Analysis III – Structural Considerations for Green Roof

Background

Analyses I & II discussed the function of adding a green roof to the project from a sustainable and energy conservation perspective, however, there are other aspects of construction that need to be considered when an architectural feature is altered to this degree. Green roofs may decrease a building's peak load requirements for heating and cooling, but they can also add a sizable load to a roof structure. As discussed in Analysis I, the green roof selected to be installed is an Extensive System. Although designed to be light weight as compared to Intensive Systems, these green roofs can still contribute an additional 20-110 lbs/sq ft in dead load. In order to ensure that the roof structure can support such a load, a structural analysis of the current roof has to be done.

Problem

The green roof system selected is an estimated additional 19 lbs/sq ft in dry weight and 26 lbs/sq ft saturated on top of the self weight of the structure. Please refer to **Figure 2.1** in Analysis II for a typical section. The current lower roof level is designed to have public access and is scheduled to have concrete pavers installed as walkways. The additional load on top of the self weight in this area is 22 lbs/sq ft. In a post-tensioned slab such as this one, the additional 4 lbs/sq ft can be assumed as negligible. The area for concern is the roof above the mechanical penthouse. The current weight experienced by this roof system is only 8 lbs/sq ft.

Objective

To analyze the current penthouse roof structure and make the necessary calculations to appropriately size a slab for the additional load to be experienced.

Analysis

In order to earn credit SS 7.2, the green roof must cover 50% of 15,800 sq ft (the total roof area) which is equal to 7,900 sq ft. The proposed location for installation is on both the lower and mechanical penthouse roof structures which totals 8,270 sq ft. See **Figures 3.1 and 3.2** on the following page for the suggested layout.

Figure 3.1 Suggested green roof layout for the lower roof. Total area is equal to **5,394 sq ft**. Please note that a through way for the window washing rig was considered.

Figure 3.2 Suggested green roof layout for penthouse roof area. Total area is equal to **2,876 sq ft.**

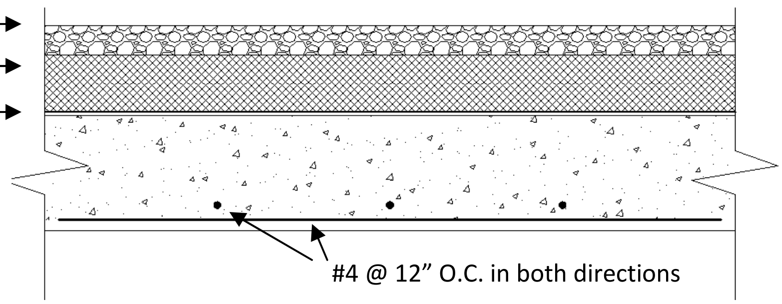
Current Penthouse Roof Slab:

8” Concrete Slab
Bottom Reinforcement: #4 @ 12” on center in both directions
F'_c = 4,000 psi

Loading (from ASCE7):

Live Load: 30 psf
Snow: 30 psf
Gravel Ballast: 5 psf
Polystyrene Foam Insulation: 1 psf
Filter Fabric: 1 psf
Waterproofing Membrane: 1 psf

Total Live Load = 30 psf
Total Dead Load = 38 psf



Current Penthouse Roof Section

Factored Loading: 1.2 D + 1.6 (L) + 0.5 (S) = 1.2 (8 psf) + 1.6 (30 psf) + 0.5 (30 psf) = 72.6 psf

Extensive Green Roof Loading:

Live Load: 30 psf
Snow Load: 30 psf
Extensive Green Roof System: 26 psf

Total Live Load = 30 psf
Total Dead Load = 56 psf

Factored Loading: 1.2 D + 1.6 (L) + 0.5 (S) = 1.2 (26 psf) + 1.6 (30 psf) + 0.5 (30 psf) = 94.2 psf

pcaSlab:

When the loading for the green roof system was entered into the pcaSlab program and applied to the current roofing system, the program reported that the current reinforcement was not sufficient. In order to be structurally sound in an 8” slab, the size of the reinforcement would have to be increased.

After reconfiguring the reinforcement in pcaSlab to accommodate the additional weight from the green roof, it was determined that the preferred alternative system would still be an 8" concrete slab, but #5 reinforcement at 12" on center would be required. Although #4 reinforcement could still have been utilized, the spacing and number of bars that would be required varied greatly from section to section. The #5 reinforcement was chosen because it proved to be more economical and logical from a construction management point of view. Since their spacing was more uniform and fewer bars were required, the schedule and budget would be better maintained.

Hand Calculations for Verification:

To begin, I followed the direct design method for two-way slabs. (Full design calculations can be viewed in **Appendix D**)

Step 1

- Uniform load determined to be 214 psf (includes self weight of 8" normal weight concrete slab)
- Minimum depth for two way slabs 4"(with drop panels) is less than the proposed 8"

Step 2

- Total static design moment was determined to be 79.3 ft-k in the short span direction
- Using the distribution factors for positive and negative moments from ACI 13.6.3, the following values were determined:

Interior Negative $M_u = 0.70M_o = 55.5$ ft-k
Exterior Negative $M_u = 0.26M_o = 20.6$ ft-k
Positive $M_u = 0.52\ M_o = 41.2$ ft-k

- Total static design moment was determined to be 95.9 ft-k in the long span direction
- Using the distribution factors for positive and negative moments from ACI 13.6.3, the following values were determined:

Interior Negative $M_u = 0.70M_o = 67.1$ ft-k
Exterior Negative $M_u = 0.26M_o = 24.9$ ft-k
Positive $M_u = 0.52M_o = 49.9$ ft-k

Step 3

- The column strip width was determined to be 7 ft
- According to ACI 13.6.4, the column strip supports 75% of the interior negative moment, 75% of the exterior negative moment, and 60% of the positive moment

	Column Strip Slab Moment (ft-k)	Middle Strip Slab Moment (ft-k)
Short Span		
Interior Negative	41.6	13.9
Exterior Negative	15.5	5.1
Positive	24.7	16.5
Long Span		
Interior Negative	50.3	16.8
Exterior Negative	18.7	6.2
Positive	29.9	20

Table 3.1 Displays the moment distribution over the slab area.

Step 4

- The minimum effective depth was determined to be 2.2" in the short direction and 2.53" in the long direction. For the slab, d = 6" & 7" will be used respectively
- For shrinkage and temperature, the minimum area of steel required was calculated to be 0.173 in^2/ft^2
- In the Long Span, ρ_{min} = 0.0021
- In the Short Span, ρ_{min} = 0.0024

Step 5

See **Table 3.2** below for design of slab reinforcement

	Location	M_u (ft-k)	b (in)	d (in)	M_u x 12/b (ft-k)	ρ	A_s (in^2)	Bars
Long Span								
(2) Half Col. Strip	Int. Neg.	50.3	84	7	7.2	0.0025	0.236	#5@12" O.C.
	Ext. Neg.	18.7	84	7	2.67	0.0021	0.200	#5@12" O.C.
	Positive	29.9	84	7	4.3	0.0021	0.200	#5@12" O.C.
Mid. Strip	Int. Neg.	16.8	132	7	1.5	0.0021	0.200	#5@12" O.C.
	Ext. Neg.	6.2	132	7	0.6	0.0021	0.200	#5@12" O.C.
	Positive	20	132	7	1.8	0.0021	0.200	#5@12" O.C.
Short Span								
Ext. Col. Strip	Negative	15.5	42	6	4.4	0.0024	0.230	#5@12" O.C.
	Positive	24.7	42	6	7.1	0.0029	0.280	#5@12" O.C.
Middle	Negative	13.9	84	6	2.0	0.0024	0.230	#5@12" O.C.
	Positive	16.5	84	6	2.4	0.0024	0.230	#5@12" O.C.
Int. Col. Strip	Negative	41.6	42	6	11.9	0.0050	0.480	#5@7 ½ " O.C.
	Positive	324.7	42	6	7.1	0.0029	0.280	#5@12" O.C.

Table 3.2 Displays the reinforcement design for the slab.

Step 6

- The nominal shear strength for the slab was calculated to be ϕV_c = 111.4 kips
- The factored shear for the slab was calculated based on the tributary area of each column to be V_u = 53.9 kips, which is well below the maximum 111.4 kips. Therefore no additional reinforcement, including drop panels, for punching shear is required.

Step 7

- The design strength for axial loading about the 24"x14" columns was determined to be ϕP_n = 898.6 kips and ϕM_n = 247 ft-kips.
- The factored axial loading experienced at each interior column is P_u = 53.9 kips which is well below the maximum 898.6 kips.
- The maximum factored moment experienced at each interior column is M_u = 95.9 ft-kips. Therefore the existing column is sufficient for carrying the additional load from the green roof system.

Cost Comparison

- As mentioned in Analysis II, the extensive green roof system to be installed will be an additional $10 per sq ft (including labor) according to Prospect Waterproofing, the current roofing contractor on the project. This will increase in the overall roof cost of $275,000 by **$82,700** (30% increase).
- The additional reinforcement required to support the green roof will add an additional 2,000 lbs to the slab and an additional **$1000.**
- Removing the drop panels will save 10 CY of concrete and 2,000 lbs of reinforcement. This would save **$2,100** in material cost and **$300** in labor.
- The total increase in cost would be **$81,300.**

The cost comparison can be visualized in **Table 3.3** below.

Description	Cost
Original Roof Cost	$275,000
Additional Cost for Green Roof Material	$82,700
Increased Reinforcement	$1,000
Concrete Material Savings	($2,100)
Concrete Labor Savings (1 day)	($300)
Total Additional Cost	**$356,300**

Table 3.3 Summary of the savings in cost of materials for green roof installation.

Schedule Impact

- The installation of a green roof would require an additional 2-3 days beyond the planned 35 days. Considering the roofing installation is not on the critical path nor is it a precursor to any other construction activity, no delays should be expected.
- Currently the concrete carpenters can install formwork at an estimated 69 sq ft/hr. With the drop heads no loner being required, there is over 500 sq ft of formwork that no longer needs to be installed. This can save nearly one work day.

Conclusion & Recommendations

To continue from the discussion from Analysis II, a green roof can add considerably to the cost of the project. It was previously determined that it would take 100 years for the building to payback the added initial cost of $82,700. The calculations in this analysis proved that the overall cost of adding the green roof could be reduced by an amount of $1,400 to $81,300 considering the excess of material and labor that was originally designed for the existing project.

If a green roof were to be installed on the project, a redesign of the structural system would prove to be economically feasible. To further analyze the cost, the installation of the traditional roofing system would require a reinvestment of $284,000 after 20-25 years for repairs/replacement assuming a rate of $3.50/sq ft for demolition and $14.50/sq ft for the new built-up roof and related flashings. An extensive green roof would not require this degree of maintenance for 50 years. The cost comparison is illustrated in **Chart 3.1** below. Including the annual savings of $845 from Analysis II, the green roof system will pay for itself after a period of 20 years when the built-up roof would have to be replaced. At this point the existing roof will have cost $559,000 and the proposed green roof will have cost $339,400. (Please note, 20 years is the extent of the warranty on the roofing system and it is being considered as a conservative estimate for the life span.)

To remain consistent with Analysis I & II, installing a green roof would be a sensible solution to achieving sustainability for 1099 New York Avenue.

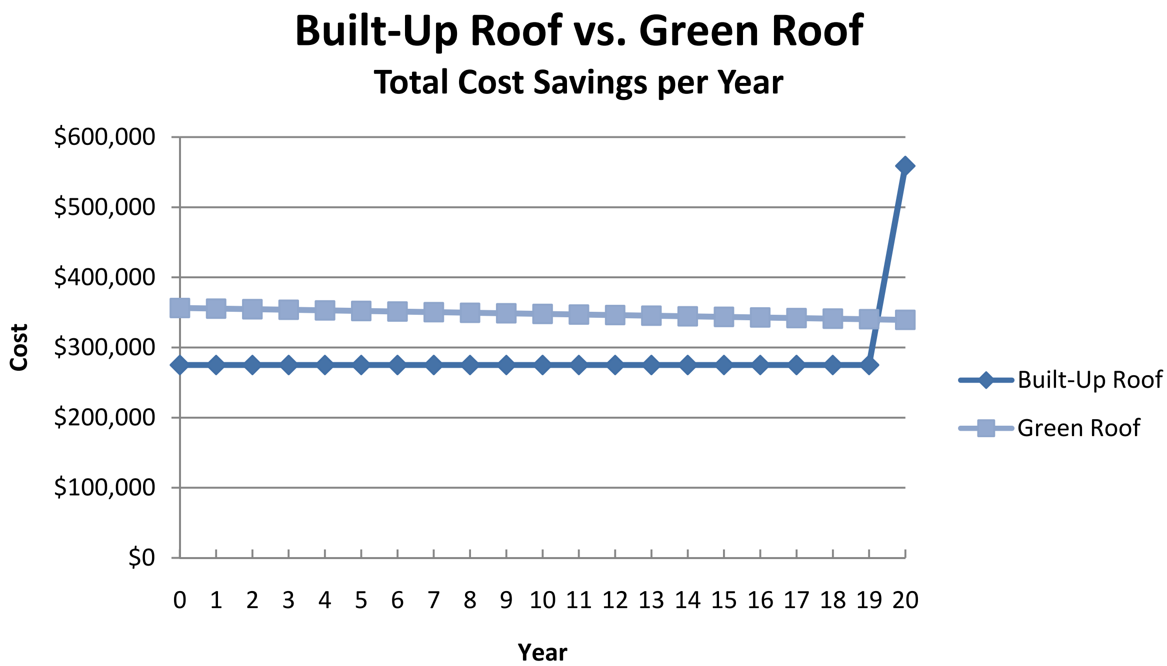


Chart 3.1 Displays the cost savings per year for a built-up roof versus a green roof. The green roof will pay itself back between year 19 and 20.