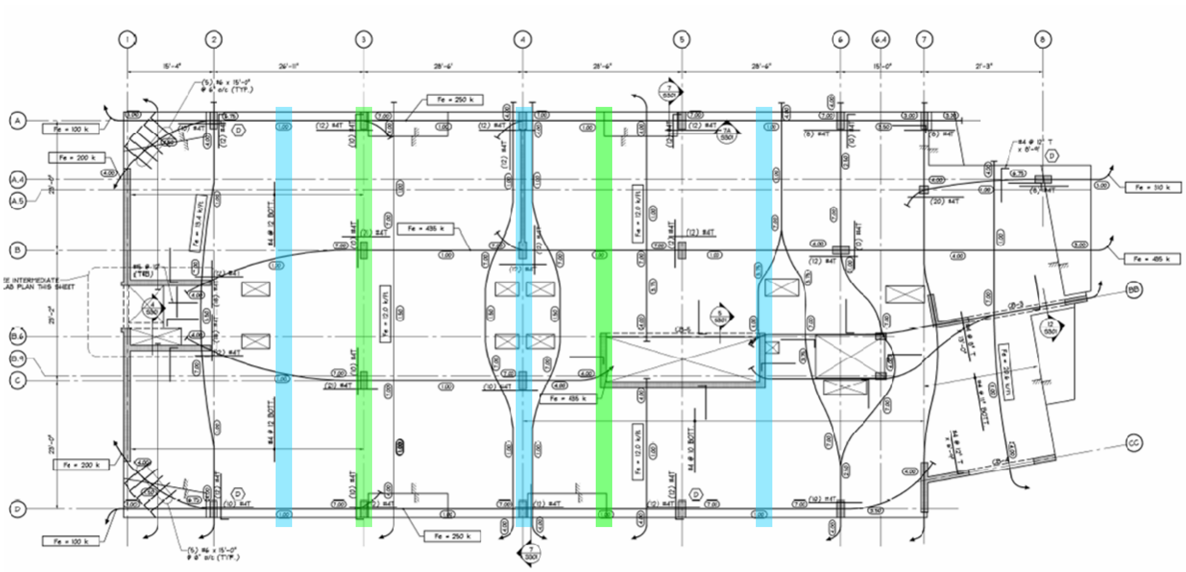
Proposed Structural System:
Staggered Truss System



Typical Floor (Levels 9-21) of River Tower Condominium:

Provided by O'Donnell & Naccarato, Structural Engineers

Existing floor plan shown for comparison
Proposed staggered truss locations shown in blue (even floors) and green (odd floors)

Introduction

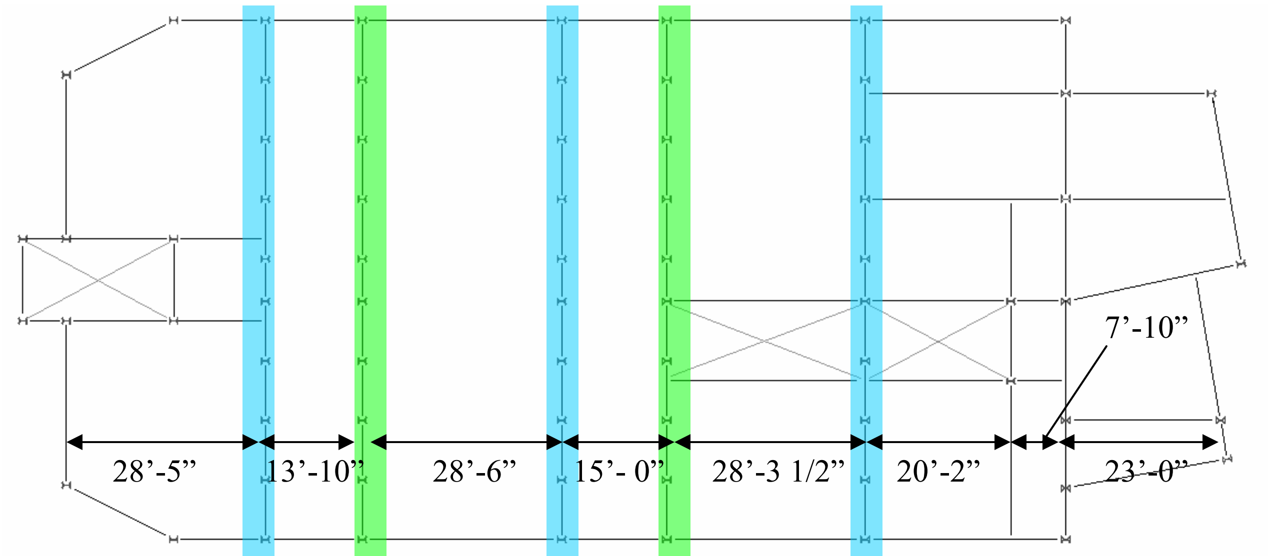
Previous technical research of the River Tower's systems confirmed the adequacy of the current post-tensioned concrete floor slab system. This system provides an efficient balance of minimal floor-to-floor height, system dead weight, and assembly installation cost. A significant reduction of system weight can be achieved using a steel framing system with precast concrete plank flooring. Ordinarily, floor thickness is a primary drawback to steel construction. However, staggered truss designs have provided a minimum amount of floor thickness using precast concrete plank flooring systems which can even rival cast-in-plate and post-tensioned flat plates in specific applications.

Utilizing the prefabrication of the trusswork and flooring systems, a staggered truss system has the potential to have very efficient erection and installation times. The elimination of most of the wet trades from the existing configuration allows for all-weather construction, which could further reduce erection times. Together with a reduction in system weight, the further spacing of the column layout can result in much greater flexibility in the design of interior spaces, and allow for more opportunity for renovation in the future. Shear walls would no longer be necessary, as trusses oriented perpendicular to the width of the building would be able to support the controlling lateral loads through its bracing. Further architectural benefits include using the precast plank and its topping as a finished floor and ceiling.

The non-symmetrical plan of the River Tower, though basically rectangular, necessitates the use of moment frames in these irregularly shaped areas where the trusswork could not logistically or architecturally be placed. These moment connections add a significant cost premium to the structure, and require complicated and expensive erection. The existing architectural layout of the River Tower was utilized to the fullest extent, which results in irregular spacing of the staggered trusses. The intent was to integrate the proposed structural system into the existing systems as much as possible. The staggered trusses were designed and placed where architects already have shared party walls between condominium units. This minimizes the number of interior columns, and results in smaller steel columns versus the existing often 16” by 52” concrete columns. This has the potential to open up individual units considerably, and result in designs with more interior freedom for designers and tenants alike.

Along with the logistics and cost benefit of changing the primary construction material from concrete to steel, there is also the issue of fire protection. This is especially critical in such a tall building, where evacuation procedures, fire and smoke control, and structural stability are controlling factors. These issues will be investigated, calculated, and analyzed in the following pages and in the accompanying appendix.

Structural Analysis



Proposed System Typical Floor Plan for Levels 9-21

Steel shown in black; even floor trusses highlighted in blue and odd floor trusses in green

Overview

As mentioned, the staggered trusses were designed in respect to the current architectural layout of the River Tower. These trusses were placed in the existing infill walls of the condominium units, as shown in the proposed system floor plan shown above. As this diagram displays, the architecture from the existing River Tower design has gone virtually unchanged, in order to accurately compare the adequacy of both systems. This has complicated the truss layout, which ordinarily relies on symmetry to work efficiency. The precast planks will span from truss to truss, left to right on the diagram, and have been sized for a 30' span. The precast plank chosen for this proposal is the 8"×4' SpanDeck by Nitterhouse Concrete Products. Please consult Appendix C for more details on this selection.

Consistencies in Design

Because the exterior factors of the building, such as footprint, height, and overall shape, were not affected by the proposed staggered truss system, the wind loading under this proposal is very similar to those of the existing conditions. Please consult page 18 of this report for a detailed wind loading diagram on the building. Updated calculations and the complete analysis procedure can be found in Appendix A. The live loading condition remains the same from the existing system, which appears on page 13 of this report and is detailed in Appendix C. Additional dead load has been introduced by the use of the 8" precast plank system, which adds an additional 82.5 PSF. The existing precast exterior wall system is self-supporting, and was used in the proposed system. Therefore, the staggered truss system was not required to support this loading. As stated previously, the parking garage that interfaces with the first seven floors of the River Tower has been assumed to be self-supporting as well, and is not within the scope of this analysis.

Proposed System Lateral Loading Conditions

Seismic Loading

The proposed staggered truss system results in a lower system dead weight for the entire structure, resulting in an even lower seismic loading condition. As with the existing design, wind loading controlled over seismic loading in either direction. However, with the proposed structural configuration, there is an even greater discrepancy between these lateral conditions. The staggered truss system has been sized to withstand floor shear loads from the controlling case, that of the wind in the North-South direction. Lateral forces in the West-East direction are resisted by the moment frames on the ends of the floor plan. Detailed calculations can be found in Appendix B, and a summary of both controlling directions of seismic and wind loading is included on the following page. The controlling wind loads from the North-South Direction, which was consistent with the analysis of the existing building, was used in the lateral design of the staggered truss system.

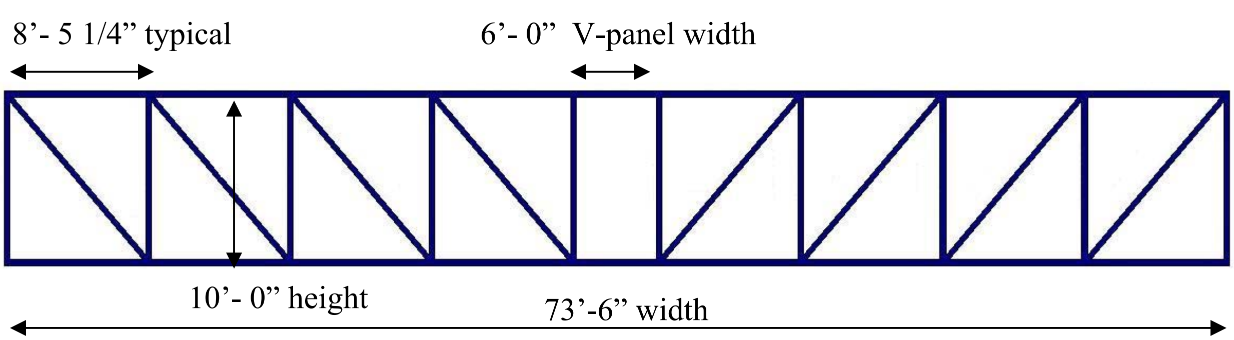
Proposed System Wind and Seismic Forces Summary (kips)

Floor	Wind (N-S direction)			Seismic		
	Lat Load	Story V	Φ_h	Lat Load	Story V	Φ_h
Roof/25	38.55	38.55	0.02	153.31	153.31	0.10
24	84.71	77.11	0.04	144.51	297.83	0.20
23	92.08	161.82	0.09	132.84	430.67	0.29
22	89.03	253.90	0.15	122.90	553.57	0.37
21	81.70	342.93	0.20	111.18	664.75	0.44
20	76.95	424.63	0.25	103.42	768.17	0.51
19	76.44	501.58	0.29	93.96	862.13	0.58
18	75.96	577.54	0.34	86.40	948.52	0.63
17	75.46	653.00	0.38	77.81	1026.33	0.69
16	74.93	727.94	0.42	70.86	1097.19	0.73
15	74.43	802.37	0.47	63.15	1160.35	0.78
14	73.93	876.30	0.51	56.46	1216.80	0.81
13	73.39	949.69	0.55	49.94	1266.75	0.85
12	72.78	1022.47	0.60	43.84	1310.59	0.88
11	72.15	1094.63	0.64	38.16	1348.74	0.90
10	71.37	1165.99	0.68	32.71	1381.45	0.92
9	70.57	1236.56	0.72	27.95	1409.40	0.94
8	69.75	1306.31	0.76	23.31	1432.71	0.96
7	68.85	1375.16	0.80	18.91	1451.62	0.97
6	69.50	1444.66	0.84	15.05	1466.67	0.98
5	69.97	1514.64	0.88	11.62	1478.29	0.99
4	68.79	1583.42	0.92	8.63	1486.92	0.99
3	67.44	1650.86	0.96	6.11	1493.03	1.00
2	65.88	1716.74	1.00	4.00	1497.03	1.00

Design of Staggered Truss System

AISC *Design Guide 14: Staggered Truss Systems* was used to determine initial sizes for the members of the staggered trusses. This design guide details the calculation of transverse shear through the rigid floor diaphragm made by the precast plank flooring system. This diaphragm transfers the shear forces taken from the staggered trusses into the remaining trusses. This creates a deep beam condition in the diaphragm that uses the trusses as "drag struts." Moment frames were used in non-rectangular spaces and where the architectural layout did not warrant truss placement.

The trusses were designed with six-foot Vierendeel panels, to span where the main corridor was located. Fortunately for this design, these corridors were located exactly in the middle of the floor plan and allowed for a symmetrical geometry to be used. A basic diagram of the typical truss design is shown below. The remaining shape was divided into four equal quadrants 8'-5 ¼" in length on each side of the Vierendeel panel, to support the full 73'-6" width of the River Tower floor in the North-South direction. This shape and design was used at every truss location for ease of design. This truss configuration is known as a Pratt truss, which places the diagonal brace members in tension. This geometry was chosen because of its widespread use in existing staggered truss systems.



Typical Staggered Truss Dimensions

Summary of Hand Calculation Results

The staggered truss system was calculated to account for both direct shear and the torsional rigidity of this specified truss configuration. Because the shear force at each floor can be centralized at that particular floor's center of mass, and the trusses have their own different center of rigidity, there is an amount of torsion to account for in the lateral resistance from the resulting eccentricity. Accidental eccentricity was also considered, although because seismic loading did not control over wind loading, plan irregularity was not accounted for in these calculations, which appear in Appendix C of this report. Lateral loads were distributed under the assumption that the planks provided a rigid diaphragm, a simplified assumption. Transverse shear taken by the diaphragm formed by the precast floor planks was checked to ensure structural stability. The method of joints analysis was used to distribute separate gravity and lateral loads to each member of the truss. Load coefficients were then used to simplify load combinations based on LRFD and ASCE methods. Resulting calculations yielded various sized W10 members for the truss chords, large W12 and W14 sections for the truss columns, and HSS 10×4×1/2 for the diagonal members.

Summary of ETABS Analysis

ETABS Nonlinear was also used to verify these assumptions for truss member sizes, as well as the additional moment frames of the structure. The computer output from this program yielded much larger members than what was expected based on the hand calculations. Truss chord members, for example, were sized as W36 members by the analysis program, and even larger W14 sections were results for the columns. This occurred even though the loading matched the same criteria as the hand calculations. The discrepancy between these results can be explained by several factors. Staggered truss designs rely on the composite behavior between precast planks and the steel trusses, especially after grouting has been applied to secure this connection.[1] It is quite possible that the computer model did not properly render this bonding condition.

Several alternate modeling possibilities were investigated, including changing the rigid diaphragm of the floor planks to a more realistic flexible diaphragm, as recommended by technical literature from the makers of *ETABS*.[2] This allows the program to more properly model the shear stresses that develop in the precast diaphragm and includes diaphragm deformation in its results. This flexible diaphragm condition resulted in slighter smaller chord sizes than previous models, but still larger than the expected hand-calculated sizes. With this reduction in chord size, the exterior truss columns failed or were massively sized, resulting in even more discrepancy with the hand calculations. A similar condition developed when three chord members were used in place of the typical one continuous member spanning the full 73.5 foot width of the structure. Again, relatively smaller chord sizes came at a result of much larger column sizes. These computer models may have not properly transmitted the lateral loads from the floor diaphragm to the trusses. The story drift

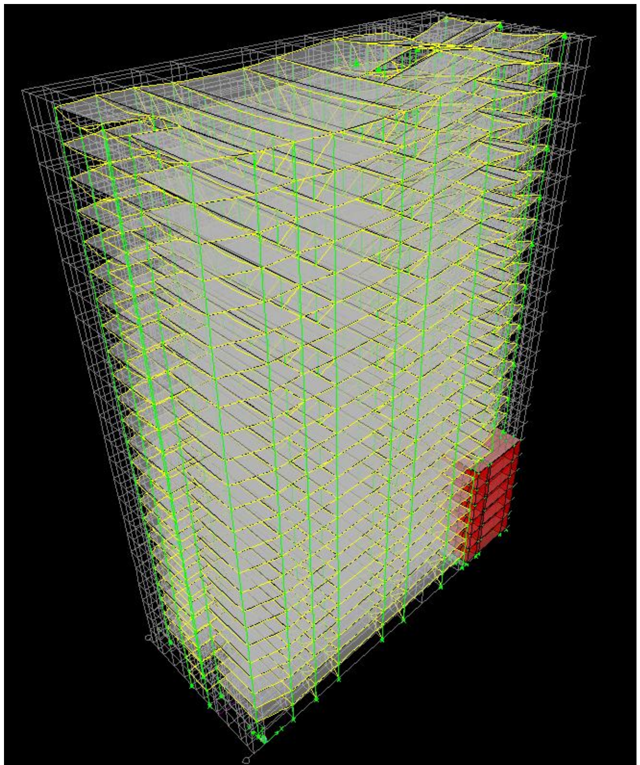


Image of the ETABS Model Deformed Shape, Parking Garage portion shown in red (not part of computer analysis)

[1] Wexler, Neil, and Feng-Bao Lin. *AISC Design Guide 14: Staggered Truss Framing Systems.* American Institute of Steel Construction, 2001.

[2] Habibullah, Ashraf. "Steel Frame Design: Staggered Truss Framing Systems Using ETABS." Computer and Structures, 2005. <http://www.csiberkeley.com/Tech_Info/StaggeredTrussTechnicalNote.doc>.

results from *ETABS*, which are in the thousandths of an inch, support this notion.

The results of these computer outputs have been provided in Appendix D of this report. A realistic interpretation of these results, based on the inconsistency of the truss chords in particular, is that the final design member sizes likely lie somewhere in between the hand calculations and computer output. The consistency of the hand calculations with those of the design guide, along with previous projects, confirms the adequacy of that process. Of course, these existing projects were much smaller buildings, often no larger than five stories in height, which could also explain this difference in results. The computer analysis, modeled with a rigid diaphragm brought the most successful of the computer results, and was used to price this system in the following cost analysis section. Because of the theoretical nature of this research, it was judged that this was still an accurate assessment to compute system cost, with the size discrepancy accounted for in the final determination.

Impact on Foundation Requirements

The River Tower's current structural system of post-tensioned concrete slabs provides minimal floor-to-floor heights, minimizing the overall height of the building. This is crucial to reduce the overturning moment on the structure. Resistance to overturning is also aided by the overall building weight provided by the concrete slabs, columns, and shear walls. River Tower's location along the waterfront of the Christina River in Wilmington, DE, necessitates the use of deep piles based on the type of soil on the site. This will not change this designation, even with the reduced system weight of the proposed staggered truss system, but it will reduce the number of 200 ton HP12×84 steel piles. Despite the reduction in system weight, the building weight of the 25 stories counteracts the worst overturning moment brought by the controlling lateral load case of the wind in the wide direction. These figures appear after the wind calculations in Appendix A of this report.

Additional Concerns

Most of the floors of this 25 story tower are generally 10.25 feet in height, although particularly at the very lower and upper floors, this dimension changes. For the purposes of this analysis, all floors were assumed to be a consistent 10.25' height, which would present minor changes to the analysis presented in this report. There were also instances where interior hallways and closets intersected with this truss placement. In this rare situation, proper architectural changes, though minor, would have to be considered. For purposes of this research, it was assumed that any doorways or openings besides the Vierendeel panels could be fit in between the braced members. In reality, this yields a 2'-10" wide doorway with the standard 6'-8" rough dimension, and does not take into account the thickness of chord or column members. Architectural changes were withheld from the scope of this report. These dimensions do not even account for the thickness of the chords, which stand to be at least 10 inches deep, which would further hinder access through these hallway portals within each truss. This does not become an issue for every condominium unit, but provides a significant architectural problem to correct. The thickness of the chords and other structural members can be isolated to the flange widths of these members, but with finishing and fireproofing procedures, this could further restrict ceiling heights. Similarly, the thickness of the HSS brace members in the trusses can result in unsatisfactory thickness in the infill walls which enclose these staggered trusses.