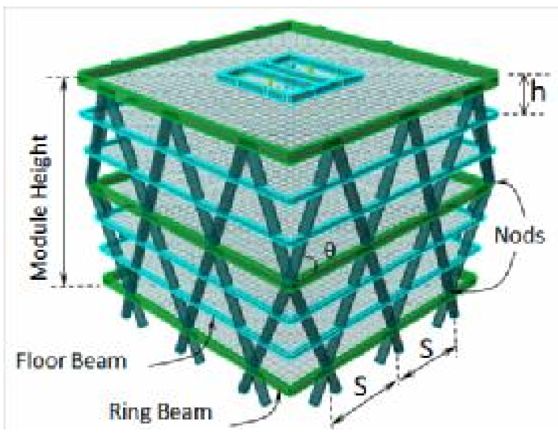
1.2. Diagrid System

The triangulated exoskeleton, or diagrid, has recently become one of the contemporary innovated trends of high-rise tabular structural system. In the last two decades, diagrid system has been widely applied as one of high-rise tabular structural systems, due to its distinguished architectural aesthetics and structural efficiency in carrying lateral loads offered by the distinctive geometric arrangement [8]. Diagrid consists of perimeter inclined columns intersecting with horizontal components (ring beams) forming up a series of triangulated truss system, as shown in Figure 3. Ideally, for a diagrid structure, the perimeter diagonal components can withstand both lateral and gravity loading without any additional structural support. As the structural elements are mostly located at the exterior of the building, a diagrid can be characterized as a tube system. Within the basis of tube systems, the diagrid system can contribute to the lateral stability of the building, eliminating the need of a central core system [9].

The concept of a diagrid system is to convert the resulting building moment, shear and torsion into "axial force" in the diagonalized members. Hence, eliminating the vertical columns which mainly are built to carry gravity loads and might not be able of providing lateral stability [8]. The triangulation of the diagrid "tube" is not by itself able to achieve full rigidity in the structure. Therefore, ring beams at the floor edges are typically linked to the diagrid to integrate the structural action into a coherent tube. Floor beams can also frame into the diagonal members. As there are normally multiple floors intersecting with each long diagonal of the grid, these intersections will occur at the nodes as well as at several instances along the diagonal. The size of the diagonal grid is determined by dividing the height of the building into a series of *modules*. The "*module*" refers to the number of floors that the diamond shape of the grid spans from tip to tip. The diamond shaped modules typically span 4, 6, or 8 stories depending on the total number of stories and the angle of diagonal members (θ). Figure 3 illustrates the structural system and components of a typical diagrid system. As can be seen, the building height is divided into several *modules* connected by ring beams at their nodes and floor beams in between. The structural system of a typical diagrid system and typical module characteristic are shown in Figure 3 (a) and (b).



a) Isometric View of a Diagrid



b) Diagrid Module System

Figure 3. Configuration of Diagrid Structural System

The structural efficiency of diagrid system helps in avoiding, exterior, interior and corner columns, therefore allowing significant flexibility and implemented unique floor plans. Diagrid spans larger distances compared to conventional structures. Materials consumed by diagrid structures are reduced compared to conventional tabular structures. Further, when glass material is used with the diagrid, it allows substantial amount of daylight inside the structure. In terms of structural viewpoint, diagrid structures are more effective in minimizing shear deformation because they carry lateral shear by axial action of diagonal members. Moreover, diagrid structures generally do not need high shear rigidity cores because lateral shear can be carried by the diagonal members located on the periphery [10]. However, designing the diagrid can be very intricate due to the complex computer models and construction methods. It is difficult to predict which approach will regulate the global stiffness demand or member strength demand due to the design variables such as module size, diagonal angle, and bending shear flexibility ratio. Also, the vast formwork required to construct such a concrete diagrid structure raises the construction costs.

The main parameters affecting the lateral stiffness and structural efficiency of diagrids are the grid density (topology) of the diagrid and the angle of the diagonals [11]. The grid density or topology in diagrid structures may change intentionally across the height and the width of the structure according to the intensity of the internal forces in diagonals. The diagrid pattern is adjusted according to the amount of force in the members such that the diagonals are denser where the forces are larger [11].

The optimal angle depends on several factors such as the form, story height, aspect ratio (height to width ratio), lateral load distribution (wind or earthquake), and locality of the building. Finding the optimal diagonal angle for a diagrid structure is an important and essential step in the design process. Moon et al [12] found that (a) the optimal angle of the diagonals to achieve maximum shear rigidity for a diagrid system is about 35°, and (b) the optimal angle of the diagonals to achieve maximum bending rigidity is 90°. As a real structure needs to resist both shear force and bending moment, it is expected that the optimal angle of the diagonal members of a diagrid structure will fall between these two angles. Short buildings with low aspect ratio (height/width) behave like shear beams, and tall buildings with high aspect ratio tend to behave like bending beams. Thus, it is expected that as the building height to base width increases, the optimal angle also increases. In general, the diagonal angle in the range of 60° to 75° was found to be the most efficient angle for 36-60 story range which give less structural response under both gravity and lateral forces. However, the optimal angle is usually unique for any particular building.

1.3. Differences between Diagrid and Framed Tube Structures

Diagrid structural systems as tall structure deviate significantly from traditional structural tabular frames in several significant aspects. Traditional framing systems are based on orthogonal geometries [9]. Diagonal components, if included in framed tube, exist as a secondary support system to create lateral bracing leaving the columns to carry the gravity loads [9]. Diagrid system has almost completely eliminated the use of columns. This is possible because diagonal elements in the diagrid system can carry gravity loads as well as horizontal loads due to their triangular configuration. Framed tube system has a greater shear lag effect than the diagrid system. Moreover, by using a diagrid system, structures require less structural materials than a conventional structural system composed of orthogonal elements. The configuration and efficiency of a diagrid system reduce the number of structural elements required on the facade of the buildings that led the outside view to be cleared.

Examples of existing landmark projects of concrete diagrid structures are shown in Figure 4 (a), (b), and (c). The Prosta Tower, Figure 4 (a), was completed in 2011 in Warsaw, Poland. The Tower has 19 floors above ground and a 5 floor car park underground with total height of 70 m [13]. Another example of diagrid building is the Guangzhou International Finance Center, China, Figure 4 (b) and (c). The tower was completed on 2010. At the time of its completion the tower was the fourth tallest building in china and the ninth tallest building in the world. The tower has 103 stories with a total height of 438.6 m. The diagrid perimeter structure was formed by inclined structural members of concrete filled steel tube 14].

(a) Prosta Tower, Poland **(b) Construction Phase** **(c) Completed Project**

Figure 4. Existing Diagrid Buildings (a) Prosta Tower, (b) and (c) Guangzhou International Finance Center, China

2. OBJECTIVE

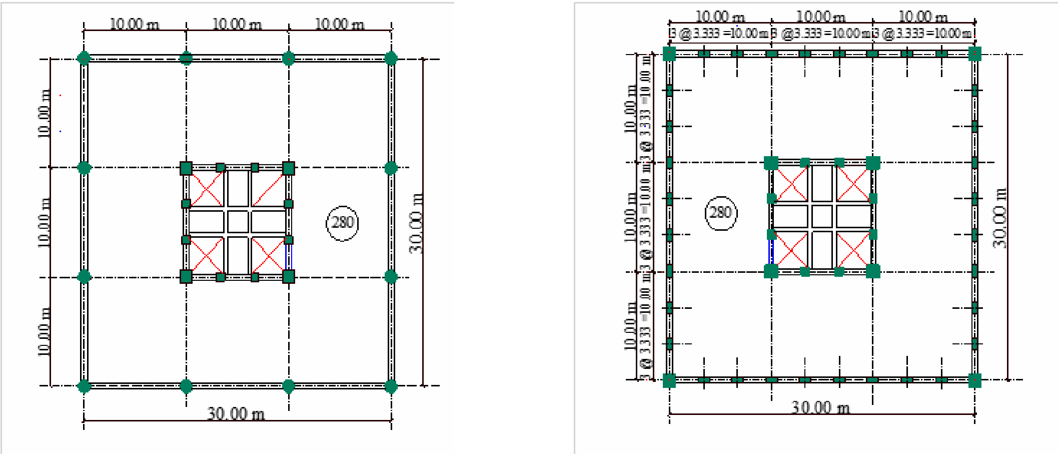
The objective of this study is to analytically investigate the efficiency of diagrid structural system versus framed tube system, under earthquake action. To achieve this objective, two scenarios of three-dimensional models of a reinforced concrete diagrid and a reinforced concrete framed tube system were generated and examined under earthquake action. Description and modeling formation of the two selected building systems are demonstrated in-details in the next sections.

3. BUILDING GEOMETRIC CONFIGURATIONS

Two high-rise buildings were selected for the analysis: a reinforced concrete diagrid and a reinforced concrete framed tube building. Both diagrid and framed tube buildings are square in plan with dimensions of 30 m in both X and Y axis as shown in Figure 5 (a), and (b). The number of stories for both structures is 36 stories, with typical story height of 3.8 m and a total height of 136.8 m. The characteristics of structural members of the buildings in the different story level were estimated from a rational design concept based on ACI -318 [15]. The floor slab for the two buildings is of a thickness of 280 mm. The core frame of both systems was designed to resist only gravity loads, and the sizes of core columns and core beams are identical for both systems.

3.1 Diagrid Building

The diagrid building consists of inclined columns provided at 10 m spacing along the perimeter as shown in Figure 5 (a). The total height of the diagrid building is divided into six identical diamond shaped modules. Each module spans six-stories, tip to tip. The angle of slope of all diagrids is 48° and was kept uniform throughout the entire height of the building. The diamond shaped module was braced at their widest and intersection points by providing stiff ring beams, every three floors, to complete the basic structurally necessary triangulation. Floor beams were provided at levels between ring beams levels. The proportions of concrete elements of diagrid building are illustrated in Table 1.



a) Diagrid Plan View **(b) Framed Tube Plan View**

Figure 5. Plan View of Diagrid and Framed Tube Buildings

Table 1. Element Dimensions for Diagrid System

Element	Base-to-12th Floor	12th -to-24th Floor	25th -to-36th Floor
Diagonalized Members	Diameter = 1200 mm	Diameter = 1000 mm	Diameter = 800 mm
Ring Beams	b=400 mm, t =1000 mm	b=400 mm, t =1000 mm	b= 400mm, t =1000 mm
Floor Beams	b=300 mm, t =600 mm	b=300 mm, t =600 mm	b= 300mm, t =600 mm
Core Beams	b=400 mm, t =1200 mm	b=400 mm, t =1200 mm	b= 400mm, t =1200 mm
Corner Core Columns	b=1200 mm, t =1200 mm	b=1000 mm, t =1000 mm	b= 800mm, t =800 mm
Core Columns	b=900 mm, t =900 mm	b=700 mm, t =700 mm	b= 500mm, t =500 mm

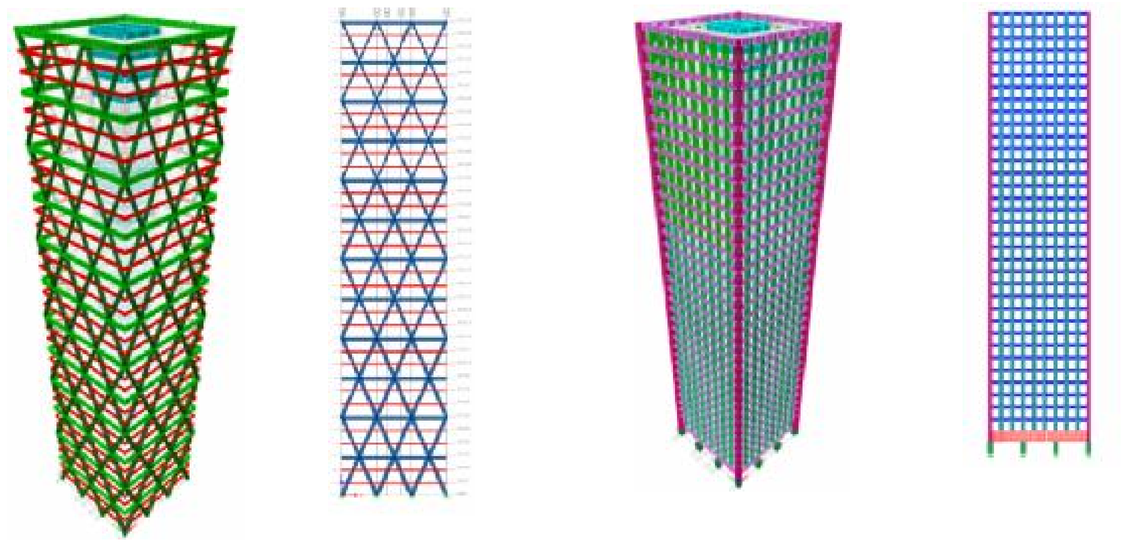
3.2. Framed Tube Building

The framed tube building has base columns at the entrance level spaced at 10.00 m as shown in Figure 5 (b). A wall transfer beam with a height of atypical floor was provided above the base columns. Peripheral columns above the transfer wall beam spaced at 3.333 m were provided at each side of the framed tube, Figure 5 (b). The peripheral columns were connected through spandrel beams at each story level. The base columns are rectangular in shape with dimensions of 1700 x 1700 mm, and the transfer wall beam was of a thickness 1100 mm. Sizes of core frame members are identical to those of diagrid building, as in Table 1. The spacing, materials, and size of peripheral columns and spandrel beams are uniform throughout the building height. The size of peripheral columns is of length 1333 mm aligned with the transfer wall beam, and 600 mm width perpendicular to the wall beam. Thus, the resulting window openings are of a regular width 2.00 m all through the building height. The spandrel beams are of size 500 width and 1200 mm depth.

4. MODELING

The Extended Three-Dimensional Analysis of Building Systems Software, ETABS [16] was employed to perform the analysis of the two selected buildings. The floor slabs for both diagrid and framed tube building were idealized with four-node quadrilateral shell elements with six degrees of freedom per node. The transfer wall beam at the ground level of the framed tube building was idealized as membrane element since the out of plane bending is disregarded. For linear static and dynamic analysis, all vertical and inclined columns and beams for both buildings were modeled by beam elements.

For framed tube building, the in-plan connections between vertical columns and beams were assumed to be fully rigid, while in diagrid model, beam and diagonal members' connections were assumed as hinge connections. In order to allow the exterior tube elements of both systems to capture the entire lateral forces, the connections of inner columns of the core frame from floor to floor were considered hinged, since they are assumed to carry gravity forces only. Floor and roof diaphragms were idealized as semi-rigid, since the semi-rigid diaphragm model is considered more accurate than rigid diaphragm and can lead to more economical designs. Connections between vertical columns in framed tube system and the foundation were assumed to be fixed, while those for diagonal members and foundation were assumed hinged. The schematic three-dimensional isometric view, and elevation view of both framed tube and diagrid models is illustrated in Figure 6.



(a) Diagrid Isometric (b) Diagrid Elevation (c) Framed Tube Isometric (d) Framed Tube Elevation

Figure 6. Schematic 3-D Model View of Diagrid and Framed Tube Systems

5. MATERIAL PROPERTIES

The concrete and reinforcement material properties adopted for the seismic design are selected so that they could typically be found in typical high-rise structures. For columns and diagrid elements, the specified concrete compressive strength f'_c = 60 *MPa* with modulus of elasticity E_c = 37,000 *MPa*, while for floor slabs and beams f'_c = 40 *MPa* with modulus of elasticity E_c = 30,000 *MPa*. The yield strength adopted for reinforcing steel f_y = 410 *MPa* and the young's modulus for steel E_s =200,000 *MPa*. The concrete self-weight = 25 kN /m^3, and the Poisson's ration = 0.20.

5.1 Modification Member Stiffness

According to ASCE 17] and UBC [18], the stiffness properties of reinforced concrete and masonry elements shall consider the effects of cracked sections. The typical stiffness modification factors for cracked section of different elements considered in the modeling cases are listed in Table 2.

Table 2. Stiffness Modification Factors

Member	Stiffness Modifier
Columns	**0.7 E_c I_g**
Diagonalized Members	**0.7 E_c I_g**
Floor Slabs	**0.25 E_c I_g**
Beams	**0.35 E_c I_g**

E_c, modulus of elasticity for concrete

I_g, moment of inertia for the gross-sectional area of the member.

6. LOADING

The two models of diagrid and framed tube models were assessed under specific loading conditions. The analyses were conducted assuming an initial unloaded condition with zero response state due to the dead load. Description of the different applied loads is presented as follows:

6.1 Gravity Loads

6.1.1 Dead Loads

The dead load consists of self-weight of the structure which can be defined by the program by multiplying the specific weight and the volume of each member, the floor cover of 2.00 kN/m^2 for all floors and roof, and the partitioning load of 2.00 kN/m^2 for all floors and roof.

6.1.2. Live Loads

The live load was assumed 3.00 kN/m^2 for all floors and roof.

6.2. Earthquake Load

The Modal Response Spectrum Analysis was employed to evaluate the dynamic response of the two models. Response Spectrum Analysis is an elastic dynamic analysis of a structure utilizing the peak dynamic response of all modes having a significant contribution to total structural response. The spectrum function was developed as per ASCE 7-10 [17] assuming the mapped acceleration parameter at short period Ss=0.60 and mapped acceleration parameter at a period of 1s, S1= 0.18, and site Class D was considered. The dynamic parameters were then calculated and listed as shown in Table 3.

Table 4. Response Spectrum Parameters

Response Spectrum	Design value
F_a	1.32
F_v	2.08
$S_{MS} = F_a \times S_S$	0.792
$S_{M1} = F_v \times S_1$	0.3744
$S_{DS} = \frac{2}{3} S_{MS}$	0.528
$S_{D1} = \frac{2}{3} S_{M1}$	0.2496
$T_o = 0.20 \times \frac{S_{DS}}{S_{D1}}$	0.423
$T_s = \frac{S_{D1}}{S_{DS}}$	0.4727
T_L	12

where,
F_a and F_v are the site coefficients,
Adjusted Maximum Considered Earthquake (MCE) spectral response for site class effects,
S_{MS} = the spectral response acceleration parameter for short periods,
S_{M1} = the spectral response acceleration parameter at 1s period,
S_{DS} = The Design earthquake spectral response acceleration parameter at short period,
S_{D1} = The Design earthquake spectral response acceleration parameter at 1 s period,
T_o and T_s are the corresponding time periods based on the spectral response acceleration parameters S_{DS} and S_{D1},
T_L = Long-Period transition period(s) as specified in ASCE 7-10.

Based on the previous dynamic parameters, the response spectral function was generated as illustrated in Figure 7. The damping ratio ζ was assumed 5 %. The elastic response spectrum developed in this analysis was adjusted in ETABS program [16], by the occupancy importance factor I and by the response modification coefficient R. For the two investigated models, the occupancy importance factor was taken as I = 1.25. The response modification factor for such systems is not listed in the codes. Since the two systems have large stiffness and low ductility, the response modification coefficient was conservatively considered as R = 3.0 [19], and the deflection amplification factor C_d =3.0.

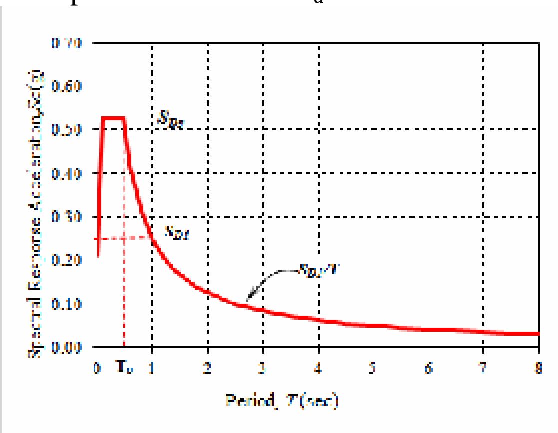


Figure 7. ASCE 7-10 Response Spectrum Curve

6.3. P-D Effects

As stated by ASCE 7-10 [17], "A mathematical model of the structure shall be constructed for the purpose of determining member forces and structure displacements resulting from applied loads and any imposed displacements or P-delta effects. The resulting member forces and moments and the story drifts introduced by P-Δ effects shall be considered. This option is particularly useful for considering the effects of gravity loads upon the lateral stiffness of building in the evaluation of overall structural stability and shall be evaluated using forces producing the displacements 18].

6.4. Modal Analysis And Modal Combination

Ritz-victors analysis was employed for modal analysis since the program ETABS [16] recommends this method because dynamic analysis based on load-dependent Ritz vectors yield more accurate results than the use of Eigenvectors. As remarked by the ASCE 7-10 [17] and UBC 18] the peak member forces, displacements, story shears, story moments, and base reactions for each mode shall be combined by recognized methods. The Complete Quadratic Combination method (CQC) was used. The CQC method shall be used for each of the modal values or where closely spaced modes that have significant cross-correlation of translational and torsional response. For directional combination, however, the Square Root of the Sum of the Squares method (SRSS) was utilized.

7. RESULTS AND DISCUSSION

The results and the discussion of the dynamic behavior for both diagrid and framed tube systems are demonstrated in this section. A comparison of modal results, lateral story displacements, story drifts, and story shears and moments for the considered two models are presented and discussed.

7.1. Modal Results

The modal results include modal time periods and frequencies, modal participating mass ratios, modal load participating ratios, modal participation ratios, modal participation factors, modal direction factors, and response spectrum modal information. However, the modal time periods and frequencies, and modal participating mass ratios will only be presented since they satisfactorily represent the dynamic behavior of the building.

The time periods and frequencies for a 10 mode shapes of the modal response for both models are listed in Table 5. The natural period of a tall building is a function of its stiffness, mass, and damping characteristics. The natural time period typically ranges from 0.05 to 0.15 times the number of stories depending upon the materials used and the structural system [20]. In general, the maximum time periods for the two models lie between the typical values proposed by Taranto 20]. As shown in Table 5, the time periods for diagrid system are smaller than those of framed tube systems. Subsequently, the frequencies of diagrid system are larger than those of framed tube system. This obviously imply that diagrid system could be stiffer than framed tube system and the framed tube system might be vulnerable to larger deformations and smaller shear forces under seismic action, as will be illustrated in section 07. The table also shows that the first two vibration modes for both models, mainly involving translation in the two plan orthogonal directions, while torsional behavior is only associated to the third mode, characterized by a significant lower period than the first two ones.

From the results, the modal mass participating ratio was found to be 99 % of the actual mass in each the orthogonal horizontal directions of response considered by the model. Thus, the number of modes considered in the analysis is enough, as per the requirements of ASCE [17].

Table 5. Time periods and frequencies of the two Models

Mode Number	**Fundamental Period (sec)**		**Frequency (Hz)**	
	Diagrid	**Framed Tube**	**Diagrid**	**Framed Tube**
1	**2.622**	**3.898**	**0.381**	**0.257**
2	**2.622**	**3.897**	**0.381**	**0.257**
3	**0.77**	**1.247**	**1.297**	**0.802**
4	**0.77**	**1.247**	**1.298**	**0.802**
5	**0.703**	**0.704**	**1.422**	**1.42**
6	**0.493**	**0.704**	**2.027**	**1.42**
7	**0.483**	**0.490**	**2.07**	**2.038**
8	**0.394**	**0.490**	**2.539**	**2.038**
9	**0.36**	**0.34**	**2.775**	**2.945**
10	**0.295**	**0.34**	**3.391**	**2.945**

7.2. Lateral Story Displacements

Both diagrid system and framed tube system globally behaves like a cantilever beam. Thus, the anticipated overall maximum deflections under earthquake excitation most likely occur at the top level of the building. From the design point of view, the top deflection is an important performance indictor for the lateral stiffness, serviceability, and stability of tall buildings.

It is impracticable to design the structure under a major earthquake elastically, and the normal approach is to provide it with sufficient strength and ductility to withstand such an event by responding inelastically. The proper design effort is achieved by controlling and limiting the displacements that could occur during the anticipated earthquake, and to ensure adequate strengths in all components of the structure to resist the earthquake-induced forces while remaining elastic [3]. Thus, the inelastic displacements corresponding to the design-level response have to be evaluated. According to the ASCE 7-10 [17], the maximum inelastic deflection at any level x (δ_{xe}) must be computed using the strength level seismic forces, and is defined as:

$$\delta_x = \frac{C_d.\delta_{xe}}{I_e} \quad (1)$$

where
C_d = the deflection amplification factor, was taken =3
d_{xe} = the elastic deflection at the location required
I_e = the importance factor

The maximum lateral inelastic story displacements versus the number of story for diagrid and framed tube systems are demonstrated in Figure 8. It should be noted that the lateral displacements for the two models were only considered in one direction, since both models are symmetric about the two orthogonal directions. In general, the lateral story displacements for the framed tube model are found to be larger than those of diagrid model and the displacement patterns are deviating from system to system since the displacements are smooth for the framed tube model while slightly fluctuating for the diagrid model. The fluctuation is pronounced at the top stories for the diagrid model starting from the 24^{th} story which imply flexible behavior at some locations of top stories than for at the bottom stories as will be explained next. Also, the top displacements for diagrid building were found to be smaller by about 31 % than those of framed tube building. This large variation of lateral displacements indicates the significance of the larger stiffness of the diagrid systems in sharing the lateral forces and minimizing the story displacements through the height of diagrid building system.

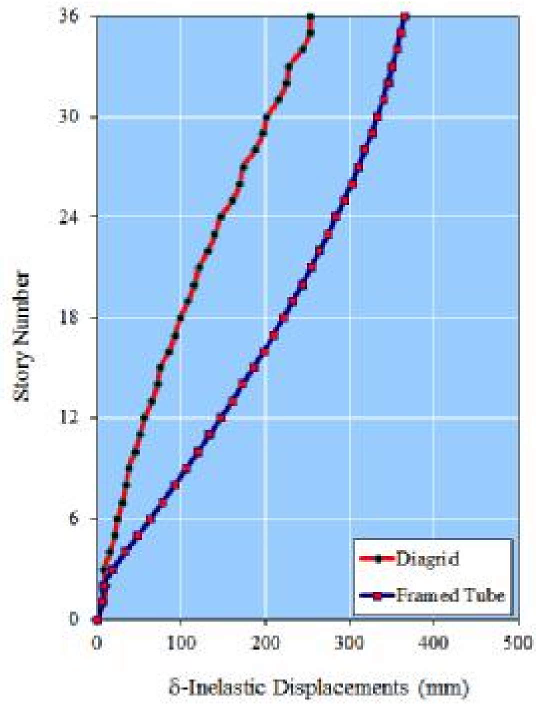


Figure 8. Lateral Story Displacements for Diagrid and Framed Tube systems

7.3. Story Drifts

The story drift is considered one of the practical engineering quantity and indicator of structural performance. The design story drift (Δ) is defined as the difference of the deflections at the centers of mass at the top and bottom of the story under consideration. Both ASCE [17] and UBC [18] require the structure under seismic loads to be designed based on the effect of both structure and non-structural elements. The inter-story drift Δ at level j, is determined from the maximum inelastic displacement δ as follows:

$$\Delta_i = (\delta_{xj} - \delta_{xi}).C_d/I_e \tag{2}$$

where
d_{xj} = elastic displacement computed under strength-level design earthquake forces at level j,
d_{xi} = elastic displacement computed under strength-level design earthquake forces at level i,
C_d = the deflection amplification factor, and
I_e = the importance factor

The ASCE 7-10 [17] requires that the design story drift (Δ) shall not exceed the allowable story drift (Δ_a). For these types of structures and for the risk category III, the allowable story drift (Δ_a) was obtained from ASCE [17], for any story, as .015 h, where h is the story height. The story drifts from the Modal Response Spectrum Analysis method are calculated for both diagrid and framed tube models as shown in Figure 9. It can be observed that the story drifts for both models were found to be within the acceptable limits (0.015 x3.8 x1000= 57 mm), specified by the ASCE 7-10. As shown in Figure 9, the story drift patterns are smooth for the framed tube models while significantly fluctuating for the diagrid models all through the building height. This is attributed to the larger stiffness developed by the connection of the stiff ring beam with diagrid members at the (Nodes), thus, restricting the story displacements at these locations, while at the intersections of floor beams of lower stiffness with diagrids the story displacements are somehow larger producing these fluctuation, as shown in Figure 10. Accordingly, providing diagrid system with stiff ring beams at the nodes of diagrid is significant in the overall performance of diagrid system under seismic action.

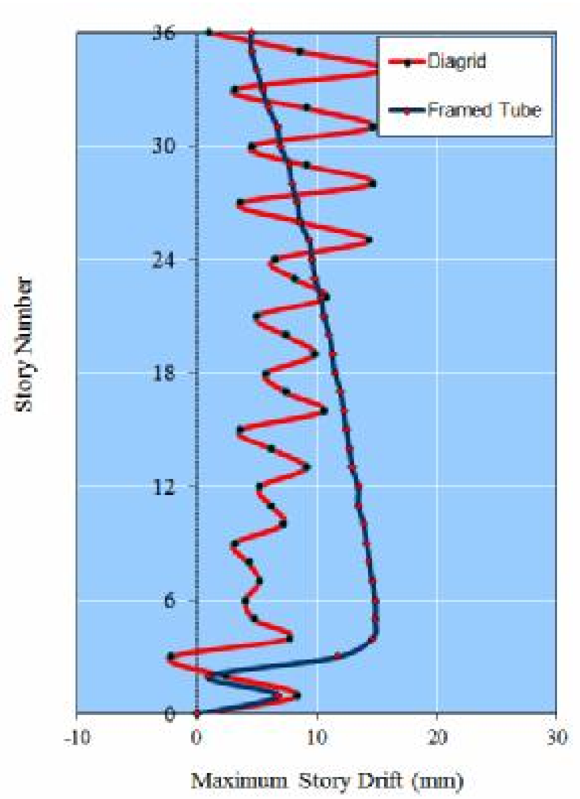


Figure 9. Maximum Story Drifts for Diagrid and Framed Tube systems

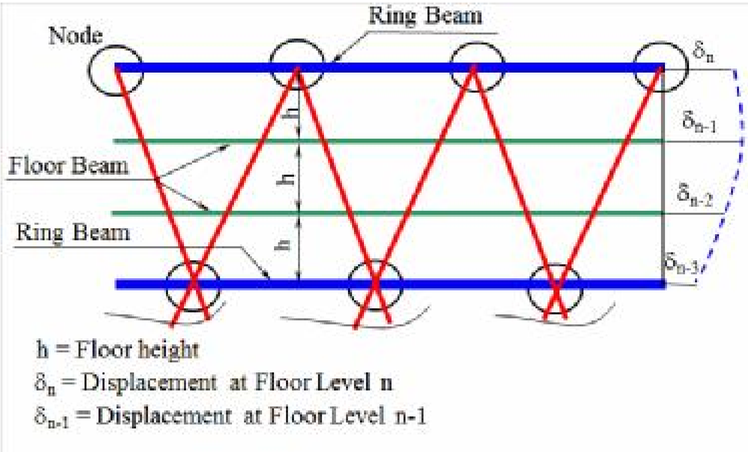


Figure 10. Restriction of Deformations at Nodes

7.4. Story Shears And Story Moments

The story shear is the mass of a story multiplied by the acceleration at this story. The total of the design story shear forces at the bottom of a multistory building is defined as the base shear force. The story moment is the product of the story shear and the height of a story.

The variations in story shear and story moments versus story number for both models are plotted in Figure 11 (a) and (b), respectively. As may be observed, the shear force demands for diagrid building are significantly larger than those of framed tube building over the entire height of the building. Also, the base shear force of diagrid building is larger than that of framed tube building with a difference at the base of about 34 %. This is due to the smaller displacements associated with the diagrid building, as explained earlier. Hence, the diagrid building is stiffer than the framed tube and consequently is prone to larger story shear forces and larger base shear force.

Correspondingly, a comparison between the story moments of diagrid with those of framed tube building is shown in Figure 11 (b). As predicted, diagrid building exhibits larger story moments over the building height than those of framed tube building. The patterns of story moments for both diagrid and framed tube building are almost uniform. The variation is lower the top stories while become larger at the bottom story with a difference at the base of about 19 %. Again, this is attributed to the smaller displacements associated with the diagrid building. Once again, the diagrid building is stiffer than the framed tube and consequently is prone to larger story moments.

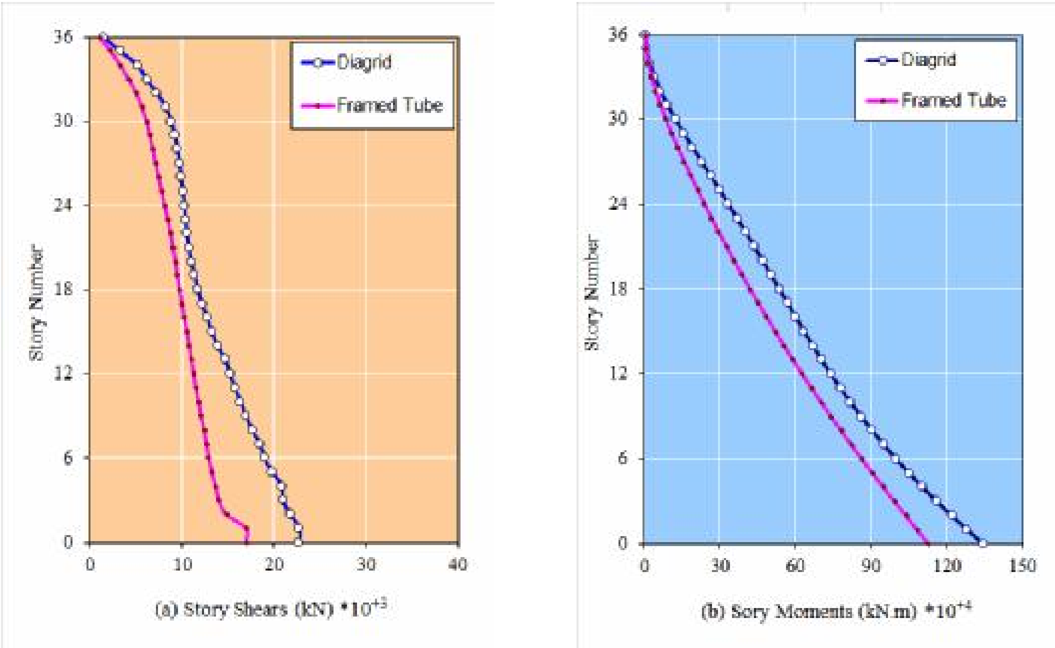


Figure 11. Story Shears and Moments for Diagrid versus Framed Tube Models

7.5. Material Consumption

In terms of economic standpoint, the overall concrete quantities of diagrid were found to be 21% less of the framed tube system as shown in Figure 12. Since the floor system and the core frame are the same for both systems, hence the reduction of material consumed is attributed to the reduced quantities of the diagonalized members along with floor beams of diagrid system versus the perimeter closed spaced columns along with deep spandrels for framed tube system.

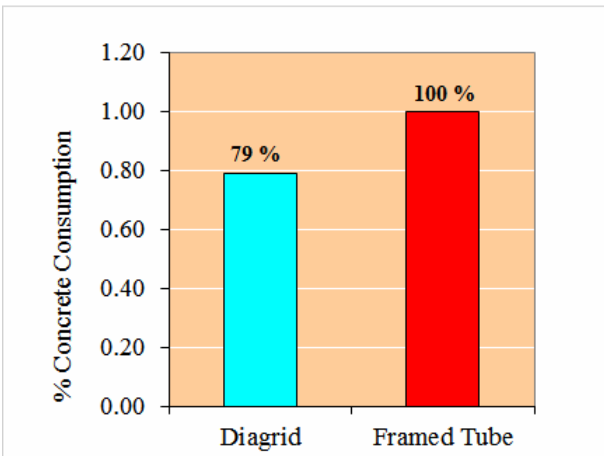


Figure 12. Material consumption of diagrid and framed tube

8. CONCLUSIONS

This paper presented an analytical investigation on the efficiency of concrete diagrid building against the concrete framed tube building system. Two models for each system with 36-stories were generated. The dynamic demands (modal results, lateral story displacements, story drift, and story shear forces and story moments) were evaluated. The following conclusions can be drawn:

- Time periods for all modes of the diagrid system are less than those of the framed tube systems, which indicates that diagrid system is stiffer than the framed tube system. Also, time periods of both systems lie between the anticipated typical time periods.
- Lateral story displacements for the diagrid model are less than those of framed tube model. The top displacements for diagrid building were found to be smaller by about 31 % than those of framed tube building. The displacement patterns were found to be smooth for framed tube model while fluctuating for the diagrid model.
- The story drifts for both diagrid and framed tube models were found to be within the permitted value given by ASCE code. Fluctuating in story drift of diagrid is attributed to the high stiffness of the connections of ring beams to the diagrid nodes at the mid and tip of each module.
- Due to its larger stiffness, diagrid system is prone to have larger story shear and story moments than for framed tube system. The base shear and the overturning moment of diagrid are larger than those of framed tube by 34% and 19 %, respectively.
- The quantity of concrete consumed by diagrid system is less by about 21 % than that consumed by framed tube.
- Overall, diagrid dominates framed tube system not only by its outstanding appearance but also by its structural efficiency and economy perspectives.

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