High Altitude Performance Center - Structures

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High Altitude Performance Center

Morgan Wilder

Advisors: Derek Swanson and Johnn Judd

Architectural Engineering

Spring 2017
For architectural engineering, the senior project was to follow the design process for structural engineers while designing a portion of the addition to the Rochelle Athletics Center. It was the responsibility of myself and two other students to provide our interpretation and solution to the structural challenges that the addition posed. My responsibilities on this project included collaborative work in positioning the columns and designing the beam and girder layout. Once a general design was determined, each member of our group was responsible for calculating loads and capacities of members. Throughout the entire project, we had a collaborative effort to design the building, seeing as three minds are better than one. However, I went beyond what was required for the project itself and used a structural analysis program to validate our pencil and paper solution we had come up with.
GENERAL NOTES:

ALL CONCRETE STRENGTHS SHALL BE A MINIMUM 3 KSI

EXTERIOR COLD-FORMED STEEL WALL STUDS SHALL BE 600S162-54 AT 16" O.C.

TRACK MEMBERS SHALL BE 600T125-54

THIS WILL ACCOMPLISH A DEFLECTION OF L/600

1. Building Code
   A. The governing building code for the Project will be 2012 IBC. The fundamental design criteria are anticipated to be as follows:
   1) 2012 International Building Code
   2) ASCE 7-10
   3) Laramie Building Code

2. Loading & Design Criteria
   A. Roof Snow Loads
      1) Design Roof Snow Load = 30 psf
      2) Flat roof Snow Load = 30 psf per local design requirement
      3) Snow Exposure Factor (Ce) = 1.00
      4) Importance Factor (I) = 1.00
      5) Thermal Factor (Ct) = 1.00
      6) Ground Snow Load (Pg) = 30 psf
      7) Rain or Snow Surcharge = 0.0 psf
      8) Sloped Roof Factor (Cs) = 1.00

   B. Wind Design Data:
      1) Basic Wind Speed = 115 mph
      2) Mean Roof Height = 30 ft
      3) Risk Category = II
      4) Exposure Category = C
      5) Enclosure Classification = Enclosed Building
      6) Internal Pressure Coeff. = +/-0.18
      7) Directionality (Kd) = 0.85
      8) Topographical Factor (Kzt) = 1.00
      9) Wind Pressure (q) = 29.9 psf

   C. Earthquake Design Data:
      1) Risk Category = II
      2) Importance Factor = 1.00
      3) Mapped Spectral Response Accelerations:
         a) Ss = 0.217 g
         b) S1 = 0.065 g
      4) Site Class = C
      5) Spectral Response Coefficient:
         a) Sds = 0.174 g
         b) Sd1 = 0.073 g
      6) Seismic Design Category = B
      7) Basic Structural System = Building Frame System
      8) Seismic Resisting System = Steel Ordinary Concentrically Brace Frame
      9) Design Base Shear V = 160 k
      10) Seismic Response Coefficient (Cs) = 0.054
      11) Response Modified Factor (R) = 3.0
      12) Analysis Procedure = Equivalent Lateral Force Analysis

3. Design Loads:
   1) Dead Load floors = 65 psf
   2) Dead Load roof = 30 psf
   3) Dead Load walls = 40 psf
      a) Wall dead calculated as average of window and stone weight
   4) Live Load at Elev. Floors = 80 psf
      - corridors above first floor (offices)
   5) Roof Live Load (snow) = 30 psf
   6) Mechanical Loads = Weight of equipment, but not less than 125 psf

65%
PLAN TITLE

FOUNDATION PLAN NOTES

ALL FOOTINGS AND COLUMNS ARE CENTERED ON GRIDS UNLESS DIMENSIONED OTHERWISE.

TOP OF EXTERIOR STRIP FOOTING = 100’

54” DEPTH

EXTERIOR FACADE RESTS ON FOUNDATION WALL.
BRACING IS INDICATED WITH A DASHED LINE OFFSET FROM THE GRIDLINES.

ALL ISOLATED FOUNDATIONS ARE CENTERED ON GRID.

ALL STRIP FOOTINGS AND FOUNDATION WALLS ARE CENTER LINE OFFSET 1’0” FROM GRID.

SLAB CONSTRUCTION
SLAB IS SLAB-ON-GRADE
SLAB THICKNESS = 10”

CONCRETE COVER IN PLACES EXPOSED TO WEATHER OR EARTH MUST BE A MINIMUM OF 2”
CONCRETE COVER IN PLACES NOT EXPOSED TO WEATHER OR EARTH MUST BE A MINIMUM OF 1”

COLUMNS
ALL COLUMNS ARE W12x40 U.N.O

FOUNDATION SCHEDULE

KEY

DIMENSIONS

FW 30
36” x 36” x 54”

FW 35
42” x 42” x 54”

FW 40
48” x 48” x 54”

FW 50
60” x 60” x 54”

FW 55
66” x 66” x 54”

F 30
36” x 36” x 16”

F 35
42” x 42” x 16”

F 40
48” x 48” x 16”

F 45
54” x 54” x 16”

F 50
60” x 60” x 16”

F 55
66” x 66” x 16”

F 60
72” x 72” x 16”

F 70
84” x 84” x 16”
The floor decking is 1.5VLR19 with a 4.5" total slab depth. Girders along B2-3, B3-5, B5-7, B7-10 and B10-11 are dropped down from steel elevation by 14 inches to accommodate W14s above them to form the canilevered sections.

Elevation from tops:
1. Finished floor elevation: 115' 0"
2. Dropped girder elevation: 113' 5.5"

Bracing is indicated with a dashed line offset from the gridline. Braces are HSS 6x6x1/4 W shape - x" = camber.

Structural first floor notes:
This is more typical slab edge condition if it is away from a column.
ALL CALCULATIONS ARE ASD
ALL COLUMNS ARE ON GRIDLINES UNLESS OTHERWISE NOTED
BRACING IS INDICATED WITH A DASHED LINE OFFSET FROM THE GRID LINE.
BRACES ARE HSS 6x6x1/4
ROOF CONSTRUCTION
DECKING IS 1.5B20
DECK IS SUPPORTED DIRECTLY BY STEEL UNLESS OTHERWISE NOTED
FOR FINISHED ROOF ELEVATIONS, SEE ARCHITECTURAL DRAWINGS
OTHER ELEVATIONS:
- FINISHED DECKING ELEVATION - 129' 3"
- ROOPED GIRDER ELEVATION - 127' 10"
1.0 Introduction

The University of Wyoming has construction projects going continuously. As part of the architectural engineering department at the university, senior students are required to design a building as part of a Capstone project. This year, our professor, Derek Swanson, recently finished the design process for an addition to the High-Altitude Performance Center in Laramie, Wyoming. Therefore, our senior design capstone project was following the design process of a practicing engineer of the area.

Throughout the project, we had to take into consideration local design codes and guidelines. The design process we followed was based on individual members while utilizing design aids such as the AISC Steel Construction Manual, Vulcraft Joist Catalog, and Vulcraft Deck Catalog. Basing our design on the available design guides was conservative because we considered individual members under simply supported conditions, rather than the interconnected nature of a building as a whole. Early in the design process, Derek mentioned that our designs would likely include members of much larger sizes than what were actually used for construction. We were able to see this during site visits where we were able to compare our designs to what is currently being built on site.

The comparison between what we had designed and what I was seeing implemented in the building was fascinating, and I wondered what would cause such a reduction in the sizes of members. The spacing of members is similar to what we designed; however, the member sizes being utilized in the building are far smaller than what we had come up with. Therefore, I decided to look into what was causing this reduction in size and decided to do two additional
types analyses that are far more rigorous than the simply supported beam assumptions we were utilizing during our design for capstone.

2.0 Analysis Methods

Due to the sense of how conservative our design in capstone was, I decided to do an analysis of the building as a whole. I utilized two different methods to analyze the building we had designed. A Julia file was implemented to determine how the geometry of the structure as a whole influences the deflections under construction level loading. Due to the limitations of the Julia software, specific applications of SAP2000 were implemented to compare the structures as accurately as possible. Construction level deflections were utilized as a basis of comparison between the three analysis methods.

2.1 Julia Software

The first method was to design the building in a software program developed by Dr. Judd for advanced structural analysis that determines the deflections and member forces based on matrix algebra. To assist with the matrix algebra, the software was programmed as a Julia script which takes into account member characteristics, such as strength and orientation. Therefore, I had to specify member sections, node locations, and how they were connected through the use of coding. Beyond the geometry alone, I had to determine the loads on individual members according to construction level loadings.

The analysis was performed based on a linear analysis and does not take into account hinging action, specialized joints and how they affect the frames as a whole, or second order effects caused by geometric changes in the structure. However, the program does take into consideration how the members interact with one another, rather than everything being
considered simply support and “individual” members. This analysis helps gain an understanding of how the members of the structure off of one another and the effect the overall deflections.

There are a few limitations of this analysis method in terms of analyzing the design. All connections are considered rigid which would not be the case due to construction and cost limitations. Other limitations are due to how the program is written. All members are designed based on center line design and do not take into account the heights of steel and where the true center lines would be based on different sizing of members. Due to the complexity of the geometry, not all members in the structure could be designed accurately. This limitation resulted in a decision to focus on critical areas of the structure, such as cantilever beams and the longest spans of the floor and roof respectively. Additional members can be introduced into the file by updating the geometry accordingly. To define the geometry and materials of the model 40 pages of coding were required. Julia is only able to produce a visual model of the geometry after other aspects have been defined. The resulting 3D model is displayed in Figure 1.
These are minor limitations versus the limitation of not being able to consider composite action that was utilized in design. Each member could have been designed for composite action based on the composite moment of inertia; however, this requires a specialized moment of inertia calculation for quite a few members. Therefore, the analysis performed using the Julia file was designed to focus on the construction loads of the building with each tributary area load being converted into a line load along the member. Girder loads were designed according to whether or not secondary beams were connected to them or not as to not compound the loading.

**2.2 SAP2000 Analysis**

SAP2000 is a structural analysis program that is far more complex than the simple programs utilized in the advanced structural analysis class. The limitations of the program are limited and in many cases, did not apply to what I was utilizing it to do. SAP2000 takes far more into account than the Julia file utilized; therefore, I had to limit which analyses SAP2000 went through in determining the deflections of the members. A few limitations I had to impose on the
SAP2000 analysis were ensuring no self-weight was considered, no shear deflections were considered and ensuring the program focused on center-line analysis. A display of adjustment factors is shown in Figure 2. Additionally, SAP2000 is capable of analyzing second order effects and resulted in a nonlinear analysis.

I attempted to determine how the composite action between the concrete deck and steel members influences the deflection of members. Unlike Julia, SAP2000 has the capability of analyzing shell structures. To account for composite action, I designed a shell structure on the floor and roof in an attempt to simulate the composite action our capstone design had relied upon. The connection of a floor system to the framing system proved more challenging than I had anticipated.

After many iterations of designs that were not accounting for composite action, I noticed a reoccurring theme. Shell systems that I was implementing were only attaching themselves to specific members on the perimeter of the shell area. Therefore, these connecting members would take the majority of the distributed shell load and deflect wildly while the remaining members would only deflect slightly. Researching the issue resulted in the conclusion that there is no
simple way to design for composite action between a flooring system and the framing members. Therefore, I changed my design to account for what I had seen in previous iterations in the hope to simulate the composite action. The resulting changes are displayed in Figure 3.

To account for composite action, I utilized the trends I was noticing from earlier iterations and analyses. The solution I came up with involved the connection of two adjacent member to an area. Each area was defined as a shell and are shown as dashed rectangles in Figure 3. Having the areas connect two adjacent members allowed the constrained/connected edge condition I was trying to design. The edge conditions of the areas created act as the composite action due to having to deflect with adjacent members rather than edge members alone. The finer I made the mesh, the more realistic the overall deflections and deflected shape appeared. Two separate shell sections were defined.
The roof consisted of a thin shell of 3 inches which accommodates the decking, rigid insulation and roofing material that would be utilized in the building. This is not a truly accurate description of the roof shell considering it was designed as a thin concrete shell rather than the materials that would be utilized in construction. Therefore, roof deflections indicated are slightly lower than what would be anticipated in practice. On the other hand, the floor shell was defined as a thick shell with a depth of 6 inches. Both shells are thicker than what were designed for in capstone due to issues when running the analysis in SAP2000. When utilizing shells of similar dimensions to what was designed for in capstone, resulting deflections were drastically higher than what is expected. I do not know enough about SAP2000 to explain this issue, but the adjustments I implemented were similar enough to the actual design and capable of eliminating the drastic deflections seen in previous analyses. Each defined shell type can be seen in Figure 4.

Figure 4. Decking and Roof shells

2.3 Constants in Analysis

While each analysis method is adequate on its own to construct a building, each has its advantages. The most conservative method is pencil and paper design of each element. Julia design is slightly more rigorous and results in smaller deflections due to member interaction. The most robust analysis method, SAP2000 results in the lowest deflections but requires a better understanding of the materials and how they are connected. Each method results in a building
that will be safe; however, due to the differences in programming, and what each analysis method includes, limitations had to be imposed on each for an accurate comparison.

The pencil and paper method resulted in the least complex design and had specific deflections determined. These deflections were limited based on design codes and are the basis of comparison for the other two analysis methods. Due to the limitations of pencil and paper analysis, each method had to be limited in order to compare apples to apples.

While an actual building would not have supports with all 6 degrees of freedom restrained, I designed both computer based models with all 6 degrees of freedom restrained. All designs utilized the same member sizing with the exception of the joists in Julia. Due to not having the correct member characteristics of the joists utilized, equivalent W shapes were utilized based on allowable loads and deflections. SAP2000 was capable of designing the joists utilized in design. The geometry in all designs was as similar as possible; however, due to the complexities of Julia coding, members were eliminated and certain members were focused on. In both SAP2000 and Julia, nodes were placed at critical points for comparison to the original design and each other. Overall, the geometry, member selection, and constraints were kept as constant as possible so that the only differences resulted from the analysis methods alone.

3.0 Expectations

Each design has different considerations that were employed. Therefore, each design should have different, yet similar results. Going into the project, I anticipated that deflections would decrease as the complexity of the analysis increased. I expected Julia to obtain lower deflections than what was calculated based on member sizing alone. I also expected that Julia would overestimate the service deflections due to only considering the beams and how they interact rather than the decking. Due to how rigorous of an analysis SAP2000 can perform, I
anticipated the deflections resulting from the SAP2000 model would be marginally below what I found with the Julia analysis; in the realm of 70-85% of the calculated deflections using Julia. The deflections should not be drastically lower due to taking multiple iterations based on updated geometry rather than a single iteration in the linear program.

4.0 Conclusions

Overall, the designs turned out as I had anticipated. The deflections came out as I had anticipated. Julia resulted in a reduced deflection due to the ability of members to interact with one another and the rigid connections. SAP2000 analysis resulted in the lowest deflections due to the composite action being taken into account. The different analysis approaches each have their limitations and it is difficult to truly model exactly what will happen in the field but we can do our best to come as close as possible.

The linear analysis in Julia was the most difficult analysis method. Special care has to be taken when defining the geometry due to having no visual representation of the building until the end. I also had issues with singularity issues in the matrix algebra of my first file. In other words, it is easy to make an error and have elements not connected where you anticipated them being. Also, the nodes and orientations of members cannot easily be modeled due to having to define each member individually. Another complication of defining the members and elements is the design is prone to error with typing of individual members with how long a file can get for a complex building. Defining nodes for secondary beams adds additional places where errors can be made.

Determining the specific output you want from Julia is also relatively easy; however, specific nodes and members must be looked at individually or put into groupings such as I have done. (Figure 6.)
The deflection model is not representative of the deflections due to having to adjust the magnitude of the deflection to get an accurate representation of the overall geometric change. If the magnitude is set to one, the deflections are not easily shown when the deformed and undeformed model are plotted together. When the magnitude of deflection is set to 1, the deflections are easier to see in the interactive diagram; however, not as easy as in SAP2000. An accurate deflection diagram required 20 magnification and is shown in Figure 7.

Figure 6. Combined output of cantilever tip displacements from west to east.

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While Julia is user driven, and it is easier to know exactly what you are analyzing, SAP2000 can be considered easier to use in analysis. The complications with SAP2000 occur due to how complex of a program it actually is. SAP2000 can analyze a wide range of structures and a wide range of conditions simultaneously. Therefore, special care has to be taken in order to limit what it is taking into consideration during the design process. Sometimes limiting the program is not as simple as one might expect and it actually becomes harder to analyze a specific portion of the design. Even with the wide range of capabilities of SAP2000, it too has its limitations.

The largest limitation of SAP2000 I noticed was the user. For example, I know there should be ways to connect two nodal displacements degrees of freedom together; however, I could not figure them out and had to connect the nodes together with a very stiff member to try and accomplish the same thing. Parameters for this member are shown in Figure 8.
Figure 8. Parameters for connecting member to simulate constrained nodal displacements

The program is complex enough that it is difficult to know exactly what it is doing without having formal training on the program and additional experience to verify the outputs it is presenting. Some errors are easy to notice, whereas others may be due to a lack of understanding of how the program is performing the analysis, what was actually modeled, and what type of analysis was being performed. An example of an easy to spot error is shown in Figure 9 where a column base was not restrained properly. Therefore, it is a great resource the more you get to know how to utilize it; however, results obtained from SAP2000 analysis should be verified with another analysis method to determine if the results are feasible.
Throughout this project, I learned the limitations and difficulties associated with various analysis methods. Each analysis method I performed has its advantages and weaknesses. Julia is easier to pinpoint the effects of what is being analyzed but more difficult to model complexities that occur in a real building. Specific outputs of Julia are easier to obtain; however, SAP2000 is capable of showing a larger variation of output displays, such as the moment distribution displayed in Figure 10. SAP2000 is great at handling many complexities involved in the design process; however, it can be difficult for a newer user to truly understand how to model what they are wanting accurately, as well as determining exactly what analysis method is being used. It is also easier to adjust specific parameters of the design, such as load combinations, rather than having to redesign all individual members in Julia to accommodate the change in load.
combination. As the analysis method becomes more complex, the overall design can be honed and perfected to reduce costs and overall costs.

Figure 10. Moment distribution in SAP2000 model

5.0 Output differences *(Julia followed by SAP2000)*

Deflected Shapes
Personally, the geometry of SAP is better due to seeing the extruded shapes and how all members deflect rather than how their centerlines displace.

Node Displacements
While both programs have a good way of displaying nodal displacements and rotations, SAP2000 is easier to see both the deflected shape and how it corresponds to the structure as opposed to just an individual point. Julia allows for the structure but the graphing program warps the building by forcing a specific scale.

Additional bonus SAP displays.

SAP is capable of displaying the results in a multitude of ways. For instance, it can display the displacements of the entire structure (1), the moments running through the members so you can see issues, such as the column missing in (2) and the moment distribution in the members (3) in visual format rather than numbers at specific locations like Julia is capable of.

(1)