Journal of Architectural Engineering Technology
ISSN: 2168-9717
Manikandan, J Archit Eng Tech 2016, 5:4
DOI: 10.4172/2168-9717.1000179
Research Article
OMICS International

Skyscraper Design and Behaviour of Steel Structures and Connections Complexities from Constructability Perspectives

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Abstract

The use of high grade steel and concrete in high-rise buildings has increased significantly in the past 20 years mainly owing to improvement in all the materials, technologies and associated methods related to prepare, supply and pour the concrete. Cementations materials, admixtures, aggregates, pumping techniques, transportations and elevation methods…etc. all these enchased possibilities are illustrated by taking 150 story high rise structural model; analyzed and designed by using the software ETABS-2013, to withstand the gravity loads and also the lateral loads considering Wind 100 mph, Exposure-Seismic Zone-I, soil profile type SD, Occupancy category 1.0 and Ductility factor, R=5.5. The type of ultra-high strength concrete cylindrical strength has been considered as 107 MPa @ 28 days to bear the high load and straining action at lower portion of the core wall, Steel sections and plates are confirming to ASTM-A992-Gr:70 Ksi are considered for Built-up column sections and floor beams. In addition Shear Studs conforming to ASTM-A106-Gr:1020 with composite metal deck have also been considered to be have as rigid diaphragm to act as monolithic unit against the heavy lateral loads.

This paper clearly would show that the Design and constructability considerations, serviceability requirements and international codes compliances such as ACI-318, ASCE-7, IBC-2011, UBC-1997, further it would prove that the combination of R.C. concrete and steel composite sections could be the best solution for such tall skyscrapers to meet the client interest and expectations.

Keywords: Illustrated; Analyzed; Serviceability; Constructability; High resistance concrete

Constructability

The time of designing the Skyscraper building the significance of constructability have been reorganized, which have been addressed one by one on this paper by the assistance of Mr. Mansoor Rao-Chief Structural Engineer and Associate, Gulf Consult-Kuwait.

Construction constructability is one of the prime factor to be considered during the design time to obtain the buildable structural system and complete the projects on time and within the budget, hence the construction complexities have been addressed such as selection of materials properties, connection types, method of construction sequence, loading conditions and combinations on the contract design drawings and documents to facilitate the works during the construction phase and avoid the dispute between the involved parties, variations, unwanted debates and setback in the projects to meet the client interest and expectations [1].

Aim

This paper is to address some of the design and construction challenges with design evidence as a case study of sky scraper 600 m tall model in ETABS-2013 and LIMCON, MIDAS-SET for connections to facilitate the complication during the design as well as construction phase from the constructability perspectives to complete the projects with in intended time and budget.

Scope and Limitations

The main scope of this paper is to describe the design considerations, challenges and constructability issues by taking the case study of 150 stories tall sky scraper model in ETABS-2013 to address the drift, shear wall thick, grade of materials and construction challenges from the constructability perspectives.

To have an optimum focus on the selected aim and reduce the work load and have some limitation been made not to include the following

- Foundation
- Façade
- Concrete hydration and Elastic modules
- Detailed Connections
- Equipment Erection

Design Challenges

These would start in first place due to the client needs and interest on the architectural vision and unique in shape to represent the culture, economy, country and its states status. Where to obtain balancing the structural needs versus project demands is always a challenge especially for the tall buildings (Figure 1).

Further designing the structure by maintaining the selected Architectural intent in addition to bear the design gravity and lateral loads by selecting the construct able structural system's, materials, methods would be a greatest challenge to complete the project to suite the client needs with in the scheduled time and budget.

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Received December 10, 2016; **Accepted** December 20, 2016; **Published** December 26, 2016

Citation: Manikandan M (2016) Skyscraper Design and Behaviour of Steel Structures and Connections Complexities from Constructability Perspectives. J Archit Eng Tech 5: 179. doi: 10.4172/2168-9717.1000179

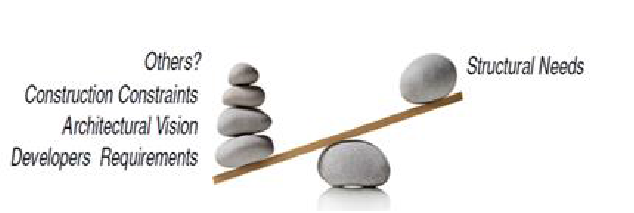

Figure 1: Balancing the structural needs vs. project.

Label of Case Study Model

Inspired by many examples from the day to day practice that, the 3D model have been created by considering the following system, geometry, materials, loads and norms of international codes.

System

Steel structure connected with high grade thick concrete core wall in addition out-rigger system have been connected at every 40 story interval to keep in structure in position against the lateral loads to limit the drift and P-Delta, further composite concrete metal deck with shear studs and thick slab at mid portion of the core wall in lobby location have been considered to have a rigid diaphragm system.

Geometry

Radial ordinate 21 numbers of bays spacing 17°C at lower portion 14 numbers of bays spanning 25.7°C at top of the structure and typical story height is 4 m and number of story is 150, so the total height of the structure is 600 m, where the core wall thickness is 2.75 m at base and 0.8 m at top been assigned on the model.

Materials

The materials are selected by considering the availability in the market and to suite the design requirements to firm the selected structural systems, such as standard steel sections confirming to ASTM-A992 (High Strength Low Alloy Gr70), steel plates confirming to ASTM-A992 Gr70,steel tubes confirming to ASTM-A500 Gr 50, Shear Studs confirming to ASTM-A108 Gr1020, Bolts confirming to ASTM A490,Anchor bolts confirming to ASTM-A307, welds confirming to AWS D1.1, electrodes E70XX,Concrete Grade K1350 for walls and Fire proofing: 4 h (Compliance to the local regulations) ASTM –E736,ASTM-E119,ASTM-E84 (Carboline Co.) and Concrete core wall K1350 Kg/cm^2 [2].

Loads

Loads and combinations are assigned in the model as Live loads are as per IBC, Wind load is 100 mph, Exposure-C and Gust factor 3 sec, Seismic Zone: 1, Zone Factor: 0.075, Occupancy Category I:1, Response Modification (Ductility), Factor R: 3.5,Temperature: 30°C and S.I.D, Floor finishes, Partition, Claddings/Curtain wall and MEP as per the trades drawings.

Codes Conformance

The following international codes and their norms have been assigned and confirmed to meet the requirements of AISC-14 Edition,AISC-360 for steel, ACI-318-11 for concrete, IBC-2011 for minimum loads, ASCE-7-10 for winds and UBC-1997 for seismic and P-Delta analysis (Figures 2-7).

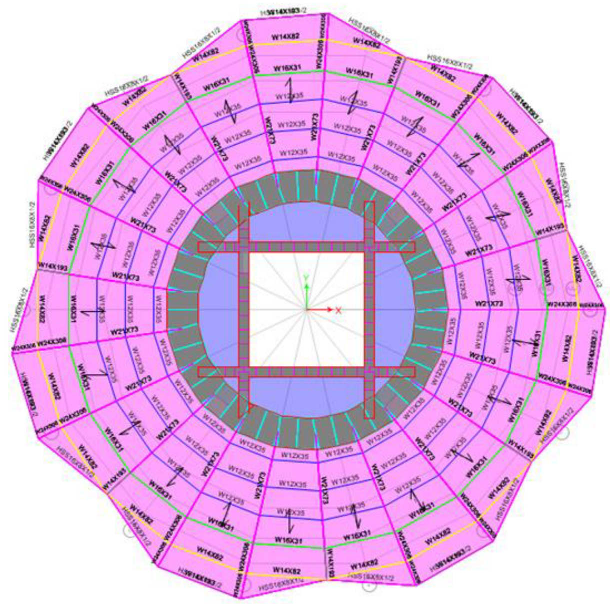

Figure 2: Floor plan G.F to 5th.

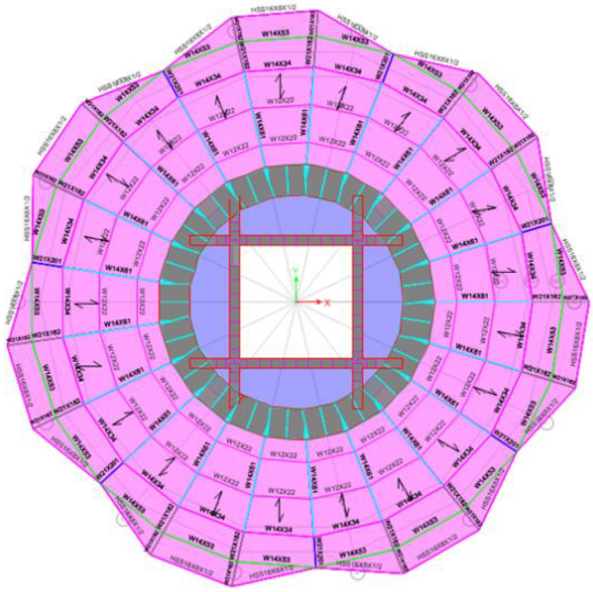

Figure 3: Floor plan 6th to 39th.

3D-Model of Sky Scraper

A 3D ETABS-2013 model of 600 m tall Sky Scraper has been illustrated below, where there is floor reduction at every 40 floors and gradual rotations on every floor edges are assigned to have a twisted curtain wall envelope to meet the architectural unique shape and intent. Further as floor goes up the gravity loads are also reduced due to the floor area reduction and reduced live load factors, so number of columns and core concrete wall thickness are also reduced at every 40 floors interval where sloped steel columns are used to support the floor above at perimeter as on (Figure 8).

Further out-rigger systems are installed at every 40 story intervals

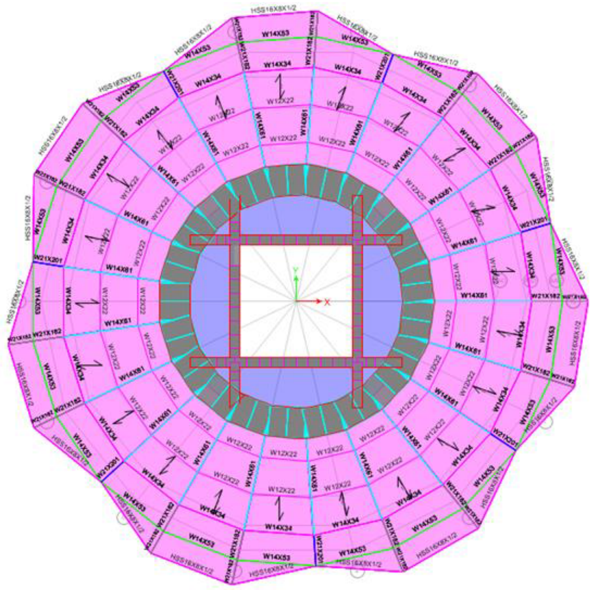

Figure 4: Floor plan 40th to 74th.

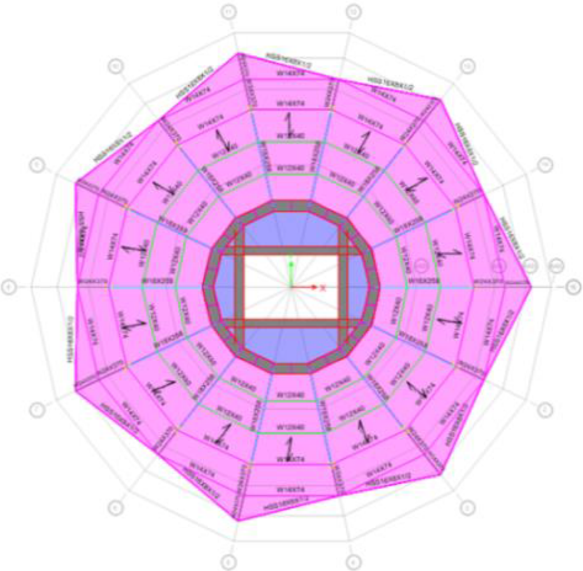

Figure 6: Floor plan 111th to 149th.

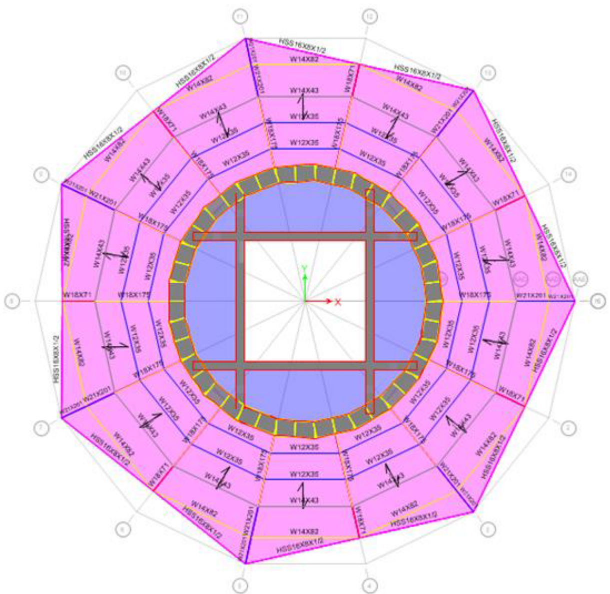

Figure 5: Floor plan 75th to 110th.

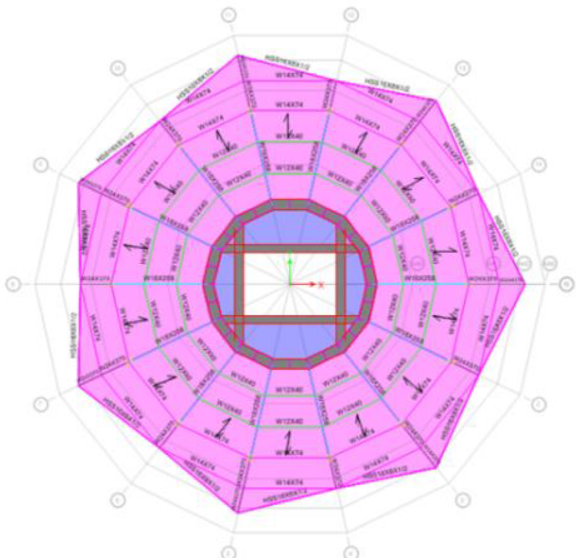

Figure 7: Floor plan 150th.

to stabilize the vertical tall structure and bear the lateral loads such as wind and seismic impact and limit the drift and P-Delta effect to such an ultra-tall sky scraper refer to (Figure 9). Furthermore the high grade steel built-up sections are assigned by considering the internal stiffeners as on (Figure 10), which are helping to have a compact optimum size of the columns, it benefits to have a more floor space.

The concrete core shaft wall has been assigned at centre of the building plan, which is having 2.75 m thick at bottom, 0.8 m at top and also having wall reductions at 40 story intervals. It is acting as a back born of the structure by connecting the steel floor beams, bracings and out-rigger systems. In addition, it gives shaft space at canter to accommodate the elevators, stairs as a fire escapers and electro mechanical items such as big size ducts, chiller pipes, bus ducts (Figure 11).

Member Assignments

Fabrication details at columns intersections part are shown in Figures 12 and 13.

Analysis and Drift Check

ETABS-2013 has been used for analysis, design and graphical representation in line with ASCE,ACI and AISC for Drift check, concrete and steel design respectively, where all the sustainability, safety and serviceability been conformed, further by the help of Mr Mansoor Rao, Mr Khalid and Mr Samiur Rahman the constructability

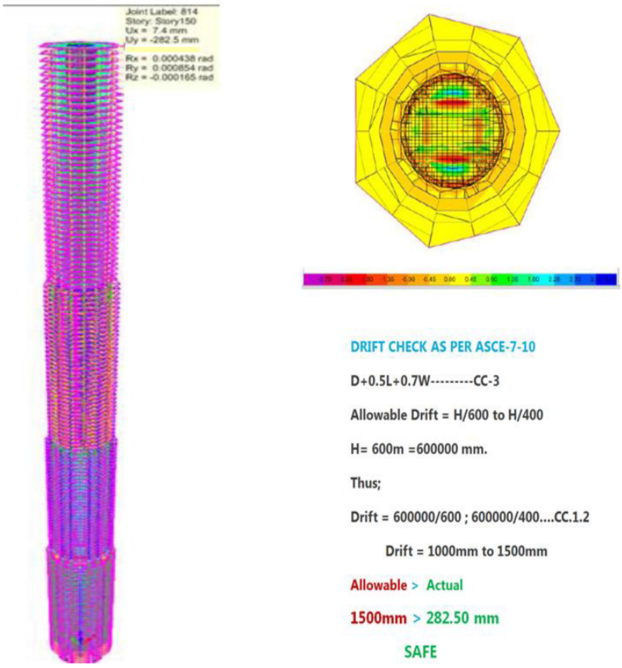

Figure 8: Fabrication details at columns intersections.

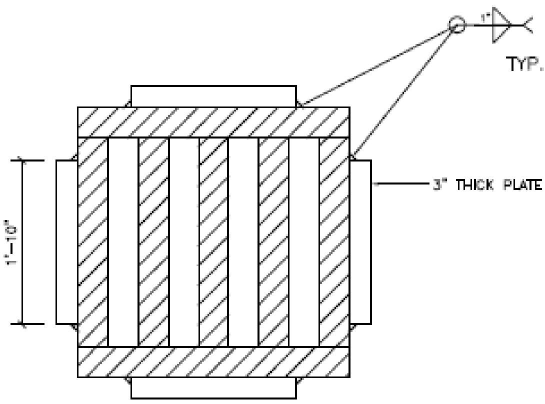

Figure 9: Build-up sections for Column's.

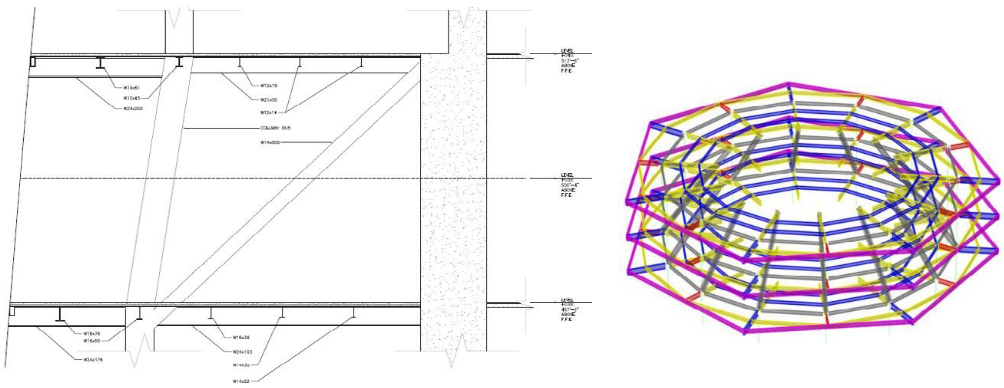

Figure 10: Outrigger assignments @every 40 floors intervals with high grade W14 x 750.

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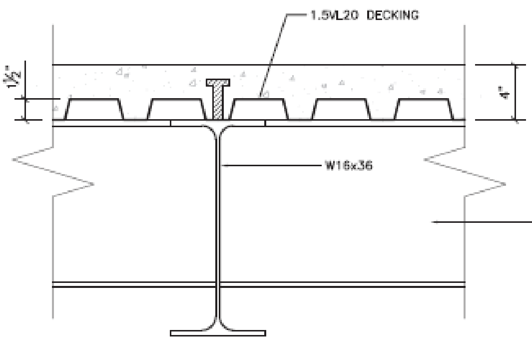

Figure 11: Floor systems.

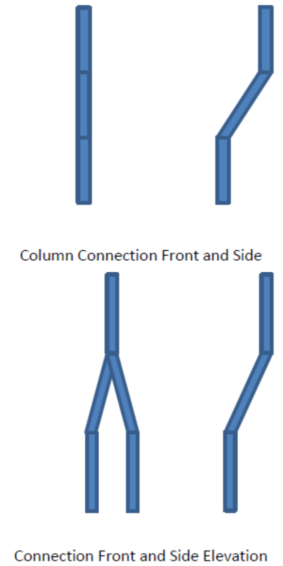

Figure 12: Fabrication details at columns intersections.

requirements such as connections, members intersections, Ultra High strength concrete, pump ability to ultra-high levels and slip form systems been considered and facilitated (Figure 14).

Core Wall Design

High grade K1340 Kg/Cm² and 2750 mm thick been assigned to bear the high shear 3500 KN, which has extracted from the ETABS model at bottom portion of the core wall and designed as per ACI-318 Clause 11.2 (Figure 15).

Grade of Concrete=K1070 Kg/cm²

Wall Thickness D=2750 mm; Effective, d=2750 - 75=2675 mm

$$Vc = 0.1\left[7\lambda\sqrt{f_c^{'}}\right]b_W d \text{ ....Eq 11-3 (ACI-318 Clause 11.2)}$$

Vc=0.17 x 0.85 x (107) 0.5 x 1000 x 2675

Vc=3998374.99 N; V_c=3998.375 KN

Vu=3600 KN (From ETABS Model)

Vc>Vu

3998.375 KN > 3600 KN; Hence Safe.

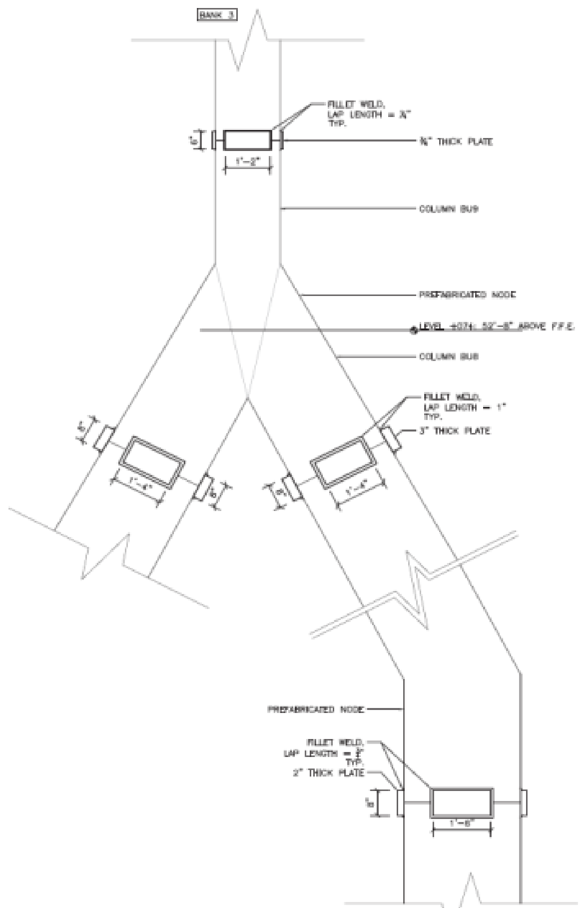

Figure 13: Fabrication details at columns intersections part.

Ultra High Strength Concrete

The Mix Design of K1340 Kg/cm² has been confirmed by shear wall calculation as per ACI 318-11 clause 11.2 to bear the critical straining action on the core wall and limit the wall thickness, where the client could have more space on floor, which could increase the floor rent to the client. It is significant from the financial perspective for such an ultra-high sky scraper building. Therefore to meet the design requirements and needs in the sky scraper tall buildings the high rich ultra-high strength concrete is unavoidable [3,4].

Further to make a mix design and pump into 600 m tall for such an ultra-high strength concrete, to define the mix configuration, pump pressure, concrete properties, friction loss, hydrations, air –entering, temperature, humidity and water cement ratios…. etc. are indispensable, as a guide line there is mix design in Figure 5 has been given for the high strength concrete, however trial site mix is necessary on site to make sure the crucial influences in high grade concrete prior to pour (Figure 15).

Steel Connection Design

The connection designs have been performed in LIMCON software by taking the straining actions/forces from the ETABS model, where the fabrication and erection facilitations are considered such as moment connection on columns with beams, bracings, base, splice connections by taking the high grade bolts ASTM A490, plates ASTM

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS

	HIGH-PERFORMANCE BRIDGE GIRDERS Colorado DOT	PARKING STRUCTURE Milwaukee Airport	TEST HIGH-STRENGTH MIX	TEST HIGH-STRENGTH MIX	BRIDGE DECK Colorado DOT
	MIXTURE 6	MIXTURE 7	MIXTURE 8	MIXTURE 9	MIXTURE 10
References	Leonard, 1999	Data from SFA Member	Burg & Ost, 1994	Burg & Ost, 1994	Xi, et al, 2003
Compressive strength *(Note 1)*	45 MPa @ release 69 MPa ultimate	14 MPa @ 36 hrs 39 MPa @ 56 days	89 MPa @ 28 days 115 MPa @ 3 yrs	107 MPa @ 28 days 126 MPa @ 3 yrs	32 MPa @ 28 days
Rapid chloride test, coulombs	N/A	< 1,000 from cores at 2-10 months	N/A	N/A	1,400–1,600 @ 56 days
Other requirements	N/A	N/A	N/A	N/A	N/A
Entrained air *(Note 2)*	Unknown	Unknown	N/A	N/A	8.5%
Slump	Unknown	160 to 190 mm	250 mm	240 mm	140 mm
Maximum aggregate size	Unknown	Unknown	13 mm	13 mm	Unknown
Cement, kg/m³	433	335	475	475	288
Fly ash, kg/m³	0	59, Class C	59, Class C	104, Class C	58, Class F
GGBFS, kg/m³	0	0	0	0	0
Silica fume kg/m³	21	23	24	74	12
Maximum w/cm	0.28	0.35	0.287	0.231	0.41
Water, kg/m³ *(Note 3)*	127	146	160	151	147

Note 1. Strength shown is f'c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 35 MPa has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

Figure 14: Recommended starting silica-fume concrete mixture proportions.

A992 Gr 70 and weld as 70XX, further the heavy nodal connections are designed in Ansys software to facilitate the heavy as well as complicated connections to make sure the firm connectivity and their stress passing ratios (Figures 16 and 17).

Further the steel connections and members nano behaviours have been carefully studied inparticular the brace buckling deformation and fracture due to cyclic elastic loadings as per AISC-14 edition, AISC-360. The appropriate currective actions are taken in connection design to avoid any minor consequesnces on Glass aluminum curtain wall envolope,which could eliminate or minimize the client maintenance cost and non- panic situation of engineering consultant in case of failure during the building in service.

Steel Fabrication and Erection

It is essential to pre-assemble the complicated heavy steel connections on the fabrication yard prior to shipping the steel fabricated materials to the site. It helps to save the time, man power and equipment during the erection on the allocated time besides to avoid such an alarm situations on the heart of the city among the traffic and public movement (Figures 18 and 19) [5].

Coordination

As an example, the steel design engineers are not allowing the contractors to puncture the steel beam in web to pass services items such as HVAC ducts, chiller pipes and electrical bus ducts …etc, this could lead impact on architectural false ceiling level by lowering than the design level, further that could affect the spandrel glass transom level on curtain wall envelope. In order to resolve such a typical coordination issue the steel beam web could be opened as beam design in MIDAS-SET software by bringing the forces from the ETABS model to configure the openings in beam web. As a benefit of this technical coordination the architectural interior false ceiling head room level and curtain wall envelope could be maintained, on other hand the services items could be accommodated as details on design. As a conclusion for such a replicated technical coordination issues, a vital coordination, interest, involvement is required between the involved parties to suite the issue on time to meet the design intent and void any technical, construction setbacks during the construction phase (Figure 20) [6].

Slip Form System

The Slip form system is to construct the heavy thick concrete walls on tall buildings and it helps to cope up the scheduled activities on time, thus it is essential and un-avoidable.

Due to gradual lift of slip form system as 300 mm/hr in core wall, all the construction activities to be synchronized, planned and executed to meet the time intent and set back in the project.

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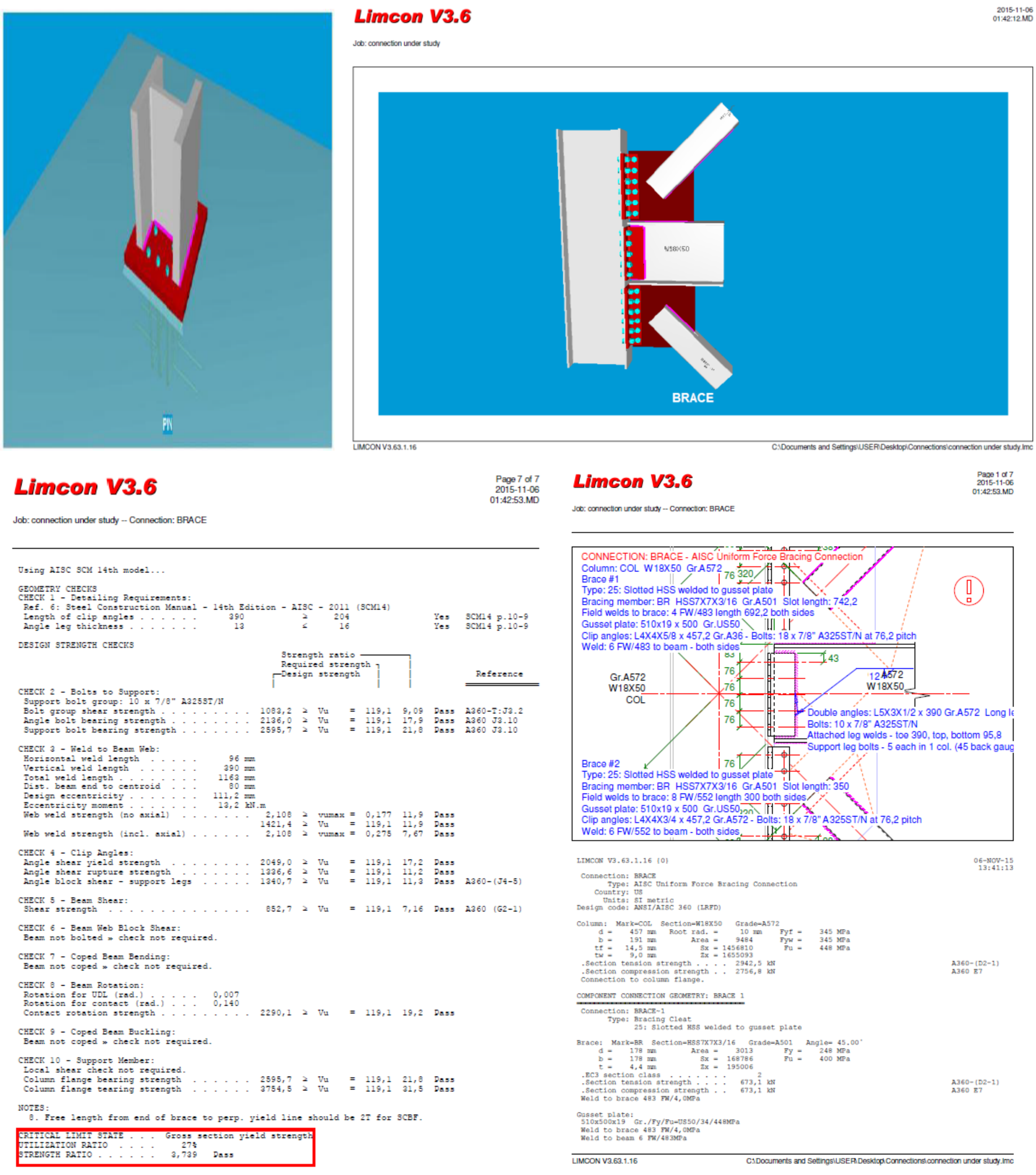

Figure 15: Ultra-Strength Concrete Mix; Source Silica Fume user's manual-2005.

Figure 16: Brace buckling deformation.

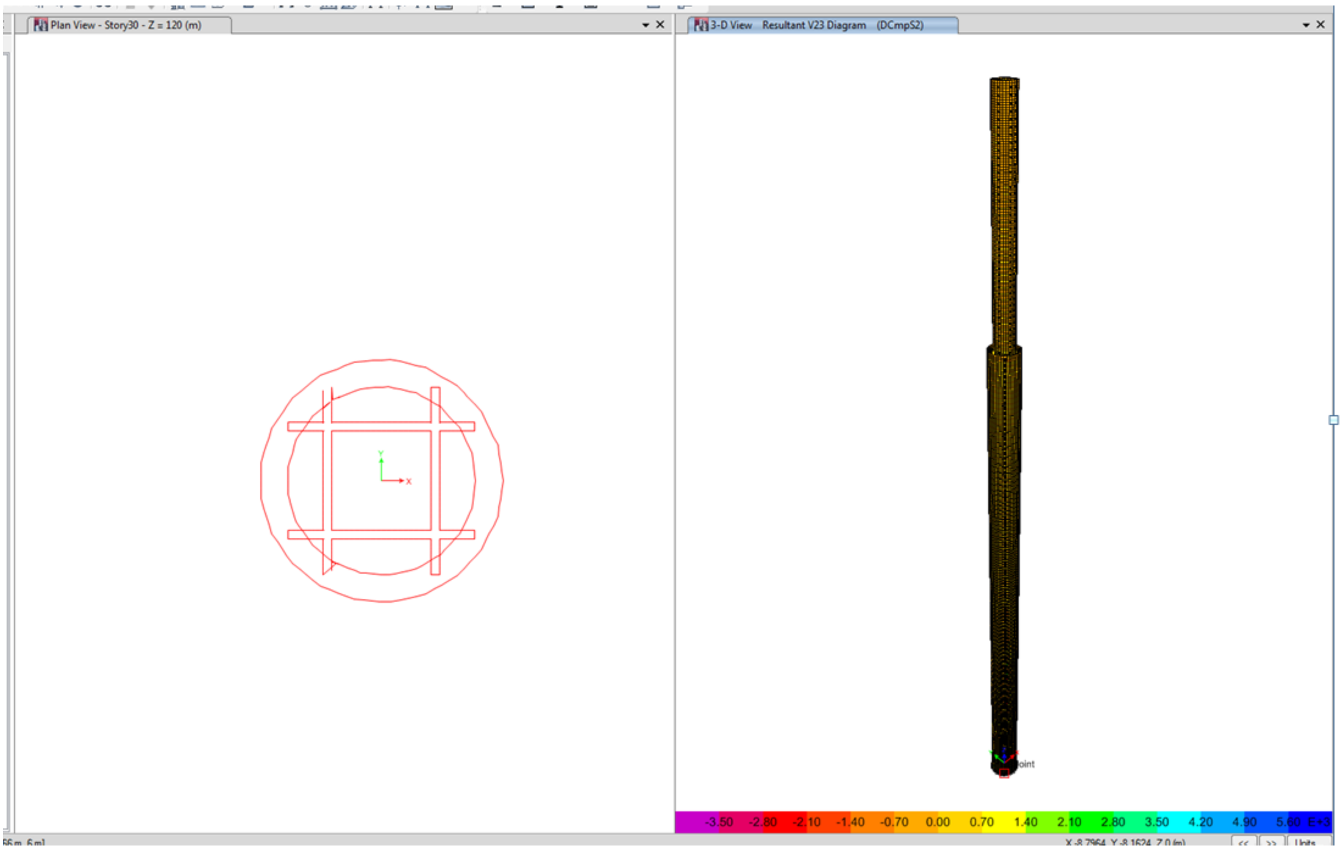

Figure 17: The shear force diagram of core wall from ETABS-2013.

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Figure 18: Heavy Steel assembled truss erection at high level.

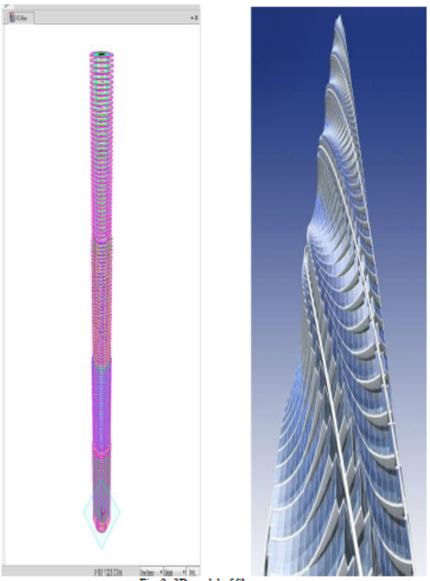

Figure 19: 3D-model of Sky scraper.

Figure 20: Initiation/Progression of tearing.

In particular the reinforcement and embedded items fixation in place to be preceded and structural steel erection succeeded of the slip form systems, hence this should be well planned and organized on site to avoid any stoppage on the slip form system activity till to reach top of the structure.

Thus the slip form work on sky scraper would act as a back born of the construction on site (Figures 21-25).

Conclusion

- Design Consultant should provide the constructible connection details on the contract drawings, which could clarify the connection types.
- Working together in a design and built team in the design stage can prevent many constructability complexities, which could save time and materials during execution phase.
- On other hand the Design and Built-team is not always possible,

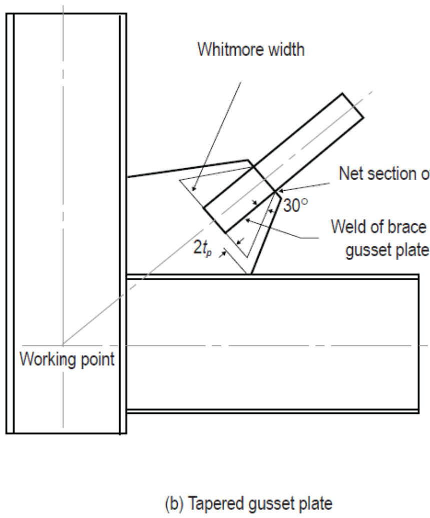

Figure 21: Tapered gusset plate.

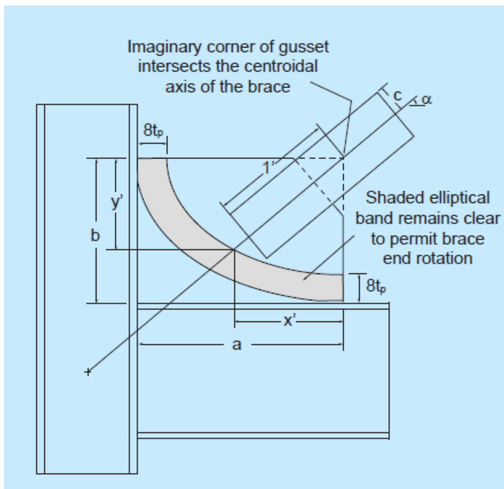

Figure 22: Centroidal axis of brace.

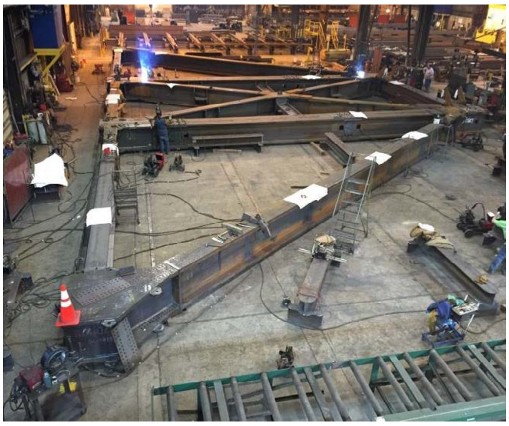

Figure 23: Pre-Assemble in fabrication shop.

Figure 24: Services accommodations within false celling head room.

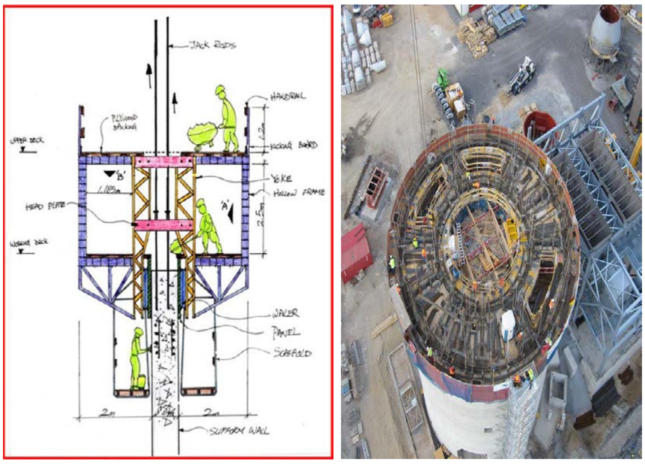

Figure 25: Symmetric of slip form systems and its site photo.

thus the Design Engineer has to be aware that his design has to be constructed with in indented time and budget.

- BIM to be assigned from the beginning of the design to avoid any coordination issues and to meet the design and architectural intent.
- 3D finite element program would bring the considerable material savings and adequate systems.
- Tight QA/QC procedures to be implemented on the project to have expected quality and to meet the design intent during the construction phase.
- The experienced professionals need to be assigned from beginning of the project to make sound preparations for developing valid constructible detailing, specifications and monitoring the project on the construction phase, for this context the experienced professionals should not be engaged with any other project works to have his focus and dedication on the assigned job.
- Thus the Engineers and Professionals to involve eagerly with full of interest and dedication in the design as well steel construction by considering all the consequences to multiple (or) maintain the demand of steel in the construction Industries.
- Further study and appropriate tests are required for elastic modules of the concrete by taking consideration of the specific mix and material properties such as aggregates, admixtures, supplementary materials of cement…. etc.
- Further study is required to deal the hydration process and massive excessive heat due to pouring concrete for thick raft or piles cap for such ultra- height skyscrapers.

Acknowledgements

The Author would like to thank Mr. Mansoor Rao, Mr. Sami ur Rahman and Mr. Khalid Ahmed - Gulf Consult-Kuwait for their guidance to refine and frame this technical paper.

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