Structural Analysis

Overview:

During the structural analysis of the Courtyard by Marriott in Lancaster, Pa, a redesign of the lateral and gravity system from masonry bearing and shear walls to a staggered truss system was performed. The building's foundation was kept as spread footings and the floor system remained as 8" pre-cast hollow core planks. The basic layout of the building was changed to accommodate the staggered truss systems efficiency. The layout of the building is now a 74' x 252' rectangular shape in order to yield the most efficient economical and structural results from the staggered truss system. The height of the building was also altered slightly. The 52' building was increased in height by 1' to obtain equal floor to floor heights and provide a higher first floor height. Another change made to the structure of Courtyard by Marriott in the structural analysis was the roof. It was transformed to a flat roof with a green roof system incorporated into it.

For the analysis of this building with the staggered truss system, hand calculations were done following the Steel Design Guide 14: Staggered Truss Framing Systems in order to design a typical truss member for this building (which can be found in the appendix) and a computer analysis was also done using ETABS.

Lateral Loads:

In using the IBC 2003 to determine the new lateral, it was found that the seismic load case still governs over the wind load case. The wind forces remained relatively the same as the existing structure, as well as the seismic forces. The seismic force decreased slightly overall. This is because of the extra load presented on the roof of the building from the 8" pre-cast hollow core plank and green roof addition. The hollow core planks add an extra 65 psf, while the green roof will add an extra 25 psf.

The existing system has a much lighter roof system which consists of metal deck with concrete and cold-form trusses. Another reason for the similar seismic loads in the two systems is that the seismic response factor used fot the staggered truss system was 3 and the seismic response factor used for the reinforced masonry shear walls was 3.5. A seismic response factor of 3 for the staggered truss systems is a more conservative value for the overall behavior of the system. Also, if this value is used in steel buildings, then there is no need to design special seismic connections. Since the building is located on the east coast, there is no need to consider special seismic connections. The following tables and figures show the results of the new wind and seismic load cases.

Wind Loads

V = 90 mph Exposure B I = 1.0 h = 53 ft					
Height (ft)	Windward Force (psf)	Leeward Force (psf)		Total Wind Force (psf)	
	N/S & E/W	N/S	E/W	N/S	E/W
0-15	6.83	-6.13	-3.06	12.96	9.89
20	7.43	-6.13	-3.06	13.56	10.49
25	7.92	-6.13	-3.06	14.05	10.98
30	8.39	-6.13	-3.06	14.52	11.45
40	9.11	-6.13	-3.06	15.24	12.17
50	9.71	-6.13	-3.06	15.84	12.77
60	10.19	-6.13	-3.06	16.32	13.25

Table 4. New Wind Loads

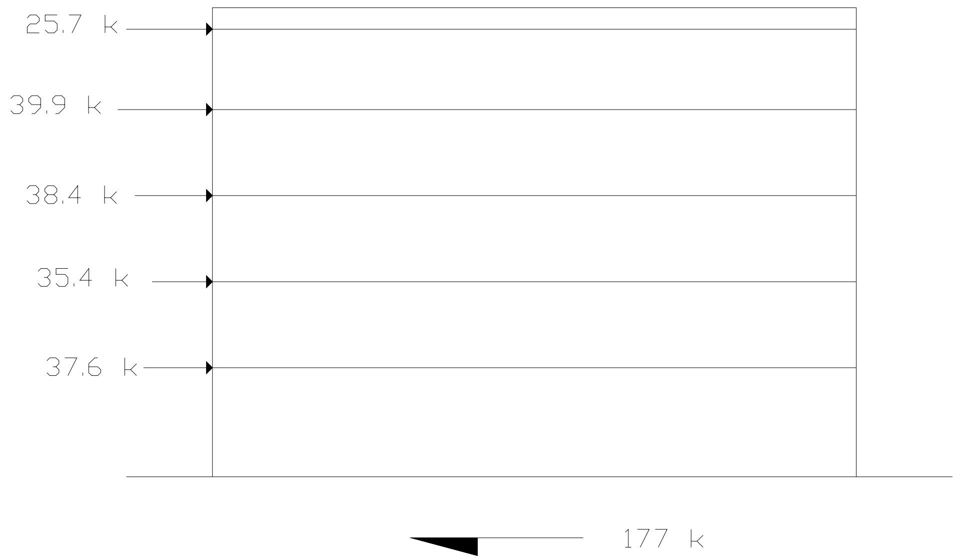

Figure 8. New Wind Story Shear - N/S Direction

Seismic Loads

R = 3 Seismic Design Category B Seismic Use Category II Seismic Factor = 1.0					
Level	w_x (k)	h_x (ft)	$w_x h_x^k$	C_{vx}	F_x
Roof	1870.2	53	99,121	0.344	216.7
5	1689.4	43	72,644	0.252	158.7
4	1689.4	33	55,750	0.193	121.6
3	1689.4	23	38,856	0.135	85
2	1689.4	13	21,962	0.076	47.9
1	0	0	0	0	0
			Σ =	1	629.9

Table 5. New Seismic Loads

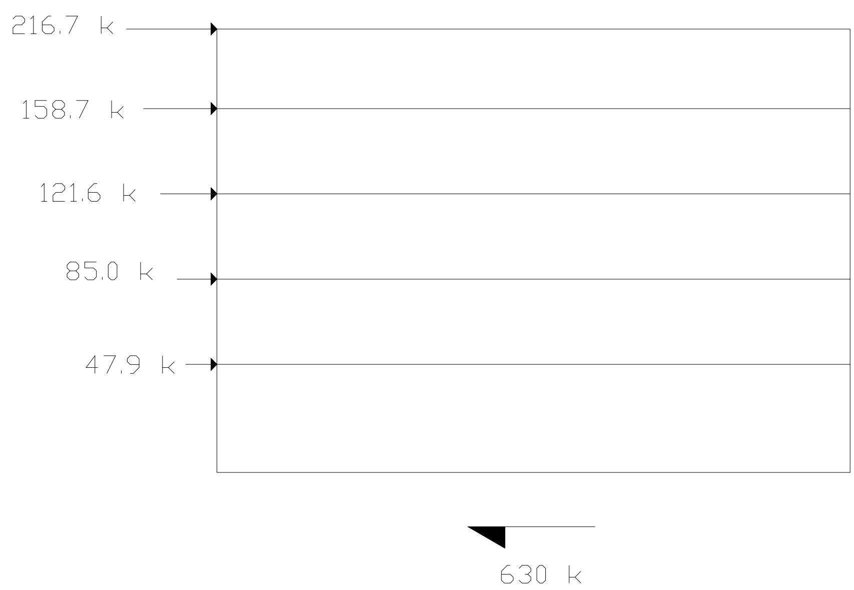

Figure 9. New Seismic Story Forces

Gravity Loads:

With the changes to the roofing system of the building, the gravity loads for the new system remain relatively similar to the existing system. The new total dead load equals 122 psf, while the dead load of the existing system is 121 psf. If the roof changes were not being considered and the roof from the existing system were to remain in the new system, the total dead load case would reduce to 89 psf. The following table provides all loads that contribute to the gravity loads of the building.

Dead Loads:		
8" Precast Hollow Core Plank	=	65 psf
Leveling Compound	=	5 psf
Structural Steel	=	5 psf
Partitions	=	12 psf
MEP, misc	=	10 psf
Green Roof	=	25 psf
	Σ =	122 psf
Live Loads:		
Guest Rooms/Corridors	=	40 psf
Mechanical Rooms	=	150 psf
Stairs	=	100 psf
Wall Loads:		
E.I.F.S.	=	15 psf
Studs	=	3 psf
Aluminum Sheathing	=	2 psf
Gypsum	=	3 psf
	Σ =	23 psf
Snow Load:	=	30 psf

Table 6. New Gravity Loads

Staggered Truss System:

The staggered truss frame designed for the Courtyard by Marriott in Lancaster, PA was designed with steel framing members and 8” pre-cast hollow core planks. Moment frames are used along the longitudinal direction of the building, while staggered trusses are used in the transverse direction. The stair wells and elevator openings will be framed with steel beams.

The hollow core planks will span 28’ from truss to truss. The planks will span from the bottom of one truss to the top of the next truss. The trusses will span the total width of the building, 74’ and they will be placed at every 28’ down the entire 252’ length of the building on alternating column lines. These trusses are one-story deep (10’ for this design) and are located in the walls between rooms with a vierendeel panel at the corridors. They are only supported at their ends on the longitudinal rows of columns that are placed around the exterior of the building on the north and south sides. These columns are oriented with their strong axis parallel to the transverse direction of the building. There are no interior columns, only spandrel columns. A typical floor plan is shown in **Figure 10**.

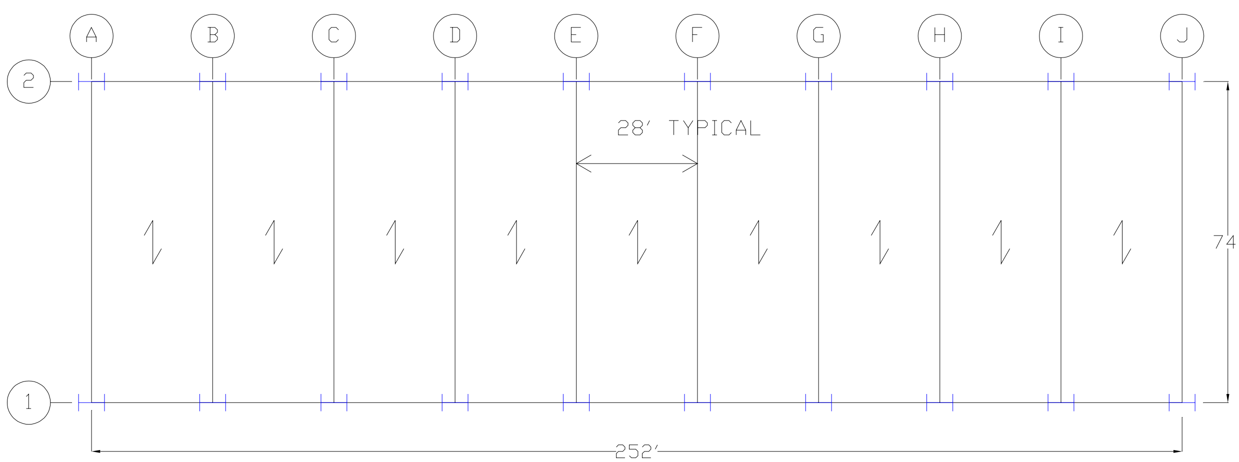

Figure 10. Staggered Truss Floor Layout

The two figures shown below show typical sections where the trusses are placed on odd stories and even stories. In **Figure 11** the second floor is being hung on the third floor truss by the hangers, while the roof is being posted up in **Figure 12**.

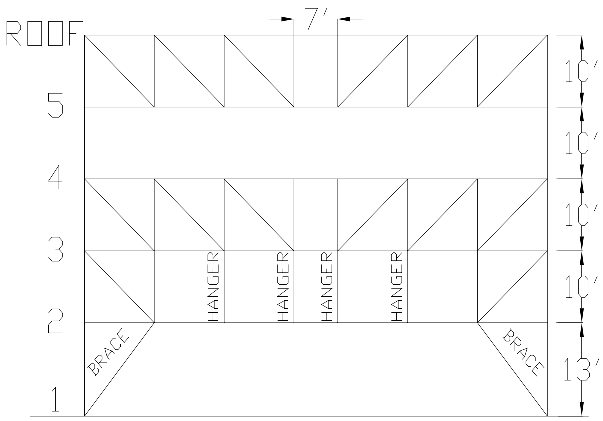

Figure 11. Odd Story Trusses

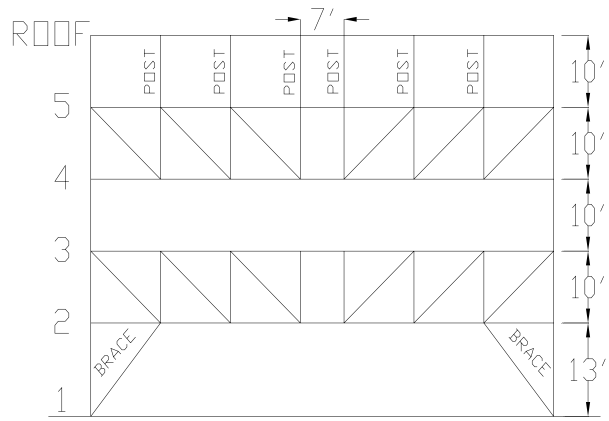

Figure 12. Even Story Trusses

The hollow core plank floor system is a very typical system used in hotel construction as well as staggered truss systems. The plank is connected to the truss chords with welded plates to provide temporary stability during erection. Then shear studs are welded to the chords, reinforcing bars are placed in the joints, and the grout is placed. When the grout cures, a permanent connection is achieved through welded studs. The hollow core planks will act as the diaphragm in the staggered truss system. In order for the plank to distribute lateral forces to the truss, it must act as a deep beam. Calculations including the diaphragm action with hollow core slabs can be found in the appendix.

Most common trusses are designed with W 10 chords and HSS web members connected with gusset plates. The chords must have a minimum width of 6" to ensure adequate plank bearing during construction. For the design of trusses in the Courtyard by

Marriott, W 10's and HSS 10 x 6's were design goals. The trusses are manufactured with camber to compensate for dead load. They are transported to site, stored and then erected. They can be erected in one piece generally up to 60' in length. In this case they will need to be transported in two pieces and spliced together in the field.

Design of Staggered Truss Members:

As suggested by Design Guide 14 the design of a typical truss member was done and then later analyzed using ETABS. The hand calculations typically ignore secondary effects such as moment transmission through joints, which may produce unconservative results. The typical truss used for analysis in the hand calculations was a truss located on the second floor on grid F (TF1). Truss dimensions can are shown below in **Figure 13**.

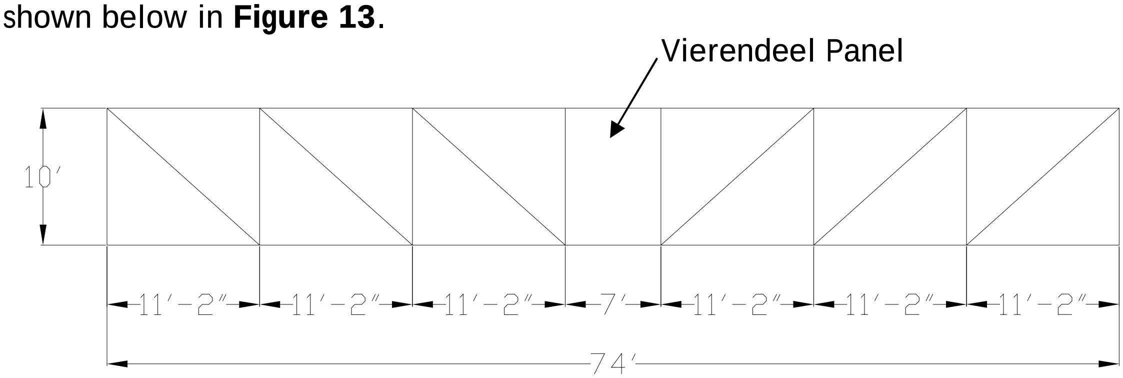

Figure 13. Truss Dimensions

The calculations begin with the design of the web members (vertical and horizontal members). The truss was first analyzed for gravity loads. A distributed load for the gravity load was found: w = (122 psf + 40 psf) x 28' = 4.53 k. This was then used with the tributary area to find the concentrated loads at the top and bottom joints of the truss members. The member forces were then found due to service gravity loads through the method of joints. Detailed calculations can be found in the **Appendix**. **Figure 14**, below, shows the resulting forces.

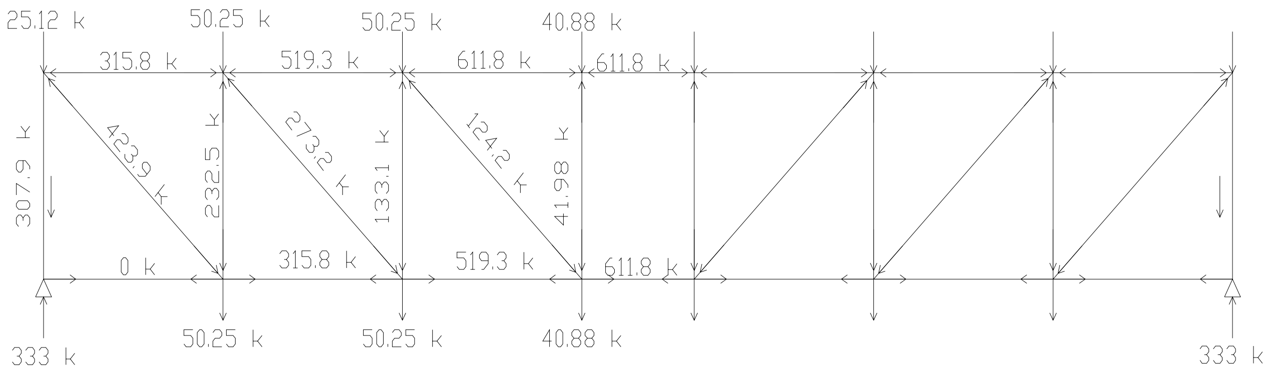

Figure 14. Member Forces Due to Gravity Loads

The truss was then analyzed for lateral loads. From previous calculations in the diaphragm design, the design shear strength was found (165 k) along grid line F. Because of anti-symmetry in the truss about its centerline for this load case, half the load was placed at each end of the top chord (horizontal reactions at supports = 82.5 k). Half the truss was analyzed as a free body and the shear force in the top and bottom chords of the vierendeel panel were assumed the same force in shear: V = ½(82.5 x 10)/37' = 11.15 k. The chord at the end moment at the upper vierendeel joint panel is equal to the shear x ½ panel length: M = (11.15 x 7)/2 = 39.02 ft-k, V = (39.02 + 0)/10 = 3.9k. The member forces were then found due to lateral loads through the method of joints. Detailed calculations can be found in the **Appendix**. **Figure 15**, below, shows the resulting forces.

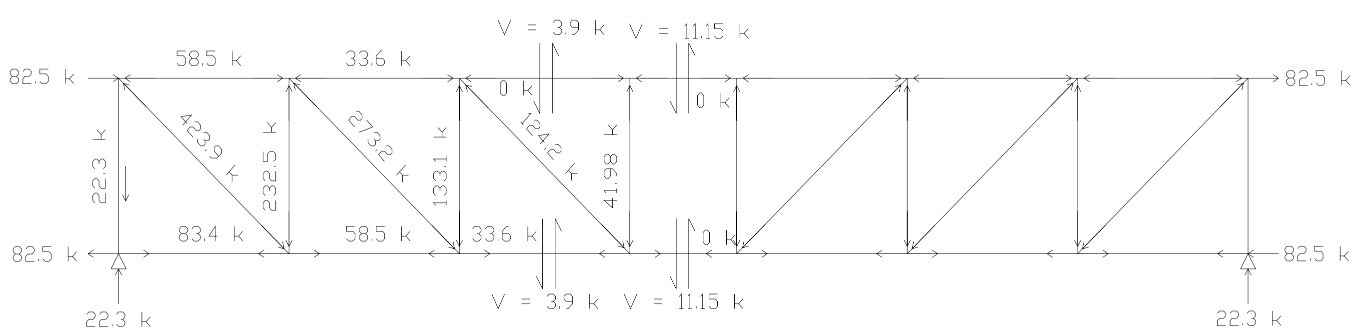

Figure 15. Member Forces Due to Lateral Loads

After the member forces for lateral loads have been calculated, they can be combined with gravity forces in order to find design forces. Once both these forces are calculated, forces for other trusses can then be computed using load coefficients. These load coefficients will be found for different load cases. The load coefficients are calculated in detail in the appendix.

In order to chose the correct size members load combinations must be defined to see which will control the design of the members. The loads used in the load combinations were: Dead Load = 122 psf
Live Load = 40 psf
Reduced Live Load = 20 psf (50% LL Reduction)

The following load combinations were taken into consideration per code IBC 2003:

1) 1.4 D
2) 1.2D + 1.6L
3) 1.2D + 1.6W + 0.5L
4) 1.2D + 1.0E + 0.5L
5) 0.9D + (1.0E or 1.6W) – no need to calculate, will not govern

The following table shows results of the load combinations and selection of member sizes. The numbers in bold under the load combinations indicate the governing combination for that story. More detailed calculations can be found in the **Appendix**.

Diagonal Members - Typical Truss (TF1)									
	Wind		Seismic		Load Combinations				
Floor	**ϕ_h**	**$\phi_{ecc}*\phi_h*F_w$**	**ϕ_h**	**$\phi_{ecc}*\phi_h*F_w$**	**1**	**2**	**3**	**4**	**Member Sizes**
Roof	0.15	5.31	0.34	42.85	445	**466.3**	418.1	454.1	HSS 10 x 6 1/2
5	0.37	13.1	0.6	75.62	445	466.3	428.2	**486.8**	HSS 10 x 6 1/2
4	0.59	20.89	0.79	99.57	445	466.3	438.4	**510.8**	HSS 10 x 6 1/2
3	0.79	27.97	0.92	115.95	445	466.3	447.6	**527.2**	HSS 10 x 6 1/2
2	1	35.4	1	126.03	445	466.3	457.2	**537.2**	HSS 10 x 6 1/2
1		□							
F in d1 of Typical Truss TF1		33.4		118.9	423.9				

Table 7. Diagonal Member Design

For the chord design of the truss, two load combinations were considered, 1.2D + 1.6L and 1.2D + 1.0E + 0.5L, since both the cases governed. The steel design for the chords must comply with the AISC Equations H1-1a:

$$P_u/(\phi P_n) + (8/9) \times [M_{ux}/(\phi_b M_{nx})] < 1.0$$

ϕ = 0.9 for Tension

ϕ = 0.85 for Compression

ϕ_b = 0.9 for Bending

The member forces of the chords on the second story due to gravity and seismic forces are computed and then combined. These calculations can be found in the **Appendix**. The following two tables will show the design of the staggered truss chords for the two governing load cases.

Chord Members - Typical Truss (TF1)				
Load Case 1.2D + 1.6L				
Floor	**Mu**	**Pu**	**Section**	**Eq H1-1a**
Roof	50	673	W 10 x68	0.93
5	50	673	W 10 x68	0.93
4	50	673	W 10 x68	0.93
3	50	673	W 10 x68	0.93
2	50	673	W 10 x68	0.93
1				

Table 8. Chord Member Design - Load Case 1.2D + 1.6L

Chord Members - Typical Truss (TF1)						
Load Case 1.2D + 1.0E + 0.5L						
Floor	ϕ_h	**Mu, s**	**Mu**	**Pu**	**Section**	**Eq H1-1a**
Roof	0.34	14	29	593	W 10 x 54	0.98
5	0.6	25	51	593	W 10 x 60	0.95
4	0.79	32	67	593	W 10 x68	0.88
3	0.92	38	78	593	W 10 x68	0.91
2	1	41	85	593	W 10 x68	0.93
1						

Table 9. Chord Member Design - Load Case 1.2D + 1.0E + 0.5L

The floor loads are delivered to the columns through the truss – to – column connections. The load from two floors can be carried by a typical one story truss, while a truss with hangers or posts the load from three floors will be carried. The maximum live load reduction of a 50% (RLL = 20psf) is permitted since the columns support large tributary areas. The table below shows the design values of the columns calculated by hand. Refer to the **Appendix** for more detailed calculations.

Column Design - Typical Column TF1											
	Axial						Moment	Load Combinations			
	Floor		Exterior Wall	Total			DL1	1.4D		1.2D + 1.6L	
	DL1	DL2 + RLL		DL1	DL2 + RLL	Ext. Wall		Pu	Mu	Pu	Mu
Roof	145	294.2	6.44	145	294	6.44	33	203	46.2	377	39.6
5			6.44	145	294	12.9		203		385	
4	145	294.2	6.44	290	588	19.3	51	406	71.4	762	61.2
3			6.44	290	588	25.8		406		769	
2	145	294.2	6.44	435	882	32.2	75	609	105	1146	90
1			6.44	435	882	38.6		609		1154	

Table 10. Column Design – Roof, 5 -> W12 x 65; 4, 3 -> W12 x 96; 2, 1->W12 x 136

ETABS analysis:

In ETABS, a three dimensional model of Courtyard by Marriott with the new staggered truss system was created. Codes used in the computer analysis were IBC 2000 for seismic loading and ASCE 7-98 for wind loads. It was found through this computer analysis that the total building due to seismic loading was 1.41" and the drift due to wind was .0078". Both of these drifts are less then the l/400 building drift that is equal to 1.59". The member size output for the ETABS analysis differed slightly from the hand calculation output. The computer analysis may offer a more accurate solution. Tables with story drifts provided by ETABS as well as other ETABS results can be found in the **Appendix**.

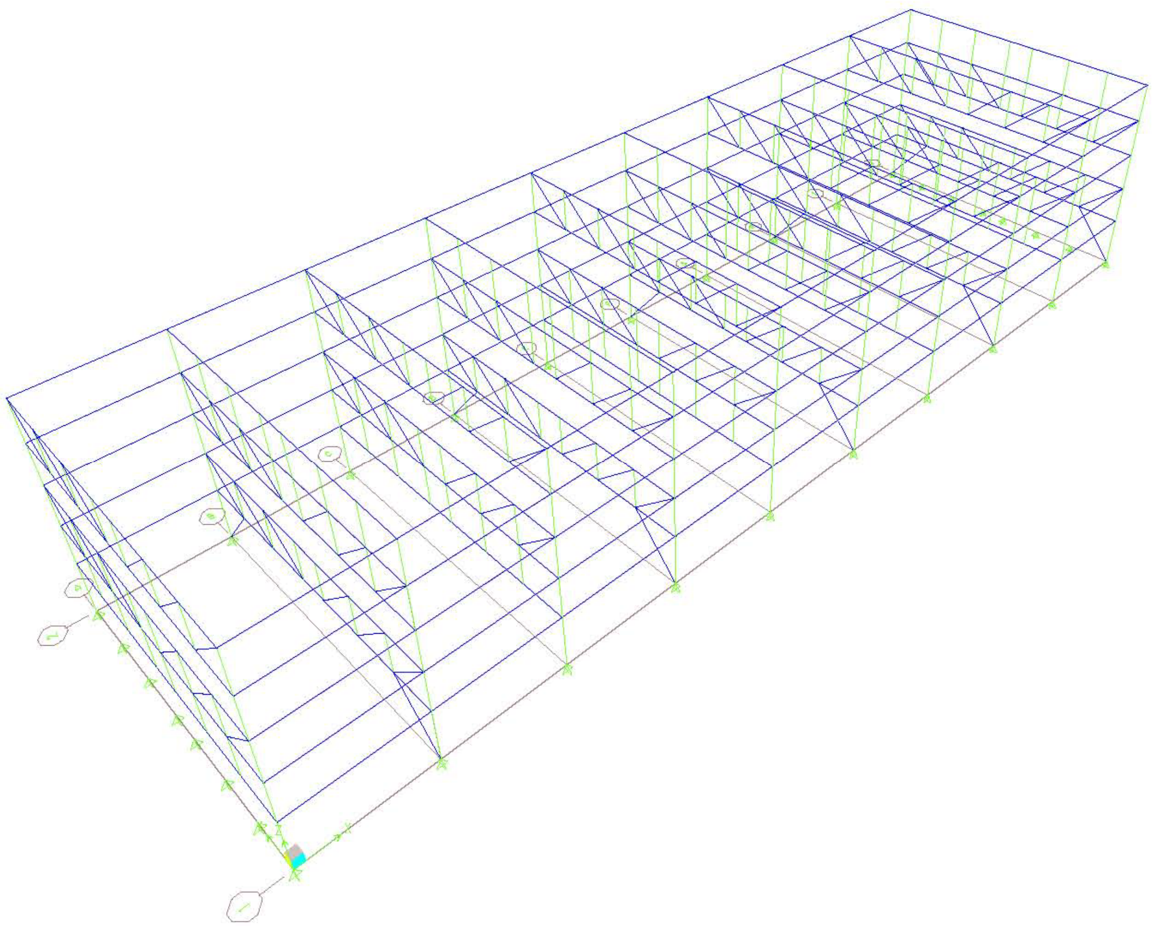

Figure 16. ETABS – 3D building view showing staggered truss alignment

In order to obtain member sizes for the trusses, beams/spandrels in columns general shapes and sizes had to be chosen at the beginning of the analysis. This would also ensure that the desired repetition in the staggered truss system would be satisfied. W 10 sections were chosen for the chords of the truss while HSS10 x 6 x 3/8, HSS10 x 6 x ¼ and HSS10 x 6 x ½ were chosen for the web members. Six inch HSS members were chosen in order to keep the thickness of the wall to a reasonable size. For the columns, W 12 sections were selected. Though W 12's were specified, some W14 columns were needed in the design. Typical truss designs are shown in **Figure 17** and **Figure 18**, while a section of the front elevation can be found in **Figure19** with spandrel beam and column sizes.

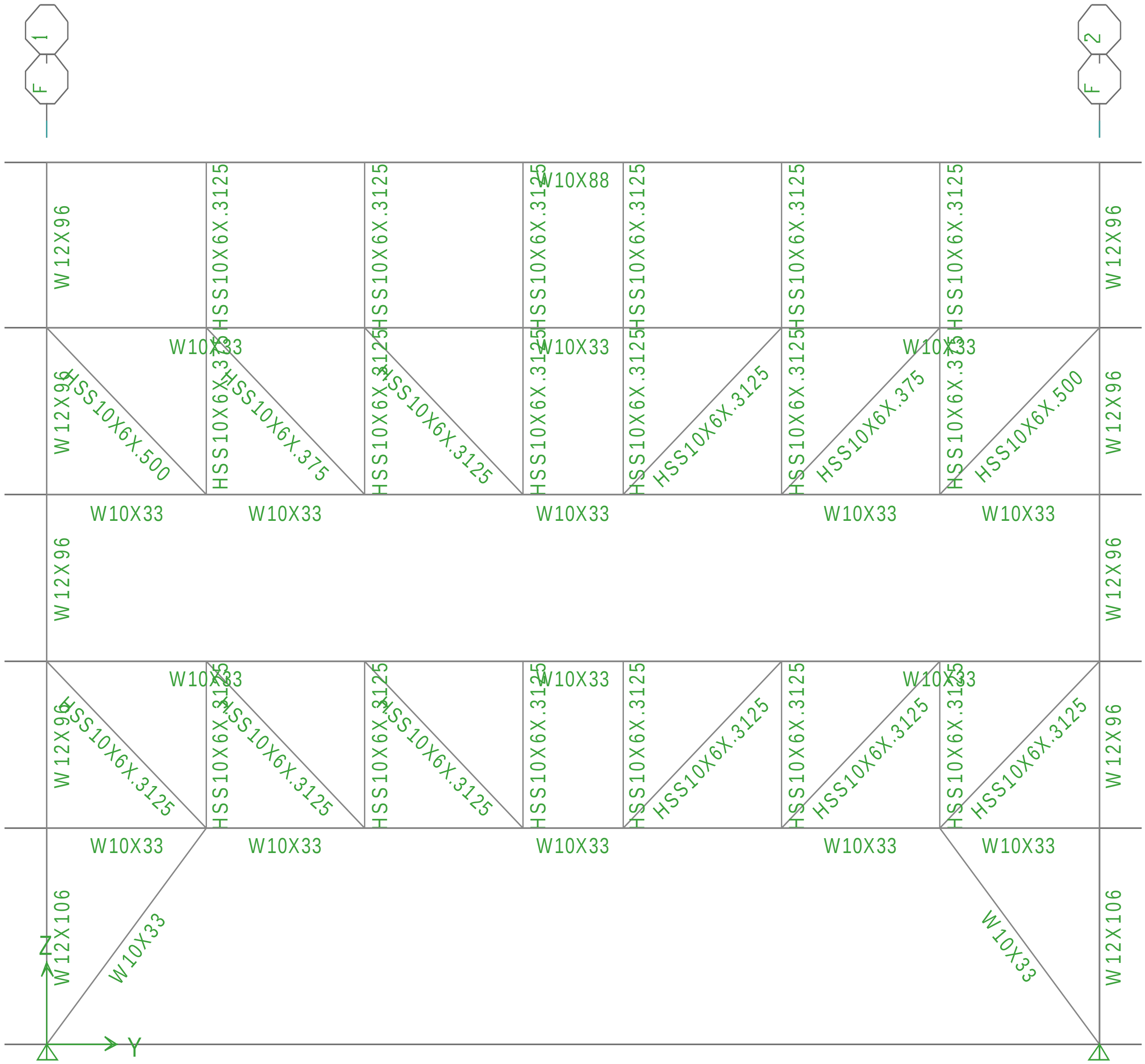

Figure 17. ETABS building section at grid line F – member sizes

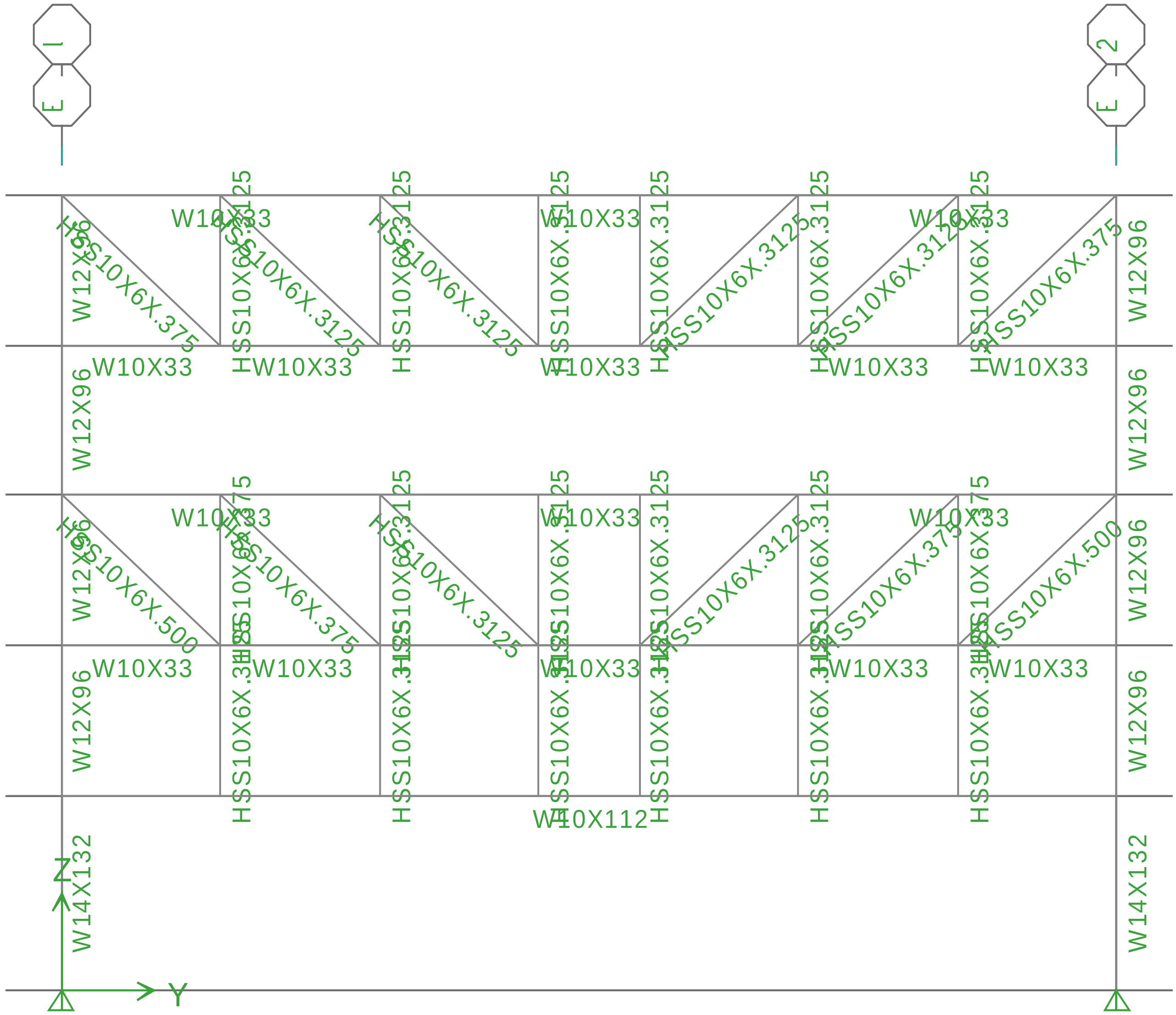

Figure 18. ETABS building section at grid line E – member sizes

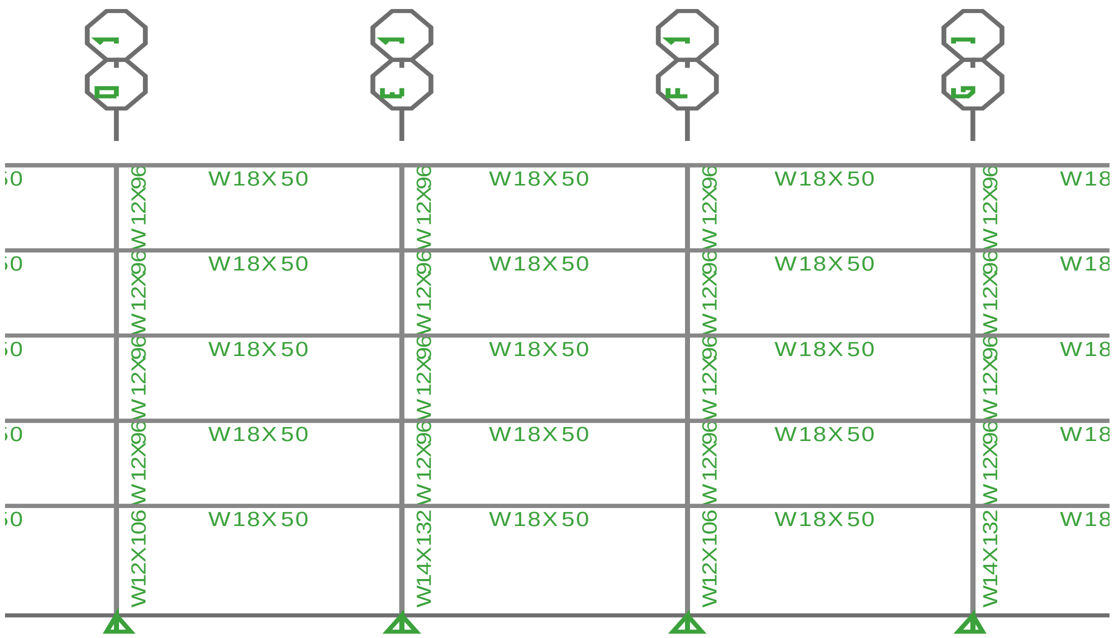

Figure 19. Section from ETABS front elevation at grid line 1

Staggered Truss vs. Masonry Shear Wall:

<u>Staggered Truss System</u>

Advantages:

- Provides large column free open space on first floor
- Provides an open floor layout for hotel rooms on upper floors
- Provide low floor-to-floor height
- Highly efficient for resistance to lateral loads caused by wind and earthquake
- Lighter system
- Quick and easy erection (especially during winter construction)

- Minimum fire protection required - since the trusses are typically placed in demising walls, (3) 1/2" layers of drywall can be placed on each side to achieve the proper fire rating. Also, spray on fireproofing can be used for which will be need at a minimum because of compact sections.

Disadvantages:

- Rectangular geometry of building does not meet the Courtyard brand of Marriott architecture and room layout
- Only efficient with repetition – if the trusses vary in length, height and member size, then the system will not yield any real benefits
- Spans larger than 60' must be erected in pieces and spliced together in the filed, possibly causing some time delays
- Misalignment of trusses during construction can cause problems with the plank alignment, offset interior walls and delay construction. Alignment tolerances are very low and construction has to be monitored closely.

<u>Existing System</u>

Advantages:

- Provides acceptable architectural and room layout for Courtyard brand of Marriott
- Provides a very stiff structural system which allows for minimum building and story drift
- Low floor-to-floor heights are maintained
- Typical type of structural system used in hotel construction
- Material easy to find locally and need not be specially shipped or fabricated

Disadvantages:

- Heavy system
- Columns used on first floor do not follow grid patterns
- Because using a combination of systems, more materials and trades are needed in order to construct the building resulting in higher cost
- Slow construction during the winter