OFFICE BUILDING-G

Eastern United States

Thesis Proposal

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Structural Option

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Executive Summary

The purpose of this Thesis Proposal is to outline the work that will be performed to satisfy the required coursework of the Architectural Engineering Senior Capstone Project. This report provides a necessary amount of information to familiarize the reader with the existing structural system of Office Building-G. A problem with the current structural design is then identified and the context of the problem is explained. A proposed structural redesign is introduced along with breadth studies on the effect the solution will have on the design and construction of Office Building-G.

The internal shear walls and perimeter columns of Office Building-G are critical members to the existing structure. However, these elements reduce the amount of rentable space and restrict the designs for the tenant fit outs. Removing these structural components would resolve this problem but it would require an entirely new structural system. An external diagrid structure is proposed as a solution which is capable of resisting the forces which had previously been resisted by the shear wall core and perimeter columns.

Diagrid structures use a system of external, interconnected diagonal members and horizontal rings, typically designed with steel. The members form a rigid shell around the building perimeter, capable of resisting both gravity and lateral loads. Diagrids have recently gained popularity in application to buildings with height to width ration between 4:1 and 9:1. If Office Building-G's 1:1 ratio is a cause for an inefficient structure, alternative applications of diagrid theory will be studied.

Introducing an external structure to a building has a large impact on the façade aesthetics and construction of Office Building-G. Breadth studies will be performed to determine the extent of the diagrid effects. These topics will be considered in the final comparison between the existing structure and the proposed alternative.

This report gives a complete description of the tasks which need to be performed and outlines the order in which they must be performed. A tentative schedule has been created which summarizes the time allotted to the given tasks in order to complete the project in a timely matter.

Introduction

Due to owner restrictions, the building name, location and tenant of Office Building-G cannot be disclosed. Neighboring an existing metro station, this 14 story building will become one the tallest of the modest skyline. Beneath the superstructure is a below grade, 4-story parking garage with space for 662 cars. On the first two floors of the building, a larger floor plan is used to accommodate for rentable space for retail, a restaurant, a bank and a loading dock. Typical floors have a square footage of 25,376 sf with a floor to floor height of 12'-3". The roof of the mechanical penthouse is 195 ft above grade and the gross square footage of the superstructure and garage combined is 649,461 sf. Figure 1 is a rendering of Office Building-G.

Figure 1

Gravity System

Gravity loads are carried down the building through a combination of interior and perimeter concrete columns and a shear wall core. The typical floor system is a cast-in-place concrete one-way slab. Thickness changes based on loading conditions but the typical floor is a 7", 5000 psi normal weight concrete slab. On the first floor, there is a 12" concrete slab designed for fire separation between the parking garage and superstructure. The slab system carries the loads to post-tensioned concrete beams with spans between 41’-5” and 45’-1 1/4”.

The post tensioned beams range in width from 18” to 48” and have a maximum depth of 24”. In Office Building-G, the typical girder is 18” deep by 48” wide. These beams collect the floor loads from the slab and distribute their reactions to the columns supporting them.

Rectangular and round concrete columns then transfer the loads down the strictly followed grid. Typical floors have columns sizes of 24” x 24”, 24” x 30”, and 30” diameter. Smaller columns are used in the mechanical penthouse due to the much lower loads they are carrying. On above grade floors, higher strength concrete is placed below columns and shear walls in the slab to accommodate for any possibility of punching shear. In the parking garage, 8” drop panels are used instead of the different concrete strengths. The typical floor plan, shown in Figure 2 below, highlights the post-tensioned beams in yellow, the reinforced beams in purple, shear walls in green and blue, and the columns in red.

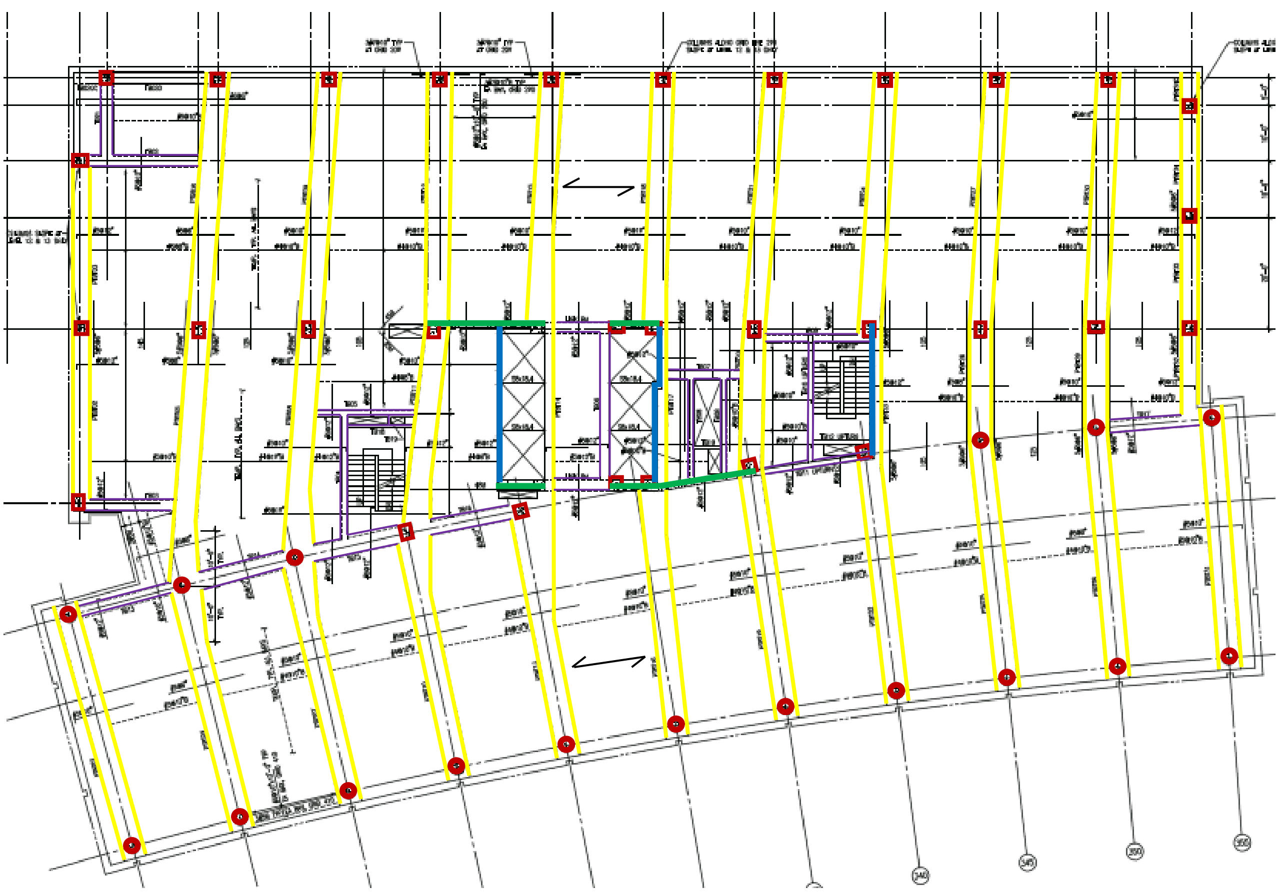


Figure 2

Lateral System:

Wind and seismic forces are resisted by an internal shear wall core. The core is made of reinforced concrete walls which have a consistent floor plan from the bottom floor of the parking garage up to the slab of the roof. Basement shear walls were designed with f'c = 10,000 psi, levels 1-4 use f'c = 8,000 psi, and levels 5-14 use f'c = 5,000 psi. Precast concrete beams attached to concrete columns using precast lateral connections provide the required resistance for the mechanical penthouse and elevator machine room.

Lateral forces are engaged by the shear walls through the use of floor diaphragms. The building façade collects wind forces that are then transferred to the respective floor diaphragm. Forces then travel through the diaphragm until the shear walls are engaged, at which point the forces are distributed based on the relative stiffness of the walls.

Foundation System:

The geotechnical engineering on the project performed a geotechnical study for the location of Office Building-G which determined the possible foundation systems as spread footings, caissons or geopiers. The structural engineers decided to use a system of spread footings under the columns, shear walls and along the perimeter concrete bearing wall. Square footage and depth of the footings are based on the load carrying capability of the soil and the vertical load on the column.

Service loads on the columns ranged greatly depending on whether or not the column extended up into the superstructure of the building. Based on the structure above the foundation, the load capacity of soil was determined to support a range of 3,000 psf to 10,000 psf. Loads on the footings varied between 60 kips to 3075 kips, once again depending on which part of Office Building-G they are supporting.

Problem Statement

Office Building-G currently relies on reinforced concrete members to resist the vertical and horizontal forces applied to the building. An internal shear wall core is responsible for resisting all of the lateral forces applied to the building and columns along with the shear walls resist the gravity forces the building experiences. Gravity loads are distributed to the columns and shear walls through the use of post-tensioned girders giving the building a structural depth of 18".

Office Building-G consists of 14 stories of rentable office space. An increase in rentable floor space would offer the owner an opportunity to see larger profits. If the majority of the columns were removed, the open floor plan would be appealing to potential tenants, also resulting in additional profits for the owner. The goal of this thesis is to maximize the profits available to Office Building-G through the removal of the internal shear wall core, all perimeter columns and as many interior columns as possible.

Proposed Solution

The application of an external diagrid structure to Office Building-G will allow for the removal of the columns and shear walls, resulting in a greater square footage of rentable space. Additionally, an external structure will allow the open floor plan to be more flexible for tenant fit outs. An external diagrid structure will be designed to resist the all of the lateral loads as well as any necessary gravity loads. The feasibility of keeping the existing structural depth of 18" through the evaluation of different floor systems will also be considered. The proposed solution is a complete redesign of the existing structural system by implementing an external diagrid structure.

Introduction

The term diagrid is a portmanteau of 'diagonal grid' and is a technique typically used for constructing large steel buildings by creating external triangular structures with horizontal support rings. The diagonal members intersect each other and the horizontal rings at a single node. The members combine to create an element similar to a moment frame. In a diagrid structure, gravity and lateral loads are resisted by all of the members, creating efficiency and large amounts of structural redundancy. A diagrid structure effectively creates a rigid shell which can be thought of as a very thin, deep beam. Figure 3 is a picture of the Hearst Magazine Tower which is an example of a diagrid structure.

Figure 3

Lateral loads are introduced directly into a diagrid structure and immediately transferred into the system of triangulated elements. This means that a diagrid does not rely on the floor system to transfer any of the lateral forces to the other parts of the structure. In fact, the core and floor system of a typical office building has little effect on a diagrid. A typical connection between a floor system and a diagrid shell is very minimal and is designed to only transfer gravity loads.

The horizontal rings of a diagrid provide much needed buckling bracing to the diagonal members. The rings tie all of the pieces together and create one solid tube. A network of interconnected nodes is formed which gives the triangulated elements another degree of stiffness.

Diagrids are designed in configurations which use every member's full ability to resist compression and tension. Due to this reason, most diagrids have been constructed out of steel but other materials can be used. Buildings which have used steel diagrids have saved an average of 20% in materials when compared to a typical moment frame design.

Design

Due to the common application of diagrids to tall buildings, design is typically based off of stiffness and deflection, the limiting criteria of most tall building designs. Stiffness based design differs from the conventional design which is primarily based on the strength of the members. Stiffness is dependent on the structures optimal deformation mode, which is based on the height-to-width aspect ratio and grid geometry of the structure.

Due to the varying shear and moment forces acting on the different stories, diagrid structures are designed in modules of 4-6 floors. Preliminary design equations used to determine the required web and flange area of steel needed are respectively shown below. Table 1 below outlines the meaning of the variables.

$$A_w = \frac{\mathrm{V L}_d}{2\mathrm{N}_{dw}\mathrm{E}_d \mathrm{h}\gamma\cos^2\theta} \qquad A_f = \frac{2\mathrm{M L}_d}{(\mathrm{N}_{df}+\delta)\mathrm{B}^2\mathrm{E}_d\chi \mathrm{h}\sin^2\theta}$$

Variables	
A_w	Area of Each Diagonal Web
A_f	Area of Each Diagonal Flange
V	Shear Force
M	Moment
L_d	Length of Diagonal
E_d	Modulus of Elasticity of Steel
ϴ	Angle of Diagonal Member
γ	Transverse Shear Strain
χ	Curvature
N_w	Number of Diagonals on Each Web Plane
N_f	Number of Diagonals on Each Flange Plane
δ	Contribution of Web Diagonals for Bending Rigidity
B	Building Width in Direction of Applied Force

Table 1

Design begins with determining the desired bending and shear deformation of the structure. The total of these two displacements is limited by the serviceability requirement determined by the design engineer. Based on the story shear and stain in members, the desired uniform transverse shear strain and the desired uniform curvature can be determined. Due to the larger bending forces on the lower floors of the building, the most efficient diagrid designs allow bending deformation to control approximately the bottom half of structure and permit shear deformation to control the top half.

The design method described above was created for “tall” buildings. Typical aspect ratios, height to base, of these buildings are between 4:1 and 9:1. The North/South and East/West aspect ratios of Office Building-G are 0.95:1 and 1.34:1 respectively. The taller the building is, the more dependent the design of the structure becomes on the serviceability requirements produced by the effects of wind. Office Building-G is much shorter than buildings which have typically applied diagrid structures and thus has much smaller wind loads. This could result in the conclusion that a complete tubular diagrid structure is not necessary.

Studies based on number of stories and aspect ratios have determined the most efficient angles of diagonal members. A general trend of these studies has shown that as the number of stories decreases, the angle of the diagonal from the vertical also decreases. Since Office Building-G has 14 stories, the most efficient angle of the diagonals may be very shallow. A drastic change in the angle of the diagonals could cause and inefficient diagrid design.

A possible solution to an inefficient design is applying 2-dimensional localized diagrid elements to strategic parts of the structure. This steps away from the typical tubular diagrid structure by creating a system of interconnected, vertically cantilevered truss-like members. Localized diagrid elements would be equally efficient at resisting applied forces but due to the lack of lateral forces transferred by the floor diaphragm, these elements would be acting as stand-alone structures.

Differing from the rigid shell of a diagrid, the system of diagrid towers would not completely surround the exterior of the building. This would allow the building façade to collect wind forces and distribute them to the corresponding story levels. This creates a scenario which is not addressed in typical diagrid design. If this solution is explored, a method of distributing the story lateral loads to the diagrids or a configuration which does not allow for the lateral loads to ever enter the floor diaphragm must be created.

This proposal requires the redesign of Office Building-G's gravity and lateral system. It is suggesting the removal of the interior shear wall core and as many of the columns as possible. The existing structural system will be replaced by an external steel diagrid. Based on these changes, a new floor system will need to be designed based on the materials used and distribution of gravity loads.

Changes to Office Building-G will require a new ETABS model to determine the structural efficiency of the designed structure. Multiple models will be created to investigate possible geometries of the structure. The models will also be used to conclude on the overall efficiency of the designs and the feasibility of the solutions discussed.

Breadth Topics

Elements of Office Building-G's design other than the structural system are greatly affected by the diagrid. Two breadth study topics were chosen based on the other aspects of the building design which would be directly altered if the proposed solution was going to be implemented into an actual building.

Architectural

Implementing an external structure to the existing façade of Office Building-G will greatly change the appearance of the building. Although the geometry of the diagrid system will depend on the structural efficiency of the members, aesthetics will be considered in the finishing placed on the structure and the glazing between the members. Renderings of Office Building-G displaying the proposed final façade will be created to show difference from the original design. Examples of the different façade options available through the manipulation of external structures will also be provided.

Architectural changes are not limited to the exterior of the building. Minor but significant changes to the typical floor plan of Office Building-G will result from an external diagrid structure. The columns and shear wall core do not take up a large amount of square footage of the floor but the appeal of an open floor plan and additional rentable square footage offer the owner an opportunity to charge a larger cost per square foot. The potential gain in income will be analyzed as part of this breadth study.

Construction

Office Building-G is currently constructed out of reinforced concrete. A steel diagrid will cause a drastic change in the necessary construction methods used. As part of the construction breadth study, a cost analysis will be performed to compare the original structure price to the proposed solution. The cost of materials, labor, and the construction timeline will be considered in the analysis of the structures.

In diagrid structures, the very critical node which connects the triangulated members to the horizontal ring has historically been a very complex and time consuming process during construction. This breadth will investigate possible node connections which will simplify the construction process. Prefabrication of the nodal elements will also be considered.

MAE Requirements

MAE requirements of the thesis proposal will be met through the creation and analysis of ETABS computer models. The coursework taught in AE 597A provide the necessary knowledge to create a computer model. Results of the computer model will be used to evaluate the building under lateral and gravity loads. As part of the construction breadth, the nodal connection will be designed and analyzed using the methods taught in AE 534.

Solution Method

The redesign of Office Building-G will be performed using the following codes and resources: IBC 2006, ASCE 7-10, AISC Design Guides, diagrid research papers and design guides, metal deck catalogs, ETABS, and Revit Architecture. The alternative floor system will be designed with the aid Metal Deck Catalogs, AISC design guides, and diagrid floor design guides. The lateral system and the majority of the gravity system will be designed with the aid of diagrid design guides and ETABS. Based on the results of the ETABS analysis, additional models may need to be created to determine alternative, more efficient designs. The additional models will be used to investigate the feasibility of a network of independent diagrid elements. Throughout the redesign process, construction implications will be a factor considered, influencing the selection of the final design. Once a final design is chosen a Revit Architecture model will be created to demonstrate the change to the building façade.

Tasks

1. Determine Loads
a. Determine wind loads based on steel structure
b. Calculate seismic loads with an estimation of new floor loads
c. Estimate weight of diagrid structure
d. Determine controlling load cases

2. Design Floor System
a. Research long span decking and alternative floor systems
b. Determine necessity for interior gravity columns
c. Consider systems capable of distributing lateral loads to structure
d. Choose system based on cost, structural depth, span length and columns needed

3. Analyze Traditional Diagrid Geometries
a. Estimate diagonal member sizes using diagrid design guides based on stiffness
b. Create ETABS model
c. Alter geometries with angle of diagonals and size of modules
d. Choose best design based on member efficiency

4. Consider Alternative Diagrid Uses
a. Alter ETABS model to have individual diagrid elements and load distributing floor
b. Determine most efficient geometry for given loads
c. Compare to traditional designs based on steel tonnage and construction difficulty

5. Choose Final Design
a. Perform cost analysis of designs
b. Consider impact of design on entire building

6. Render Architectural Images
a. Create Revit Architectural model based off of original Revit model
b. Insert the diagrid elements on façade
c. Render images to show departure from original design

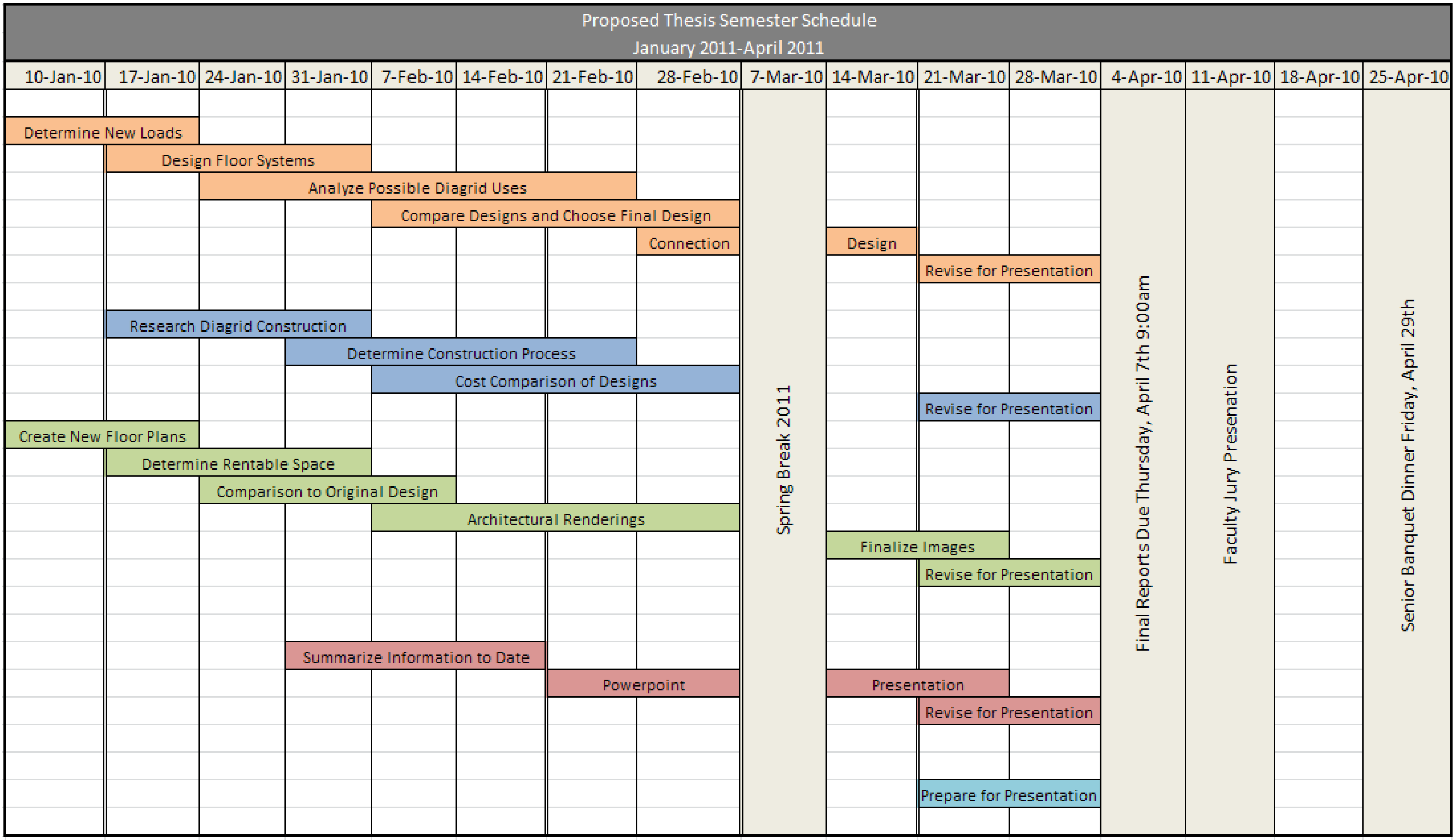
7. Analyze Connections

a. Design typical connection between diagonal and horizontal elements
b. Design connection between floor and diagrid
c. Create connection designs based on constructability
d. Determine the benefits of prefabrication versus field construction

8. Final Presentation Preparation

a. Organize, format and finalize presentation
b. Prepare for final presentation

Schedule



Milestone:	January 10th 2010:	DETERMINE LOADS		Analysis 1: Structural Redesign
Milestone:	February 14th 2010:	DESIGN FLOOR SYSTEMS, ANALYZE POSSIBLE DIAGRID USES		Analysis 2: Construction Breadth
Milestone:	March 7th 2010:	RENDER ARCHITECTURAL IMAGES		Analysis 3: Architectural Breadth
Milestone:	March 28th 2010:	CONTENT COMPLETE AND READY FOR FORMATTING		Analysis 4: Final Presentation