CASE STUDY: EVALUATION OF A TWO-LEVEL RESIDENCE STRUCTURAL PLAN (STILT HOUSE WITH OPEN SPACE ON THE FIRST FLOOR) AND COMPLIANCE RECOMMENDATIONS FOR EARTHQUAKE RESISTANCE IN PUERTO RICO USING ACI318-14 CODE

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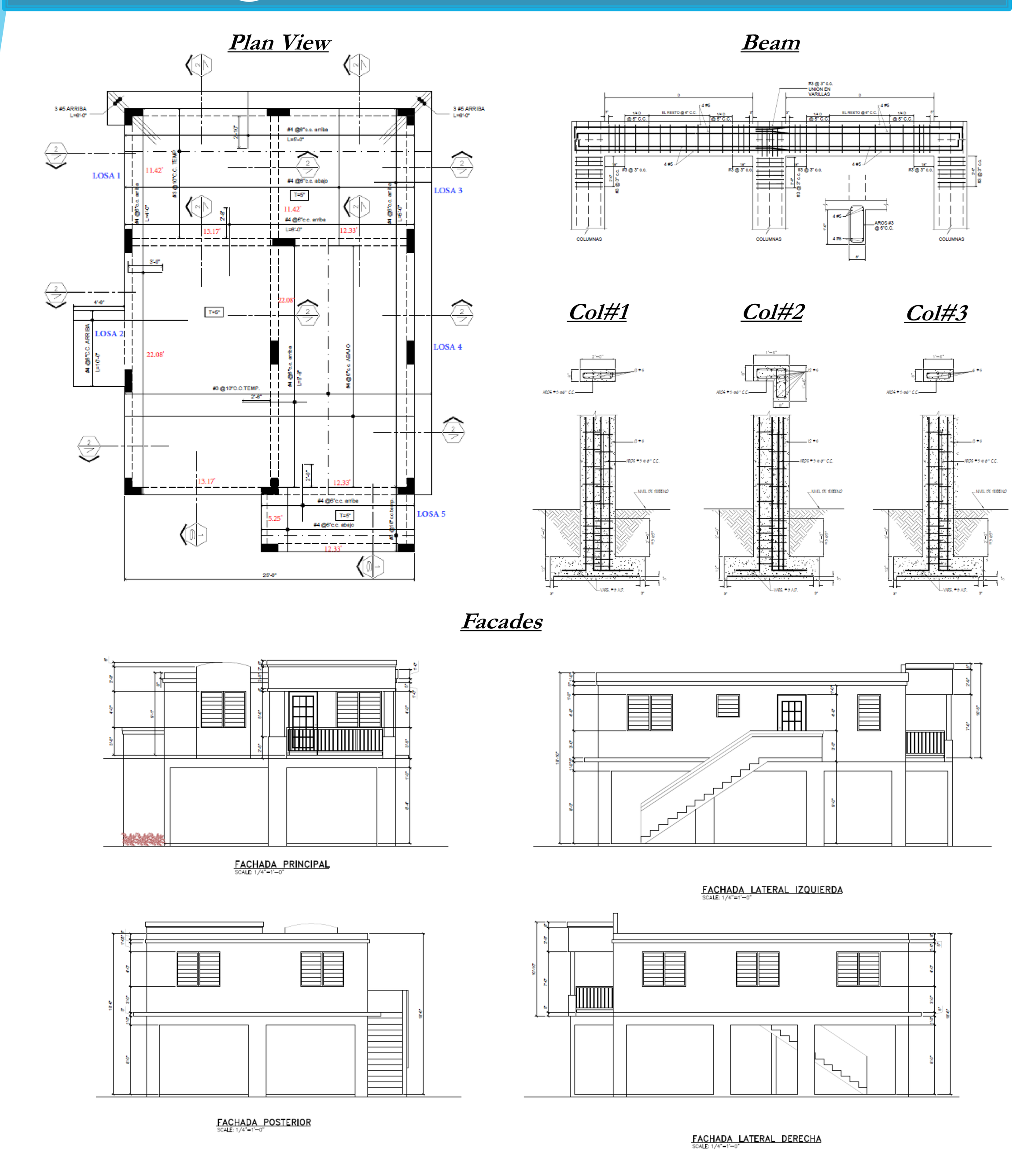
Abstract

The construction of two-level residences over columns in Puerto Rico is quite common. This type of structure (also known as "casas sobre zancos") is built for the purpose of having an open space on the first floor(ground level) while the main residence is built on the second level. In this case study an original design was evaluated against existing codes to bring it for compliance purposes. Recommendations are presented with the objective of ensuring that the structure is adequately designed as an earthquake resistant moment frame according to the code ACI 318-14. The first analysis considers the properties of materials, live loads, dead loads, and seismic loads based on the structure's own weight (applied at a distance equivalent to 5% of the centroid). It also considers the P Delta effects. All these loads are factored in and combined in order to decide which one is the worst-case scenario. The capacity of each element should be verified with the maximum load obtained from the analysis; if not compliant, the structure must be redesigned. When the cross section of an element changes in size, components, or material property, it is necessary to redo the analysis. This iterative process should be carried over until the sections obtained have a capacity (multiplied by a reduction factor) greater than the maximum demand. Furthermore, it is necessary to comply with important aspects such as the minimum spacing of transverse steel (shear), minimum dimensions of elements, maximum and minimum amounts of longitudinal steel (flexure), location of development lengths and splices, verification of strong column-weak beam criteria (MnColumns> 1.2MnBeams), among others are discussed in more detail in this article.

Introduction

On December 28, 2019, and progressing into 2020, the southwestern part of the island of Puerto Rico was struck by seismic activity. The largest and most damaging of this sequence occurred on January 7 (4:24AM AST), with a magnitude of 6.4. Days before January 7 (and days after) several tremors greater than 5.0 were registered in Puerto Rico. At least one person was killed, and several others were injured. This earthquake left 8,000 people homeless and about 40,000 others (these just in the municipality of Ponce) camping in patios, public areas, open parks, and government right of ways, because they did not feel safe in their houses, even though some of these houses had not collapsed. The damage in the houses could be noticed, especially on those over columns distributed without walls on the ground level. Many of these structures in the southern part of the island where the seismic fault has been most active (e.g. Ponce, Guanica, Yauco, Guayanilla, Lajas), totally collapsed. Many of the structures that did not collapse presented structural cracks with displacements that made their repairs very expensive and practically impossible to rebuild. As of the day of the publication of this article, seismic activity is still present. Seismic resistant requirements are mandatory and recent events make it more relevant. This article presents a detailed approach in relation to various codes, especially chapter 18 (earthquake resistant structures) of the ACI318-14 code.

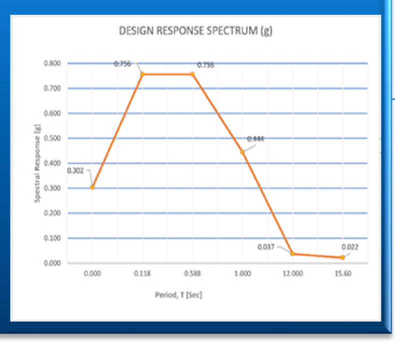
Original Construction Plan



Evaluation Procedure

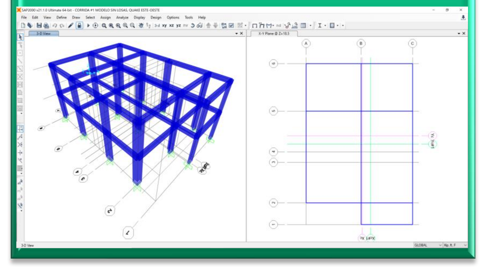
[1] Main Information and Design Response Spectrum

Using location site calculate factors and parameters given in ASCE7/16 sections 11 & 16. Calculate the weight, seismic base shear, seismic response Cs (ASCE7/1612.8-2) and compare it with the minimum 0.50 required by PR Building Code (PRBC2016, A.2.1)



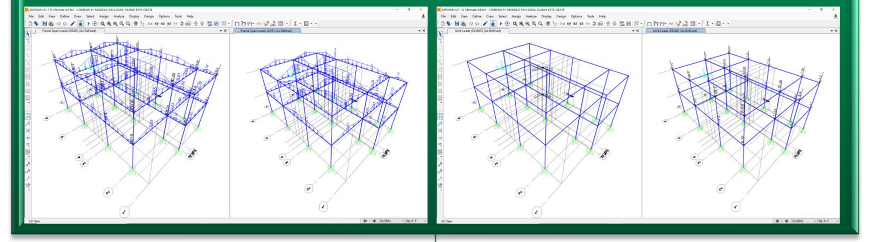
[2] Create Software Model

Using original plan measurements, open a new model in a computer software such as SAP2000 and define the grid, material properties and cross sections. Define the model as a Special Moment Resisting Frame.



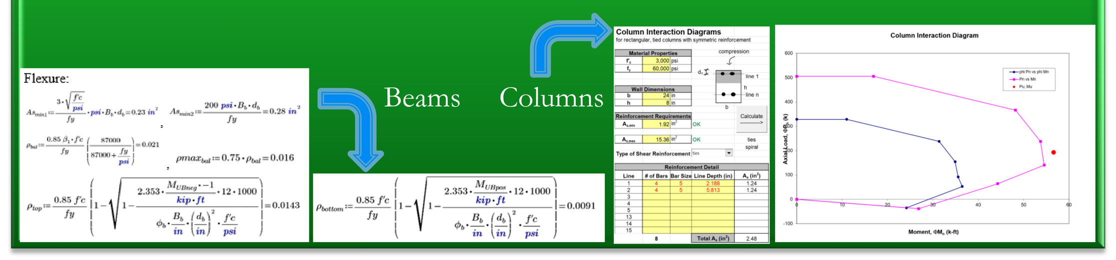
[3] Loads & Combinations

1. Calculate and distribute the beam's dead loads
2. Divide the structural slabs into tributary areas (per level/per beam)
3. Calculate and distribute the structural slabs dead loads over beams
4. Apply added dead load [20 psf] over tributary areas (per level/ per beam)
5. Apply live load [50 psf] over tributary areas (per level/per beams)
6. Calculate and distribute columns dead loads as an axial load
7. Apply static manual seismic load at 5% of the centroid
7. Define the load cases combinations based on ASCE7/16, C2.3-1



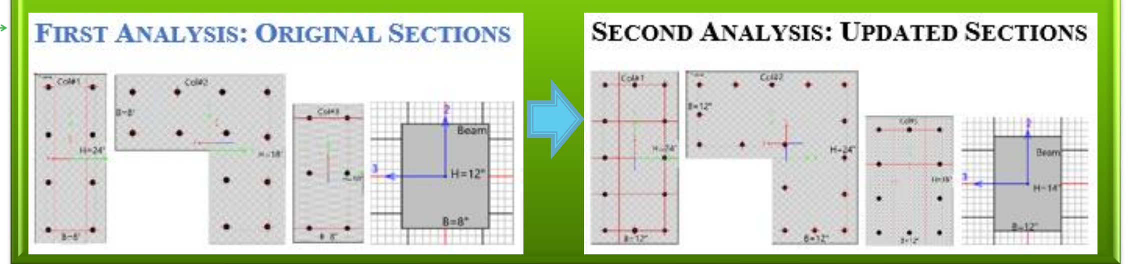
[4] First Analysis (Evaluation of Results versus Original Structural Sections Capacities)

1. The main purpose of this first analysis is to find the maximum moments, axial loads, and shears under the worst combination of factored loads in the two main directions (N-S & E-O).
2. Verify the results (demand) versus original cross sections (Capacity)
3. Verify "Strong Column – Weak Beam" (ACI318-1418.7.3.2)



[5] Update Elements Sections in Compliance With ACI318-14

1. The results of a structural design to build a two-story house in PR have been analyzed. Increase sections for full compliance of the requirements in chapter 18 of ACI318-14
2. Using the updated sections, redo steps [2] and [3]

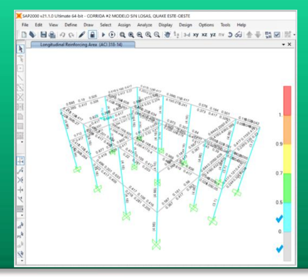


[6] Second Analysis (Evaluation of Results versus Updated Structural Sections Capacities)

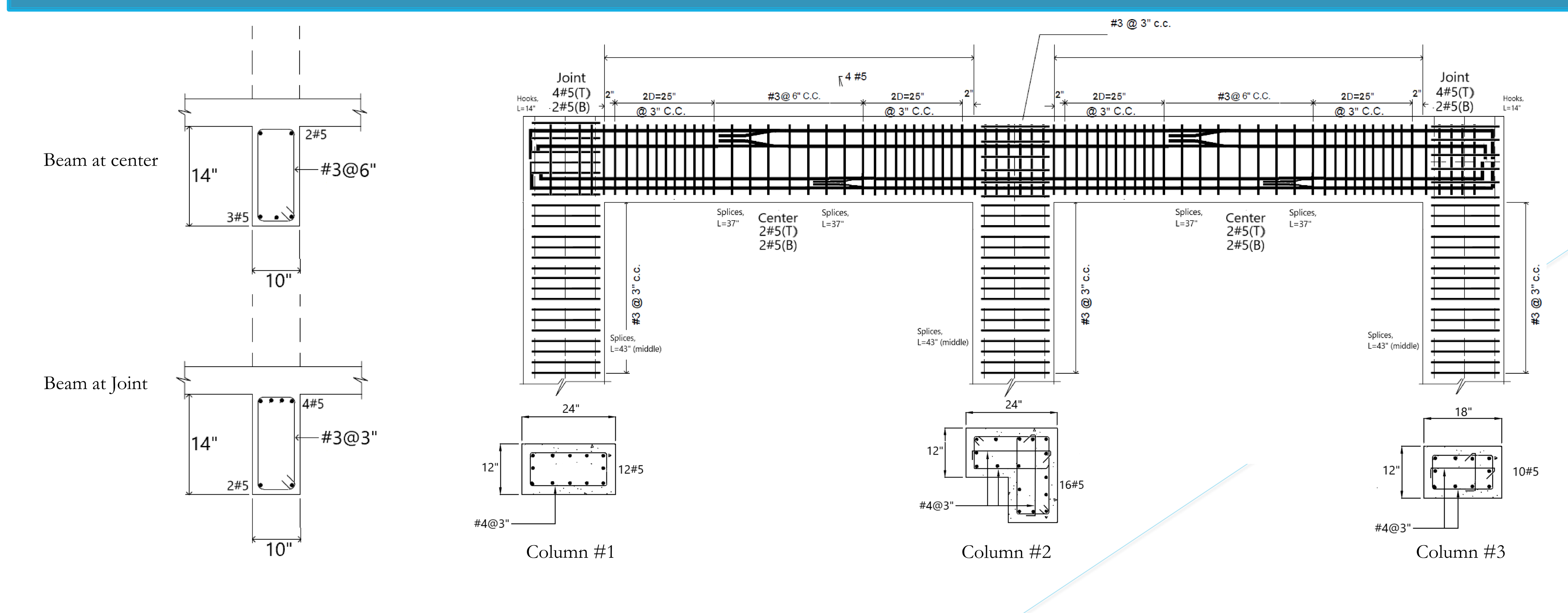
1. The main purpose of this second analysis is to find the maximum moments, axial loads, and shears under the worst combination of factored loads in the two main directions (N-S & E-O).
2. Verify the new results (demand) versus updated cross sections (Capacity)
3. Verify "Strong Column – Weak Beam" (ACI318-1418.7.3.2)
4. Check design of flexure/shear for beams and columns
5. Calculate reinforcement details such as length of development and splices

[7] Final Recommendations

Make recommendations conforming to the results and conclusions of the case study evaluation



Final Structural Details



Results and Conclusions

Hereinafter the conclusions to be applied in evaluations, analysis, and design similar to the case study presented:

1. This case study's redesign satisfies ACI318-14, 18.2.3 through 18.2.8 and 18.6 through 18.8
2. The original beam (8"x12") was increased to meet the minimum dimensions required in ACI318-14, 18.6.2.1. The final suggested dimension (10"x14") allows a greater effective depth. It is important to ensure from the beginning, that the effective depth, d>14". For a lower height it is necessary to consider the design as a T-beam.
3. The final suggested longitudinal reinforcement in beams is 4#5 top steel (negative moment) and 3#5 bottom steel (positive moment). Joints should have 2#5 bottom steel (50% of negative moment) and center of the beam 2#5 top steel (at least 25% of the maximum moment), ACI318-14, 18.6.3.2.
4. The final suggested transversal reinforcement in beams is #3@2" from the joint, #3@3" for a distance 2d=25" and #3@6" until the center.
5. The bases (widths) of all columns changed from 8 "to 12". It is important to ensure that this minimum width is met from the beginning, as established in section ACI318-14, 18.7.2.1.
6. The final suggested longitudinal reinforcement in columns is column #1-12#5, column #2-16#5 and column #3-10#5.
7. The final suggested transversal reinforcement in columns, is column #1-#4@3, columns #2&#3-#4@3" with 1 cross-tie#4 (both directions). First hoop shall be located 2" form the joint ACI318-14, 18.7.5
8. Lap splices of reinforcement are prohibited in beam-column joints. This condition is not allowed, ACI318-14, 18.6.3.3.
9. Final design (from the second run) complies with section ACI318-14, 18.7.3.2, better known as "strong column-weak beam", ΣMNC>1.2ΣMNB. About 50% of the original column's sections did not meet this capacity requirement in the first analysis, even on the first floor. The capacity in all elements shall ensure that the beams fail first, so the inertia of the columns is always greater (more rigid). Columns that do not meet this criteria on the top floor (due to no columns coming from the roof's structural slab), should be confined with the minimum tie spacing (in this case study 3") across the entire length of the column. In this case study, all columns have minimum spacing due to 6*DLong,bar, ACI318-14, 18.7.5.5.

Future Topics

This article emphasizes the earthquake resistant analysis/design, before construction begins. Some additional topics for the case of structures that are already built could be:

1. Evaluation, analysis and design of foundations for residential structures in compliance with the seismic resistant section code ACI318-14.
2. Carbon fibers application in beams and columns to achieve earthquake resistant compliance in existing two-level houses
3. Presentation of various real case studies to analyze, design and estimate repair costs of structural elements affected by seismic loads and compare with total demolition, design and new construction (best decision based on cost efficiency)

Acknowledgements

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