Major Qualifying Project
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Abstract

The Major Qualifying Project proposed a preliminary design of the steel structure and concrete footings at an oil refinery facility in Newfoundland, Canada. It was then evaluated by the project design team according to economic, infrastructural, environmental, and effectiveness constraints specific to the facility. Finally, a complete cooler foundation design was developed in STAAD Pro software, and design requirements and appropriate modeling materials for the cooler foundation were determined.

Acknowledgements

I would like to express my deepest appreciation to Professor LePage and Professor Hart for all their help throughout this project. I would also like to acknowledge my special gratitude to the staff of Stantec Inc. in Dartmouth, Nova Scotia. Jean Pielzinski, Brian Snow, and Peter Chapman helped to coordinate my project throughout the seven weeks, and gave the permission to use all required equipment materials to complete this MQP report. Thanks to other Stantec employees for being very welcoming and cooperative.

Capstone Design

The Accreditation Board for Engineering and Technology (ABET) requires that all accredited engineering programs include a capstone design experience. This requirement is met at WPI through the Major Qualifying Project (MQP). The following report considered 5 constraints relevant to the project. They are as follows:

- Economic – the cost of the project was be evaluated, including capital investment for technology and maintenance costs.
- Constructability – the project is feasible when produced with as few resources possible, including parts, labor, and maintenance. Project was examined by a number of interdependent project-related factors, including effectiveness of the foundation and the extent to which the design of the building facilitates ease of construction.
- Environmental – the foundation design considered important environmental aspects, including pollution, health and safety, and sustainability, to ensure that impacts and mitigation of the compressor project are minimized.
- Health and Safety – this project attended to the health and safety of both workers and visitors to the facility. It was designed to satisfy requirements of National Building Code of Canada.
- Ethical – this project was developed to comply with the principles of sustainable development and code of ethics of American Society of Civil Engineers. No conflicts of interest were created with either project sponsor or client.

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Chapter 1: Introduction

An oil refinery facility is designed to split crude oil into several components, which then are reprocessed into final products, such as gasoline, diesel fuel, petroleum solvents and lubricating oils. Oil refinery facilities include many process units, including storage tanks, furnaces, distillation towers, reactors, air and water cooled heat exchangers, and compressors. Oil refinery facilities require cooling systems to lower the temperature of liquid products to permit safe handling. Liquid products include, but are not limited to, oils used in the compressor, phenols, and glycol.

Stantec is an international professional services company in the design and consulting industry that provides professional consulting services in planning, engineering, architecture, interior design, environmental sciences, and many other sustainable community design aspects. It is seeking to develop design recommendations for an oil refinery compressor foundation in Newfoundland, Canada.

To support Stantec in attaining this goal, this Major Qualifying Project focused on developing a steel and concrete foundations design for the new cooler system. A cooler foundation design was developed for the cooler system, accounting for size and weight of the cooler to be installed. Steel frame loads and design specifications were determined with STAAD Pro software. Concrete footing size and shape were calculated using the load distribution values in the steel frame. Next, economic, infrastructural, environmental, and effectiveness constraints particular to the oil refinery facility in Newfoundland were identified by the design team. Using these data, a preliminary design of a compressor foundation was developed, satisfying constraints mentioned above. Lastly, final design requirements and appropriate modeling materials for the cooler foundation were determined. In order to accomplish the goal of the project, the following objectives were completed:

1) Characterize the scope of the project and existing plant conditions

2) Specify design requirements and appropriate modeling materials and tools for the preliminary foundation design

3) Make iterative design decisions during preliminary design process

4) Create an engineering presentation of the design feasibility, societal impact and tradeoffs

Chapter 2: Background

In this chapter, oil refining processes and fin fan cooler systems are introduced along with detailed information on major foundation design concepts and elements.

2.1 Oil Refinery Overview

An oil refinery is a large scale plant that splits crude oil into fractions, and uses processes to turn crude oil fractions into useful products. Products of oil refineries include fuels and lubricants for automotive, ship and aircraft engines, petroleum wax, and asphalt (European Petroleum Industry Association, n.d.). A specific type, number, and size of process units required at a particular refinery depends on several factors, comprising of the type of crude oil, final products, and complexity of the refining process.

An oil refinery completes many types of processes, which vary from one plant to the next, but always performs three basic steps: separation, conversion and treatment (United Cooling Systems, n.d.). During the separation step, crude oil is distilled and separated into several fractions according to boiling range and molecular structure. Those fractions are then processed by catalytic conversion under high temperature and pressure. Finally, different oil streams attained in the conversion step are stabilized and separated from undesirable elements (European Petroleum Industry Association, n.d.). A simplified diagram of a typical oil refinery processing units is provided in Figure 1:

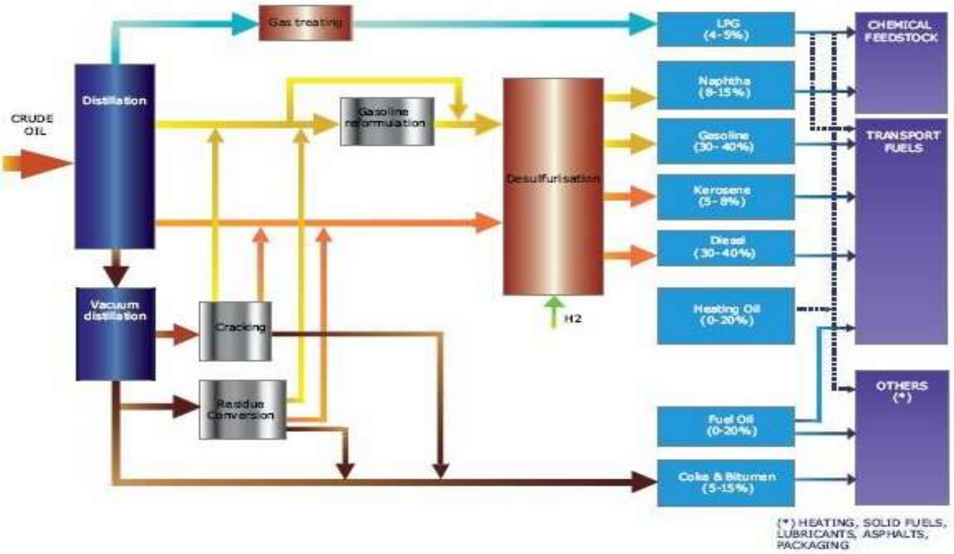


Figure 1: Oil Refinery Processing Units (European Petroleum Industry Association, n.d.)

2.2 Fin Fan Coolers in an Oil Refinery

Air Cooled Heat Exchangers, also called Fin Fan Coolers, are used in applications where large quantities of heat need to be transferred, such as chemical and petrochemical industries, power stations, and waste-to-energy facilities (Direct Dry Cooling, n.d.). In fin fan coolers, hot process fluids or gases flow through tubes, and the outside cooling air flows across the outside of the tube. (Pre-cooling for Air Cooled Heat Exchangers, n.d.) Refineries and petrochemical plants use fin fan coolers to remove excess heat from their processes, since plant operation might be limited when unable to remove the excess heat.

2.3 Cooler Foundation Design Elements

Air coolers are used in fundamentally different and sometimes extremely difficult ambient conditions. This refers to both production processes and climate-related conditions. An effective foundation design satisfies those requirements, as well as customers' wishes.

2.3.1 Building Code Regulations

The National Building Code of Canada is a set of requirements developed to ensure public safety in buildings. Foundation designs are regulated by the National Building Code of Canada and also local building codes. The purpose of a foundation is to transfer the load of a building and other associated loads between the building and the ground without exceeding capacities of the soil and rock (National Building Code of Canada, 2005). Before designing a foundation, a detailed geotechnical investigation must take place, examining ground and surrounding site conditions, including groundwater, soil and rock properties. Next, buildings and the structures associated with them should be assessed for structural capacity and structural integrity, to be able to effectively resist all loads, including dead, live, snow and winter loads and their effects on the structure (National Building Code of Canada, 2005).

2.3.2 Geotechnical Investigation

Geotechnical inspection of the building site focuses on soil, rock, and other types of earth materials that are of importance to the future foundation design. There are 5 phases to a typical geotechnical investigation, including preliminary investigations, detailed site investigations, laboratory testing of samples, report, and recommendations development (Professional Engineers Providing Geotechnical Engineering Services, 1993). Preliminary investigation involves assessment of a site and soil suitability, as well as of the elastic and shear modulus values. Detailed site inspection then requires field drilling and sampling, and groundwater records. Following lab testing of samples, a final report is developed, including findings on the field investigations and recommendations on appropriate foundation depth, potential settlement and design bearing values (Professional Engineers Providing Geotechnical Engineering Services, 1993).

2.3.3 Design Loads

Loads are forces and pressures applied to the building structure that can impose deformations (National Building Code of Canada, 2005). Every building must be designed such that all loads to be sustained during the lifetime of the structure will be sustained with an appropriate margin of safety, and deformations of the structure will not exceed acceptable levels (Butcher, 1976).

Permanent loads vary with a small or negligible altitude over time, whereas variable loads change frequently in magnitude, direction or location (Seattle Building Code, 2009). Loads that are considered in designing a cooler frame and footings are dead, live, snow, and wind loads. Dead loads are permanent loads, and consist of the weight of the materials of construction supported by the member, and the load due to earth, plants and trees. Live, snow, and wind loads are variable loads, and depend on intended use and occupancy and local weather conditions.

Chapter 3: Methodology

Stantec’s client requires a design for installing a new fin fan cooler foundation. Information to develop a design of a new cooler foundation for the facility was therefore needed. The goal of this project was to investigate different cooler foundation elements and provide a design for the most feasible one, using Staad Pro software.

To achieve this goal, the following objectives were completed:

1) Characterize the scope of the project and existing plant conditions

2) Specify design requirements and appropriate modeling materials and tools for the preliminary foundation design

3) Make iterative design decisions during preliminary design process

4) Create an engineering presentation of the design feasibility, societal impact and tradeoffs

The following sections describe methods that were used to achieve each of these objectives.

3.1. Project scope and existing conditions

Characterizing the scope of the project involved consulting different online resources on civil engineering and oil refinery processes. Also, textbooks were consulted for details on steel and concrete foundation design steps. Through background research, different elements of fin fan cooler foundation design were identified. A project scope report prepared by Stantec engineers was consulted in order to find out the planned cooler system location and dimensions, as well as information on the proposed renovation of other components of the client refinery. Finally, the STAAD Pro manual was consulted to learn necessary skills to create a 2- and 3-D model of the structure.

The next step was to characterize existing plant conditions, which involved collaboration with Stantec staff and the client plant managers. Stantec staff was consulted to identify their view on the compressor foundation design for the plant. Again, the project scope report developed by Stantec engineers was consulted. Lastly, a geotechnical investigation was conducted on site by an independent geotechnical engineer. His report provided information on current subsurface soil and bedrock conditions, as well as an estimation of the elastic and shear modulus values important for foundation design. Gathering and investigating this information was essential for identifying potential foundation design options.

3.2. Preliminary foundation design requirements

The second objective was to define the overall system configuration and provide schematics, diagrams, and layouts of the project both in STAAD pro software and on paper. To define the general framework and operating parameters, the Canada Building Code manual was consulted. Multiple structural engineering textbooks on steel and concrete foundation basics were referred to in order to fulfill this objective. After consulting textbooks and the building code requirements, a project was started in STAAD Pro for designing the steel frame of the foundation. STAAD Pro manuals were consulted throughout the entire period, in order to ensure proper use of the software and appropriate design of the foundation.

3.2.1 Steel Frame Design Loads Identification and Calculations

To start computing design loads for a foundation, it was necessary to determine width and height of the structure. Next, design loads were computed, including ground snow load, wind speed, live and dead loads. To perform the calculation of the structural steel, STAAD pro® software was used. This software helped identifying proper loads in the steel structure and allowed the production of calculation data (STAAD.Pro V8i, n.d.). Based on the loads derived by hand calculations, load tables for the member loads were developed in STAAD Pro.

3.2.1.1 Dead loads

Dead load is a permanent load that consists of the self-weight of the member and partitions, the weight of all materials of construction that is supported by the member, and the vertical load due to earth, plants and trees (National Building Code of Canada, 2005). Dead load can be calculated exactly, since it stays constant through time, and should be calculated separately for every individual foundation, from design configuration, dimensions and density of the building material. Calculation steps include conversion of weight in kg to weight in kN, and then dividing it by the frame perimeter. Assuming weight was uniformly distributed along the structure, it was then divided by the obtained perimeter. Calculations are included below:

Dead load safety factor = 1.25

Weight 13 350 lb to kN = 59.4 kN (per one cooler, provided by the manufacturer)

Perimeter of the square is (2*3.66 + 2*4.27) m = 15.86 m

Thus, force due to dead load for each separate cooler = 3.74 kN/m

In structural design, dead loads are usually assigned a safety factor of 1.2. In this project, the safety factor was assumed to be equal to 1.25. Those values were entered and calculated in STAAD Pro software, assuming gravity force was uniformly distributed. Self-weight of the steel beams was automatically added to the dead load force in STAAD Pro model.

3.2.1.2 Live loads

A live load is a variable load, due to the intended use and occupancy (National Building Code of Canada, 2005). A live load can be fully or partially in place or not present at all, and may change its location in most structures. So, in structural design live loads are provided a larger safety factor than the others (Civil Engineering Basics, n.d.). Live load thrust for this foundation comes from the vibration created by the rotating cooler fans, and can be calculated from air flow values provided by the manufacturer. Air flow thrust was then converted to kN and divided by the perimeter of the frame. Calculation of the live load was performed using the formula provided in the Figure 2:

Metric units

$$F_A = \frac{98 \times s \times Q^2}{D_1^2}$$

U.S. customary units

$$F_A = \frac{s \times Q^2}{567 \times D_1^2}$$

Where:

F_A = Axial thrust, in N (lb)

s = Specific gravity

Q = Flow rate, in m^3/h (gallons per minute—GPM)

D_1 = Impeller eye diameter, in mm (in)

Figure 2: Live Load, (NBC of Canada, 2010)

Flow rate Q 137194 ft3/m = 3884,9 m3/h (assuming SCFM is equal to CFM)

S = 1.0 unitless

D of fan = D of blade*2 = 3352.8 mm

Then F_A = (98*(1.0)*((3884.9)^2)/ ((3352.8 mm)^2) = 132 N

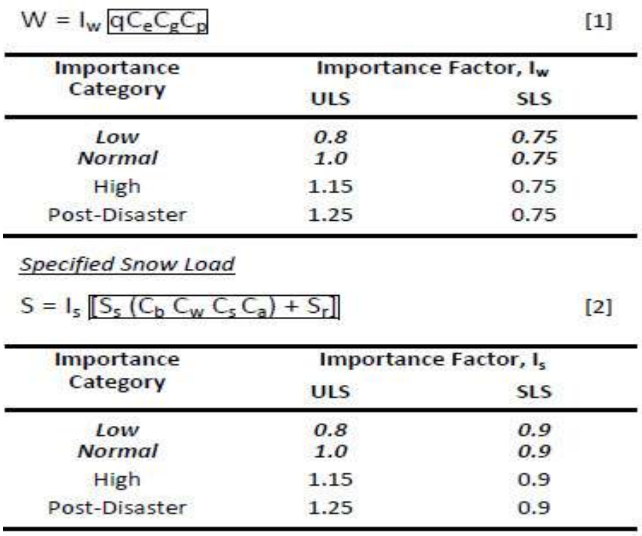
Live load for each square is 132N/15.86m = 0.00832 kN/m

Since live loads vary with time, the safety factor is greater than for dead loads, and usually equals around 1.6 For the sake of this project, the safety factor of the live load was considered to be 1.6.

The live load values were entered to the STAAD Pro model, and assigned to the top of the frame, where the coolers contact the frame.

3.2.1.3 Snow loads

Variable load due to snow, including ice and rain, is called snow load and is denoted as S. In order to assign specified snow loads, an importance category table has to be consulted and the structure has to be assigned an appropriate category. The importance category table developed for buildings and structures designed in Canada can be found in Appendix B. For this project, the importance category was chosen to be high, since it falls under manufacturing and storage facilities containing toxic, explosive or other hazardous substances category. After the importance category was selected, Figure 3 was referred to for corresponding importance factor, I_w.



$$W = I_w \boxed{qC_eC_gC_p} \qquad [1]$$

Importance Category	Importance Factor, I_w	
	ULS	SLS
Low	*0.8*	*0.75*
Normal	*1.0*	*0.75*
High	1.15	0.75
Post-Disaster	1.25	0.75

Specified Snow Load

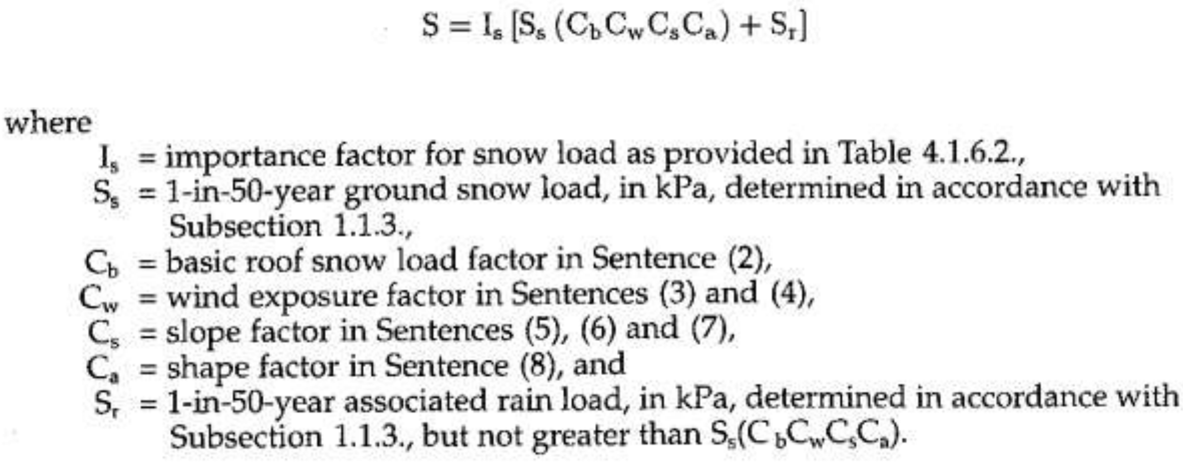
$$S = I_s \left[\boxed{S_s (C_b\ C_w\ C_s\ C_a) + S_r}\right] \qquad [2]$$

Importance Category	Importance Factor, I_s	
	ULS	SLS
Low	*0.8*	*0.9*
Normal	*1.0*	*0.9*
High	1.15	0.9
Post-Disaster	1.25	0.9

Figure 3: Wind and Snow Load Importance Factors (National building code of Canada, 2010)

A formula for calculating snow load is provided in the National Building Code of Canada.

It is as follows:



$$S = I_s [S_s (C_b C_w C_s C_a) + S_r]$$

where

I_s = importance factor for snow load as provided in Table 4.1.6.2.,
S_s = 1-in-50-year ground snow load, in kPa, determined in accordance with Subsection 1.1.3.,
C_b = basic roof snow load factor in Sentence (2),
C_w = wind exposure factor in Sentences (3) and (4),
C_s = slope factor in Sentences (5), (6) and (7),
C_a = shape factor in Sentence (8), and
S_r = 1-in-50-year associated rain load, in kPa, determined in accordance with Subsection 1.1.3., but not greater than $S_s(C_b C_w C_s C_a)$.

Figure 4: Snow Load Formula (National Building Code of Canada, 2010)

The basic roof snow load factor C_b and wind exposure factor C_w factors were provided in the National Buidling Code, were equal to $C_b = 0.8$, $C_w = 1.0$. C_s for surfaces with slope of less than 30^o is assumed to be 1.0. The shape factor, C_a, equals 1.0 in general cases, where additional snow loads are not expected from adjacent building roofs, chimneys and equipment.

Ss and Sr values specific for Newfoundland, Canada were obtained from Table C-2, C-36 Division B in National Building Code of Canada, 2005, and were calculated to be 2.4 and 0.7 kPa, respectively (National Building Code of Canada, 2010). Thus, ultimate snow load was found to be 2.86 kN/m, and serviceability snow load was 2.37 kN/m. Detailed calculations can be found in Appendix C.

3.2.1.4 Wind loads

A variable load from wind is the intensity of the pressure that the wind exerts on the structure. Properly designing and accounting for wind loads help creating safer buildings, safe from tipping or deformations from wind in various weather conditions. Wind load calculations have to be performed according to the National Building Code of Canada. The wind load formula and description of its components is included below:

$$F_n = I_w\ k\ C_f\ C_n\ q\ C_g\ C_e\ h\ l \qquad \text{(Equation 1)}$$

I_w = importance factor 1.15

k = 0.6

C_f = force coefficient = 1.15 for walls above ground

C_n = force coefficient for an indefinitely long member = 1.6 for angle $\alpha = 0^o$, structure rising above grade (Figure I-29, Commentary I, Part 4 of Divison B, NBC of Canada, 2005).

q = reference velocity pressure = 0. 58 kPa for 10 and 0.75 kPa for 50 year return periods, in Newfoundland (Table C-2, C-36 Division B, NBC of Canada, 2005)

C_g = gust effect factor = 2.0 for the building as a whole and main structural members was assumed (Section 4.1.7.1, division B, NBC of Canada, 2005)

C_e = exposure factor = 1.0 (standard)

h = 1.0 m (height of the columns)

l = 0.2 m (thickness of the columns)

Thus, the wind force on the structure columns turned out to be:

F_n = 1.15*1.15*0.6*1.0*0.75kPa*2.0*1.0*1.0m*0.2m = 0.38 kN/m

The rest of the calculations are included in the Appendix D.

When entering the load values in STAAD, different load combinations were considered. It was important to keep in mind that sometimes partial wind loading can put more stress on the structure than full loading, since wind pressure patterns can produce additional torsion when the wind-load sector shifts (NBC of Canada, 2005). Thus, National Building Code of Canada was consulted for different load combinations. Since the structure designed in this project was not tall enough to get multiple unbalanced loads due to additional torsion, only cases A and C from the NBC Table I-16 Full and Partial Wind Loads were considered. They are included in Figures 5, 6 and 7:

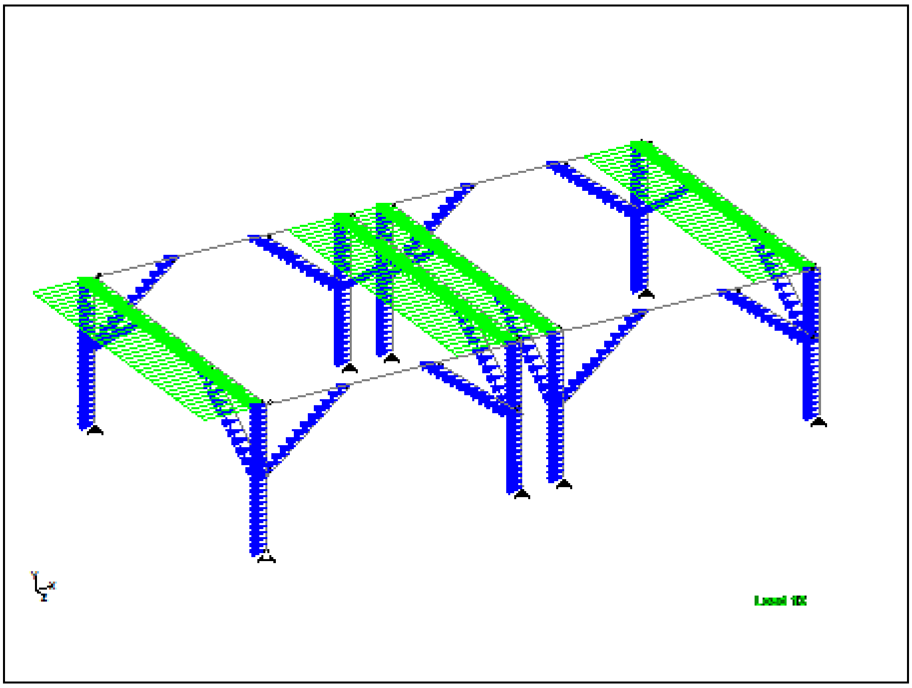


Figure 5: Wind in X Direction

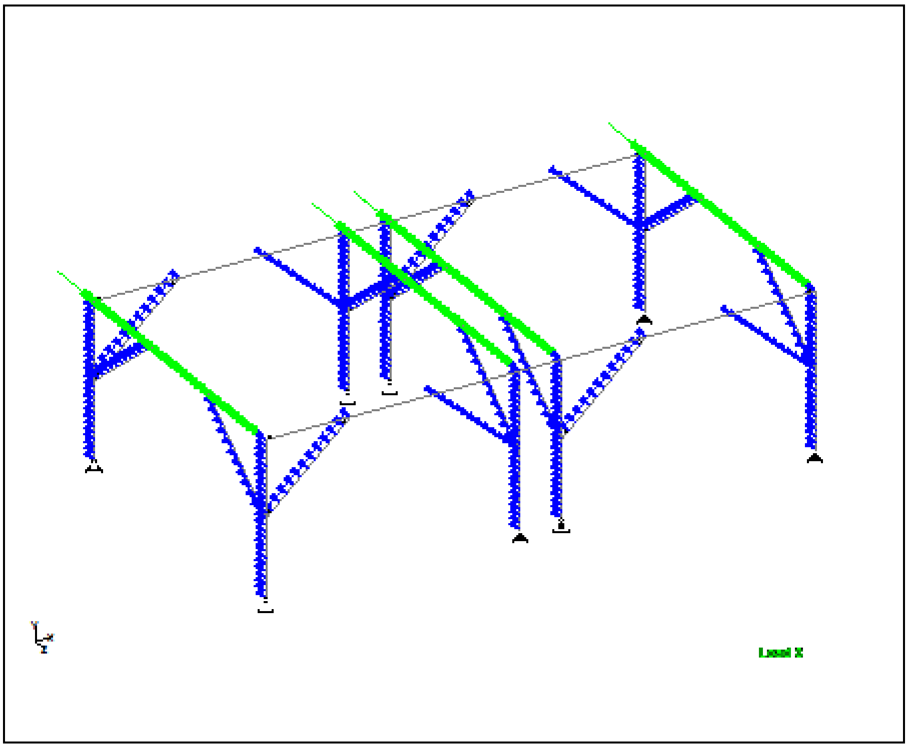


Figure 6: Wind in Z Direction

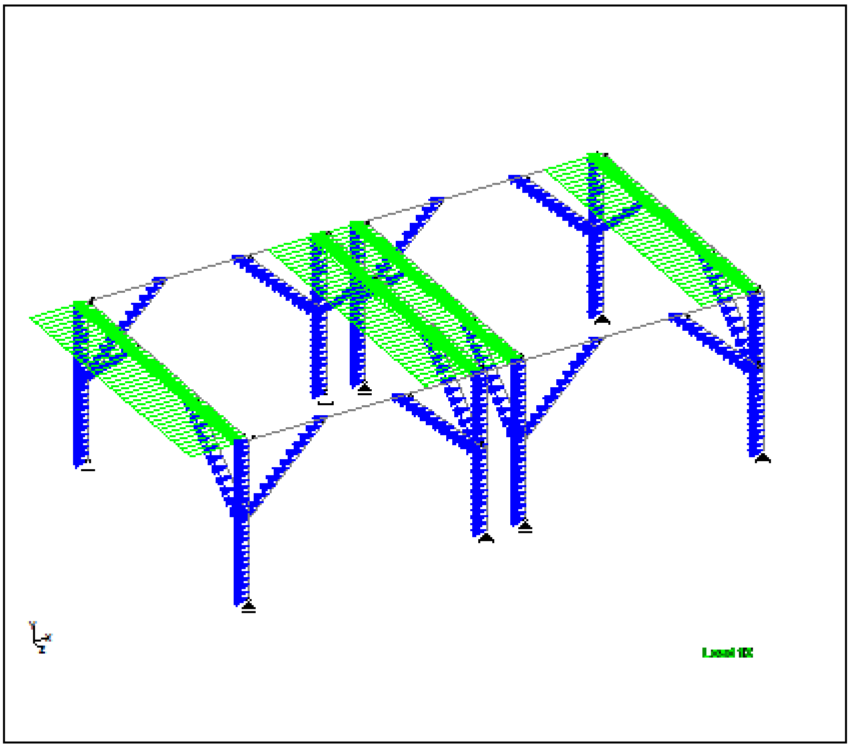


Figure 7: X and Z Wind Directions Combined

The three wind load combinations included above were used in the analysis of the whole structure, described in Section 4.2.1.

3.2.1.5 Earthquake loads

Every building should be designed to meet the requirements in Section 4.1.8 in National Building Code of Canada on earthquake load and effects. All structures should be designed with a clearly defined load path to transfer the inertial forces cause by earthquake activity to the supporting ground. For the purpose of this project, the minimum lateral earthquake force, V, was calculated according to the formula for braced frames:

$$V = S(T_a)*M_v*I_E*W/(R_d*R_o) \qquad \text{(Equation 2)}$$

Site Class B – Rock.

Importance factor I_e = 1.3 for high importance category.

W = dead load = 5.33 kN

M_v = higher mode factor = 1.0 (from Table 4.1.8.11, NBC of Canada, 2005)

For Newfoundland Argentia Table C-2, c-36 division B, $S_a(0.2) = 0.17$, $S_a(0.5) = 0.12$, $S_a (1.0) = 0.074$, $S_a (2.0) = 0.024$, PGA = 0.060.

S_a (0.2)/S_a (2.0) = 0.17/0.024 = 7.08

Ta for braced frames where h_n I in meters = 0.025*h_n = 0.025*2.44 = 0.061

Found R_d and R_o from table 4.1.8.9 in NBC of Canada, 2005.

R_d = ductility-related force modification factor reflecting the capability of a structure to dissipate energy through reversed cyclic inelastic behavior (for tension-compression braces) = 2.0

R_o = overstrength-related force modification factor accounting for the dependable portion of reserve strength in a structure designed according to these provisions (for tension-compression braces) = 1.3.

S (T) = design spectral response acceleration, expressed as a ratio to gravitational acceleration, to a period of T.

S (T) = Fa*Sa(0.2) for T<= 0.2s = 0.136

F_a = 0.8 for site class B

F_v = 0.6

V = S(Ta)*Mv*IE*W/(Rd*Ro) = 0.362 kN

However, for the purpose of this project, the earthquake load was ignored, since it came out to be a very small value compared to the wind load.

3.2.1.6 Steel Frame Sizes and Elements

The design team selected 8 by 10 inches beams, appropriate for the size and material of the structure, for the preliminary design. Flanges of the frame had to be wide enough for subsequent bolting, which was taken into consideration when picking the beams size. In addition, W shape was chosen for design beams. In petroleum industry, hollow circular or rectangular beams are not often used, because they corrode. In hollow sections, it is usually hard to see the issue until they collapse. In our particular project, braces were placed on every corner of the steel frame, in order to assist the frame in resisting wind forces and vibration exerted by the coolers. Bracing systems provide lateral support to columns and the compression flange of beams and girders (Handbook of Steel Construction, 2009). The frame was connected with pinned joints, which allowed transferring loads moments associated with column base to the column top, and resisting gravity loads. A pin-jointed frame design was chosen because it is a cheap and effective alternative to a moment connections frame.

The location and number of braces and pin joints is illustrated in Figure 8:

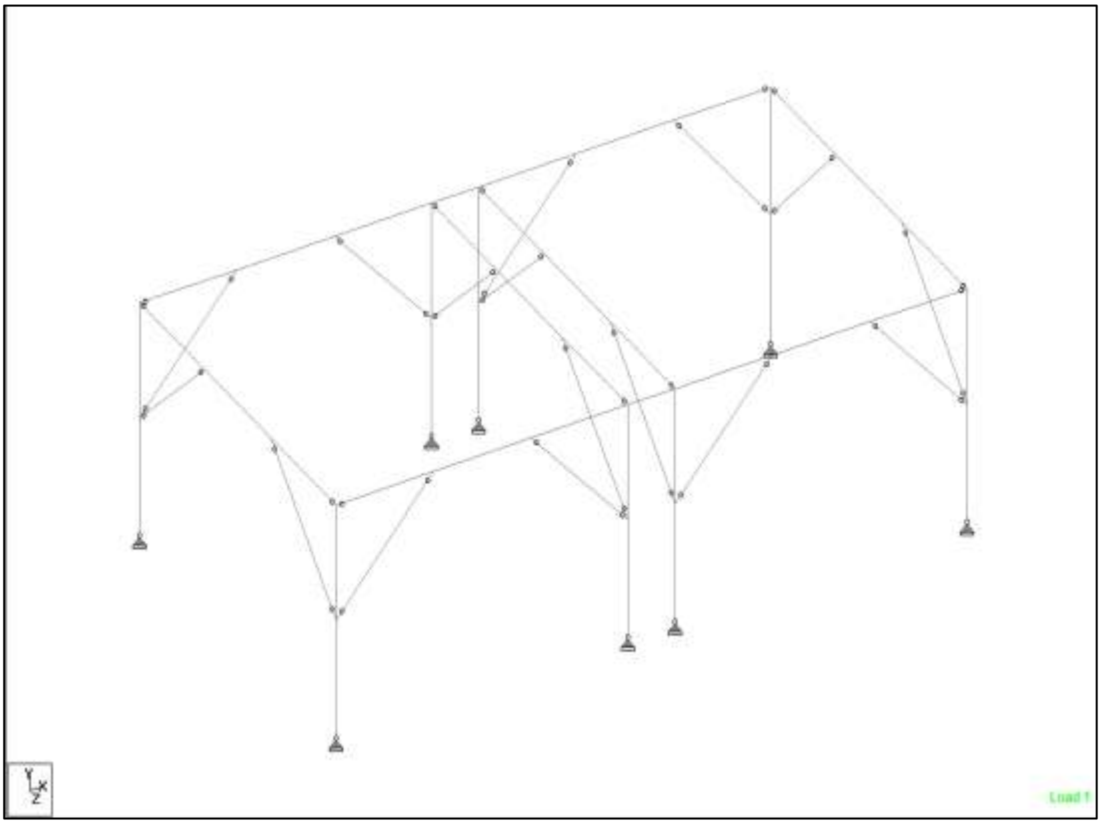


Figure 8: Frame Braces and Pin Connections

3.2.2 Concrete Footing Design Loads Identification and Calculations

Completing the steel frame design gave the design team load values necessary for concrete footing calculations. Steel frame column height, width and specified column loads in both horizontal and vertical directions were used in concrete footing design calculations. Other factors were taken into account in designing the concrete footing, including soil type and design concrete strength.

3.2.2.1 Soil Bearing Capacity

Soil under the footing plays a key role in calculating design requirements of the footing. The footing exerts pressure on the soil beneath it. Thus, it is important to identify the given soil types and corresponding bearing capacities.

Table 1: Soil Bearing Capacities

(Table 401.4.1; CABO One- and Two- Family Dwelling Code; 1995)

Class of Materials	Load-Bearing Pressure (pounds per square foot)
Crystalline bedrock	12,000
Sedimentary rock	6,000
Sandy gravel or gravel	5,000
Sand, silty sand, clayey sand, silty gravel, and clayey gravel	3,000
Clay, sandy clay, silty clay, and clayey silt	2,000

It can be seen from the Table 1 that generally, finer soils (clay, silts) have lower capacities than coarse granular soils (sands and gravels). However, some clays or silts have higher bearing capacity than the values in the code tables. Therefore, the bearing value capacity of the soil is obtained from the geotechnical investigation of the site. After a detailed investigation of the soil at the client oil refinery location, the soil below the ground surface was identified to be bedrock. The geotechnical investigation performed analysis of the bedrock samples, and found the average compressive strength to be 118 MPa (Stantec Staff Interview, 2014). Since the foundation is to be located on bedrock with a great compressive strength, the size of the footing will depend more on the structure overturning, not the settlement. Other important soil parameters were also obtained from the geotechnical report prepared for Stantec. The typical angle of internal friction for bedrock is assumed 30°. The average dry unit weight of the soil equaled to 2726 kg/m^3, relative fill density above foundation – 30, compactness condition varying from compact to dense.

Table 2: Relative Density of Soils (Standard Penetration test, n.d.)

Correlation between SPT-N value and friction angle and Relative density (Meyerhoff 1956)			
SPT N3 [Blows/0.3 m - 1 ft]	Soi packing	Relative Density [%]	Friction angle [°]
< 4	Very loose	< 20	< 30
4 -10	Loose	20 - 40	30 - 35
10 - 30	Compact	40 - 60	35 - 40
30 - 50	Dense	60 - 80	40 - 45
> 50	Very Dense	> 80	> 45

3.2.2.2 Loads Due to the Steel Frame

To design the concrete footing, loads at the top of the steel column should be known. Thus, design loads at support points were extracted from STAAD Pro into Table 3:

Table 3: Design Loads Summary (STAAD Pro)

	Node		Fx (kN)	Fy (kN)	Fz (kN)
Max Fx	1	8 1.25D + 1.5S + 0.5L	4.529	37.286	2.602
Min Fx	19	12 0.9D + 1.4WIND X	-22.497	-7.972	-0.976
Max Fy	20	16 1.25D + 1.4WIND X + 0.5S	-7.944	72.068	-2.817
Min Fy	21	13 WIND X DIR	-3.629	-18.371	-0.003
Max Fz	3	8 1.25D + 1.5S + 0.5L	3.963	42.271	3.816
Min Fz	20	17 1.25D + 1.4WIND Z+ 0.5S	-1.061	41.484	-21.402
Max Mx	1	1 DEAD LOAD	1.972	16.583	1.132
Min Mx	1	1 DEAD LOAD	1.972	16.583	1.132
Max My	1	1 DEAD LOAD	1.972	16.583	1.132
Min My	1	1 DEAD LOAD	1.972	16.583	1.132
Max Mz	1	1 DEAD LOAD	1.972	16.583	1.132
Min Mz	1	1 DEAD LOAD	1.972	16.583	1.132

Factored loads are the product of a specified load and its principal load factor. Specified loads include loads due to dead, live, snow, earthquake and wind loads. Both specified and factored loads were necessary in computing the footing size. Values used for the concrete footing design are obtained from Table 3.

Specified vertical load at top of column = 57.7 kN

Factored vertical load at top of column = 57.7 kN* 1.25 = 72.1 kN

Specified horizontal load at top of column = 16.1 kN

Factored horizontal load at top of column = 16.1 kN*1.5= 22.5 kN

3.2.2.3 Design for stability, shear and moment

In order to design a sound footing for the existing steel structure, calculations on the sheer, stability and moment on the footing needed to be performed. First, the existing parameters of the steel frame columns were used, with the column width taken as beam plate width for the column, and appropriately sized for the steel column width:

Table 4: Steel Column Parameters

Parameters	Value	Units
Column height from footing	1115	mm
Column width (x-dir)	305	mm
Column width (z-dir)	762	mm
Column height above grade	200	mm
Specified vertical load at top of column	57.5	kN
Factored vertical load at top of column	72.1	kN
Specified horizontal load at top of column	16.1	kN
Factored horizontal load at top of column	22.5	kN

Other starting parameters for concrete footing design included soil parameters discussed in Section 3.2.2.1 and concrete parameters, presented in Tables 5 and 6, respectively:

Table 5: Soil Design Parameters

Parameters	Value	Units
Fill thickness above footing	815	mm
Fill density	18	kN/m^3
Concrete slab thickness above footing	100	mm
Soil Allowable bearing capacity	29500	kN/m^2
Angle of Internal Friction of Soil (f)	40	degrees

Table 6: Concrete Specifications

Parameters	Value	Units
Compressive strength footing (fc')	30	MPa
Density of concrete	23.5	kN/m^3
Reinforcement yield strength	400	MPa

First, vertical load on the footing needed to be calculated. Two different vertical values, Pf and Ps were assumed to be equal to the specified and factored vertical loads in the column support. Thus, Ps = 72.48 kN, Pf = 90.6 kN. To calculate the one-way shear in the footing, equation 3 was utilized,

$$Vc = 0.18*\Lambda*Fc*sqrt(fc')*bw*d \qquad \text{(Equation 3)}$$

where $\Lambda = 1$

Fc = 0.6

fc' =30 MPa

bw =1200 mm

d = tk-db/2-cover =215 mm

thus, V_c = 0.18*landa*Fc*sqrt(fc')*bw*d = 152.62 kN

V_f = Qf*fftw*(ftl/2-cw/2-d) = 17.79 kN

Since Vc ‹ Vf, the footing has allowable one-way shear. Detailed calculations on the two-way shear are presented in Appendix G.

Moment in the footing was calculated for X and Z directions, according to Equation 4,

$$Mf = (w*l^2)/2 \qquad \text{(Equation 4)}$$

X direction, where w = Qf* width = 97.77 kN/m

l = length/2-column length/2 = 397.00 mm.

As, min (x dir) = 0.002Ag = 720 mm^2

As,min (x dir) = 0.2*sqrt(fc')*bt*h/fy = 986 mm^2

Mf = (w*l^2)/2 = 7.70 kN/m

More detailed calculations on shear and moment are included in the Appendix G. These calculations enabled our design team to move to the next subsection.

3.2.2.4 Concrete Footing Sizes and Elements

Footings are structures designed to transmit column or wall loads to the soil below the structure, to minimize excessive and differential settlement, sliding and overturning of the structure.

Shallow footings for columns can be differentiated as combined, isolated, strip and mat footings. For the purpose of this project, only isolated and combined footings are considered. Isolated footings are chosen when individual columns are to be supported, where columns are far apart and loads are small. Depending on the shape of the column cross section, footing can be square, rectangular or circular. Isolated footings are essentially slabs with steel mesh on the bottom, attached to resist bending moment and shear force. A sketch of a typical isolated footing can be viewed below:

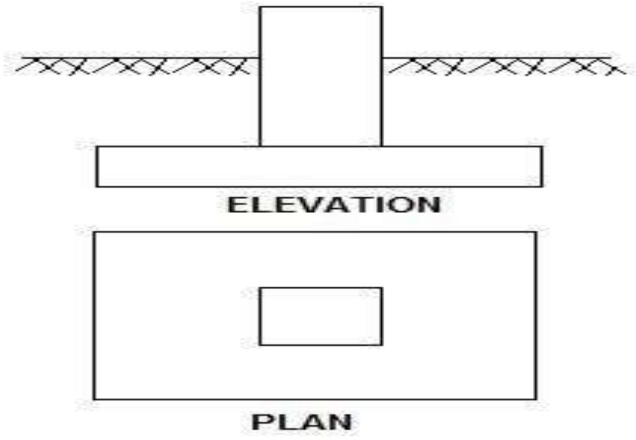


Figure 9: Isolated Footing (Types of shallow foundations, n.d.)

On the other hand, combined footing is necessary when the distance between columns is short, so that isolated footings would overlap, or footings are heavily loaded. The combined footing is usually shaped depending on the loads, to ensure that the resulting soil bearing pressure is uniform. Combined footing shapes can vary from trapezoidal to rectangular. A typical combined footing illustration is provided:

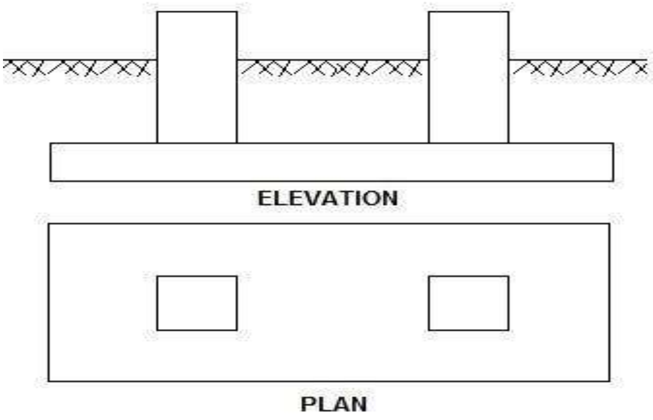


Figure 10: Combined Footing (Types of shallow foundations, n.d.)

For this project, the footing was chosen to be isolated, since the distance between the two combined footings was large. In x direction, the footings are located on the edge columns and are apart 2.16 m. In z direction, footings are separated by 2.77 m.

A project was created in Hilti PROFIS Anchor software to calculate the appropriate pedestal and base plate sizes, along with the anchor bolts type and diameter. The following parameters were set in the model to determine the optimal anchor bolts and pedestal measurements. Maximum expected load values were assumed to ensure safe design.

Table 7: Anchor Bolts Design Values

Parameter	Value	Units
Vertical Load Z	72.1	kN
Horizontal Load Y	21.4	kN
Horizontal Load X	22.5	kN
Base Plate Width	350	mm
Base Plate Length	350	mm
Base Plate Thickness	19	mm

When setting the base plate dimensions, it was important to note that the typical base plates measure 300 mm by 300 mm. Thus, it was the first base size set. However, for the column size and bolts, a slightly bigger base plate was necessary to ensure stability. Steel frame column legs were designed to be welded to the base plate with anchor bolts.

Anchor bolts design is required for every footing, to ensure stability and strength of the structure. Anchor bolts for this particular footing were also designed in the Hilti PROFIS Anchor software. After setting the starting parameters, the anchor system calculations were performed in the Hilti software. Below is the table with the resulting anchor types and sizes that could be installed in the structure.

Table 8: Anchor Bolt Options

Anchor	Size	Total
Hex Head ASTM F 1554 GR. 36	3/4	87 %
Hex Head ASTM F 1554 GR. 36	7/8	87 %
Heavy Hex Head ASTM F 1554 GR. 36	3/4	87 %
Heavy Hex Head ASTM F 1554 GR. 36	7/8	87 %
Square Head ASTM F 1554 GR. 36	3/4	87 %
Heavy Square Head ASTM F 1554 GR. 36	3/4	87 %

In this table, only grade 36 steel bolts were illustrated. The reason for that is because grade 36 steel can be galvanized, which strengthens anchor bolts and thus makes them less likely to corrode or fail.

After the base plate and anchor bolts were designed, the last footing element left to design was the concrete pedestal. Footings for columns should include a pedestal on which the member will bear. A typical pedestal and its components can be viewed in Figure 11.

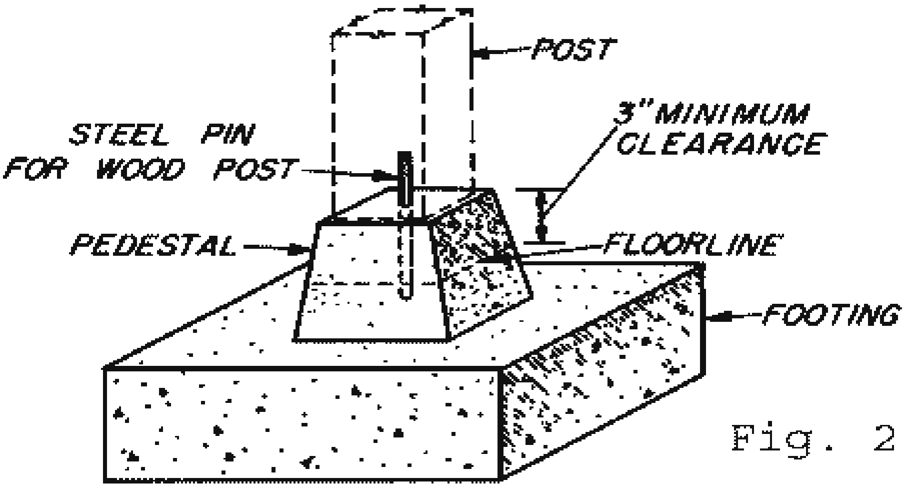


Figure 11: Footing Pedestal (Foundation Footings, n.d.)

To properly size the pedestal, Concrete Design Handbook was referred to. Calculations were performed, to identify the necessary pedestal dimensions.

Factored Load on Column (Pf) = 72.1 kN

Height of the pedestal = 1400 mm – 300 mm = 1100 mm

Factored Moment on Column (Mf) = height of the pedestal*horizontal load on the pedestal = 1.1 m*16.1 kN = 17.71 kN*m

Eccentricity e = Factored Moment on Column/ Factored Load on Column*1000 =245.63 mm

Area of Steel = p_gA_g = 0.0265*406^2 = 4368.2 mm^2.

Basic strain condition calculations:

Ey = fy/E = 0.002

xb = Ec*d/(Ey+Ec) = 229.2 mm

alpha (a) = B1*xb = 195 mm

E's = Ec*(xb-cr)/xb = 0.002018325

Cc=0.85*Qc*f'c*b*a =1362.200922 kN

C's=A's(Qs*f's-0.85*Qc*f'c) = 709.1772 kN

T = As*Qs*fy = 742.594 kN

Prb = Cc + C's - T = 1328.8 kN

Mrb = Cc(d^-a/2) + C's(d^-d')+T(d-d^) = 401.4 kNm

eb = Prb/Mrb = 0.302 m.

Since eb ≥ e, the pedestal would fail from compression.

Using these values, compression failure and tension failure of the design footing were calculated. The values were far larger than the loads expected from the steel frame; thus, the design was deemed feasible and safe. Step-by-step failure calculations are included in Appendix J. Final dimensions of the concrete pedestal are included in Table 9:

Table 9: Concrete Pedestal Design

Parameter	Value	Unit
Width of the pedestal	457	mm
Height of the pedestal	457	mm
Height of the pedestal	1100	mm

3.3 Iterative design process

This project involved iterative decision-making, in order to meet the economic, constructability, environmental, health and safety, and ethical constraints as specified by the Accreditation Board for Engineering and Technology. Design modifications and decisions are described in this section.

Before drawing the frame structure in STAAD Pro, the size and shape of the structure beams were to be chosen. When first designing the steel frame, the two fin fan coolers were to be placed closely on the two squares of the frame provided in Figure 12:

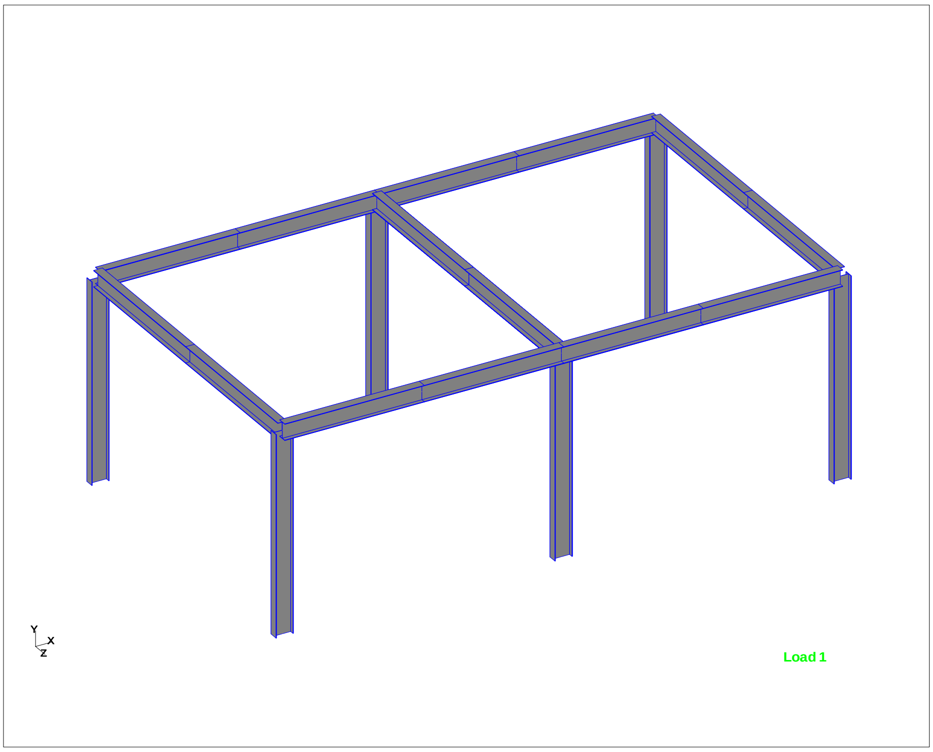


Figure 12: Preliminary Design Week 2

However, after consulting a structural engineer from Stantec, the design was changed. The shape of the steel frame was changed so that there was a 0.6 m gap between the two coolers. This adjustment will allow easier access to the frame and coolers for maintenance, and also satisfy the health and safety requirements at the oil refinery. Additionally, braces were inserted over moment connections, to keep the joints from rotating and making the structure more resistant to loads applied. The updated steel frame structure is illustrated in Figure 13:

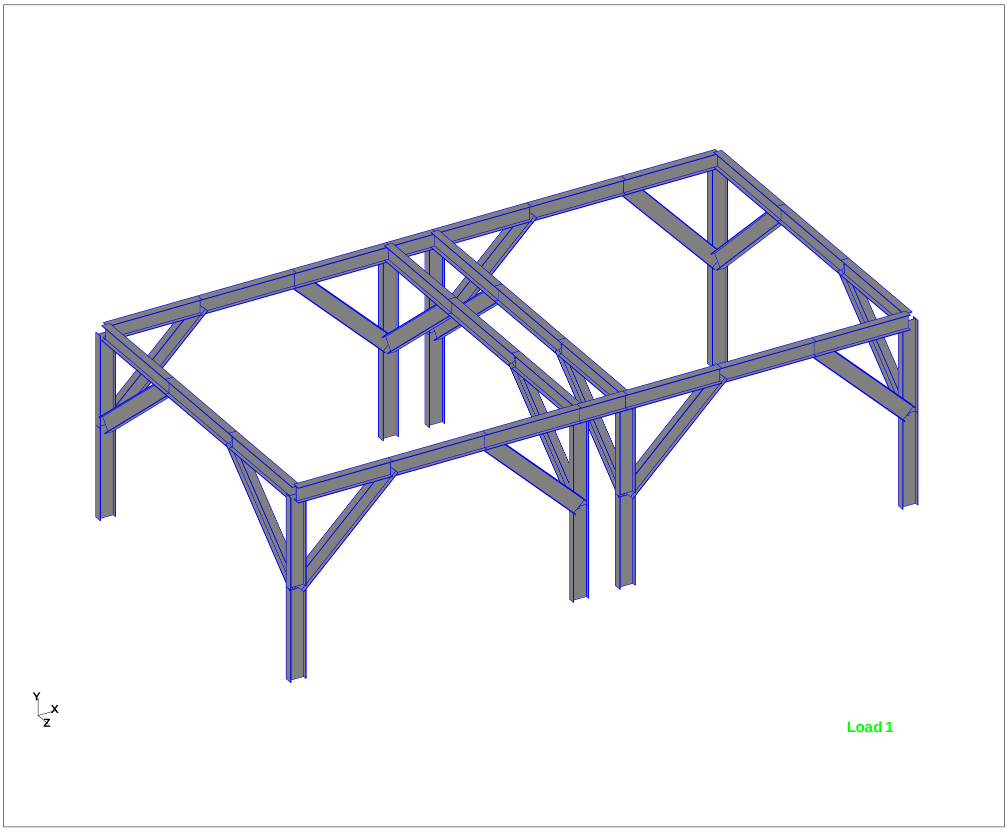


Figure 13: Preliminary Design Week 3

After having assigned all the loads applicable to the frame structure, design analysis was performed in STAAD Pro. First, it was performed with the structure made with beams 8 by10 inches thick. The structure failed in the four columns located on each end of the frame due to bending. Thus, the thickness of the beams was increased to 8 by 15 inches. After the analysis was performed, only one column had the utilization ratio of 1.012, slightly higher than the allowable 1.000. Thus, the design passed quality check and was accepted as final.

6 weeks into the project, the design team learned that the cooler was not sitting on the top of the frame. Instead, it was attached to the sides of the frame, so that the top of the cooler and the top of the frame were on the same level. This fact forced our design group to change the wind load calculations. The wind load dude to the cooler in x and z directions were recalculated. The total wind load was divided not by the perimeter of the frame this time, but by the length, since the most loads are expected on the sides

of the frame, and not the whole top. Calculations for wind load on the cooler were updated in the Methodology section 3.2.1.4.

3.4 Engineering presentation of the design feasibility

The final objective of the project was to review the design solution and help identify issues to be addressed. As part of this objective, a Results chapter was developed. It included design parameters of the final foundation, as well as the pictures of the model. This objective allowed creation of a Recommendations section of the final report, where we discussed how the new foundation design satisfies the economic, infrastructural, environmental, constructability and ethical constraints. Recommendations were developed, where the design failed to meet those constraints. Additionally, a design in STAAD Pro software was created, analyzed, and tested for feasibility using STAAD Pro analysis. A STAAD Pro report was created, which included model pictures, loads, stability and moment checks, and beam by beam information on steel type, thickness, and other data.

3.5 Methodology Conclusion

Developing a new fin fan cooler foundation design required completion of 4 objectives, discussed in the beginning of the Methodology chapter. To fulfill the first objective of characterizing the scope of the project, different sources were consulted. To complete the background research and define the scope of the project, Stantec staff, along with various online and printed resources, was referred to. To develop the preliminary design, part of objective 2, various calculations were performed, including load design calculations, and appropriate design materials and elements. Iterative design decisions were made throughout the entire project in order to make the design more feasible, and were part of objective 3. Having completed all of the objectives enabled our team to generate Chapter 4 of the report: Results and Analysis.

Chapter 4: Results and Analysis

The goal of this MQP project was achieved through fulfilling 4 objectives of the project. In this chapter, the resulting design of the cooler foundation is discussed.

4.1 Project Scope and Plant Conditions Findings

A project scope report prepared by Stantec engineers provided information on the proposed renovation of the client refinery components. The facility required a new compressor and the new frame lube oil skid with associated fin fan cooler. After the initial site assessment, the glycol fin fan cooler system was picked for all existing and the new compressors. Two 132 H coolers were chosen to be purchased from Harsco Air-X-Changers manufacturer. Harsco Industrial Air-X-Changers Model H is a skid-mounted, horizontal cooler used in a variety of applications (Harsco Industrial Air-X-Changers, n.d.) with the following performance:

Table 10: Fin Fan Cooler Parameters (Stantec Staff Interview, 2014)

Air-side Performance		**Fan Data**		**Driver Data**	
Ambient air Tem. In, f	85	No. Fans/Make	**1/Moore-CL10K**	Type Electric	**Motor**
Elevation, ft	1000	Blade Material	**Aluminum**	HP/SF	**25/1.00**
Air Flow, SCFM	137,194	HP@RPM	**18.82@275**	RPM	**1800**
Air Temp., Out, f	107.2	Dia., in/No.	**Blades 132/6**	Enclosure	**TEFC**
Min Ambient, f	-20	Series/Blade Adj.	**48HD**	Volt/Ph/Hz	**480-3-60**

Consulting the project scope package report developed by Stantec staff for the client refinery helped identify key design parameters of the cooler foundation. It was stated in the report that the fin fan should set on a structural steel frame approximately 2.44 meters high. Additionally, the frame legs were to be supported by piers, 0.03 meters above grade. Concrete footing was to be located 1.2-1.8 m below grade or on bedrock for frost protection. The cooler system was chosen to be located to the south of the extended compressor shelter. This information was chosen as a basis for the cooler foundation design.

Lastly, a geotechnical investigation was conducted on site by an independent geotechnical engineer. The geotechnical investigation found the bedrock geology at the site to be sedimentary rocks, consisting of green, gray, and black shale, siliceous siltstone and sandstone. This information meant that no settlement is expected in the area, and it was not considered in the foundation design. However, it was recommended in the geotechnical report that the footings are not placed on frozen ground. A minimum soil cover of 0.6 m was recommended to protect the foundation from frost.

4.2 Final Design Parameters

In this section, final design parameters of the cooler foundation, developed according to the Methodology chapter, are presented.

4.2.1 Steel Frame

Two fin fan coolers, with dimensions in meters (WLH) of: 3.66-4.27-2.67 each, are to be supported by the steel frame. Each cooler weighs approximately 543 kg (as provided by the manufacturer). A space steel frame was created, sized appropriately to support both coolers. Dimensions of the frame in meters are as follows (WLH): 4.27-7.92-2.44. A table with Steel frame parameters can also be found in Appendix E. Steel braces were inserted on columns on 4 ends of the frame for better load distribution and stability of the structure, 1.22 meters away from the frame top. The frame was designed so that there is a 0.6 m gap between the two coolers, for easier access and safety of the maintenance workers. Figure 14 illustrates all the parameters:

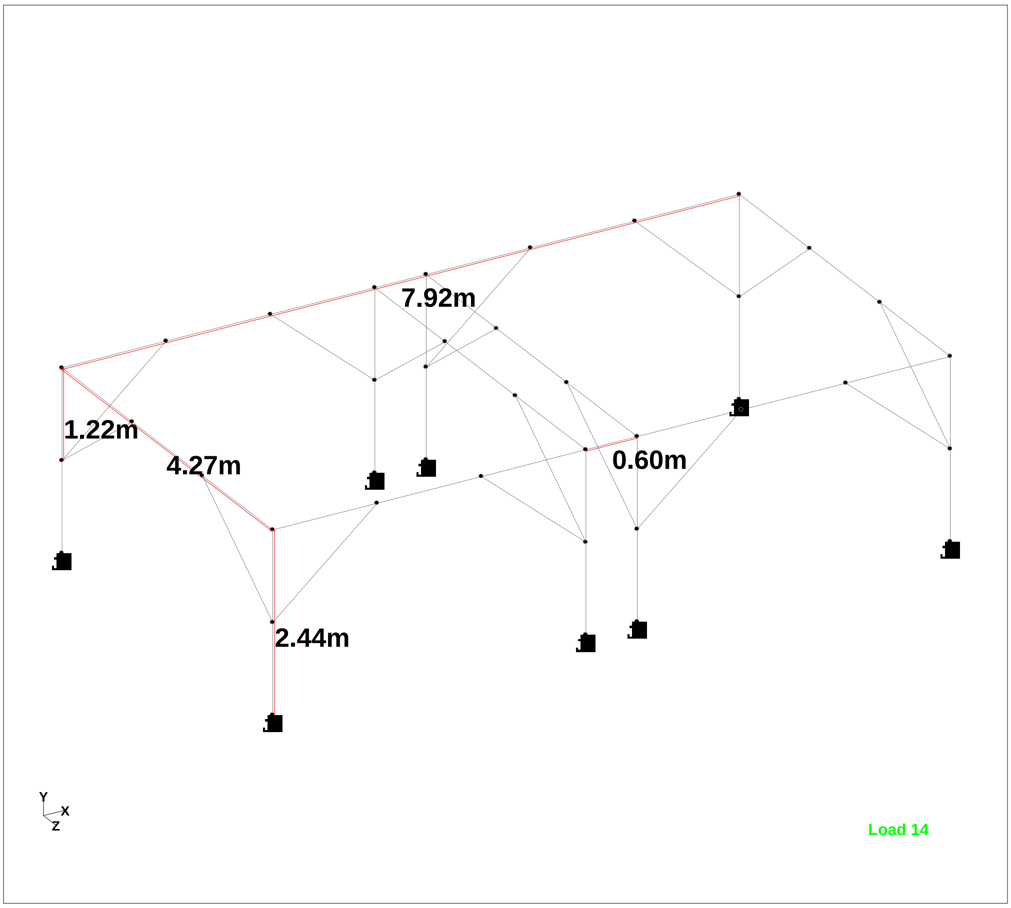


Figure 14: Final Steel Frame Dimensions

The picture of the model in Figure 14 has red lines to indicate dimensions of the frame, and corresponding numbers are illustrated, as well.

Detailed information on the beams used in the frame is provided in Table 11:

Table 11: Beam Properties

Section	**Area** (cm^2)	I_{yy} (cm^4)	I_{zz} (cm^4)	**J** (cm^4)	**Material**
W8X15	28.645	141.519	2E 3	5.008	Steel

This width is enough to support all expected loads and load combinations in Table 12. Load combinations in the format that they were entered into STAAD Pro are located in Appendix F.

Table 12: Load Combinations for Ultimate Limit States

Load envelopes	Load Combinations
1	1.4 D
2	1.25D + 1.5L + 0.5S
3	1.25D + 1.5S + 0.5L
4	1.25D + 1.4W + 0.5L
5	1.25D + 1.4W + 0.5S
6	0.9D + 1.4W
7	0.75WX+0.75WZ

The final model in STAAD Pro is included in Figure 15. It includes the full beam sections, final parameters, and the largest wind load combination illustrated. In STAAD Pro software, this model can also be viewed in 3-D.

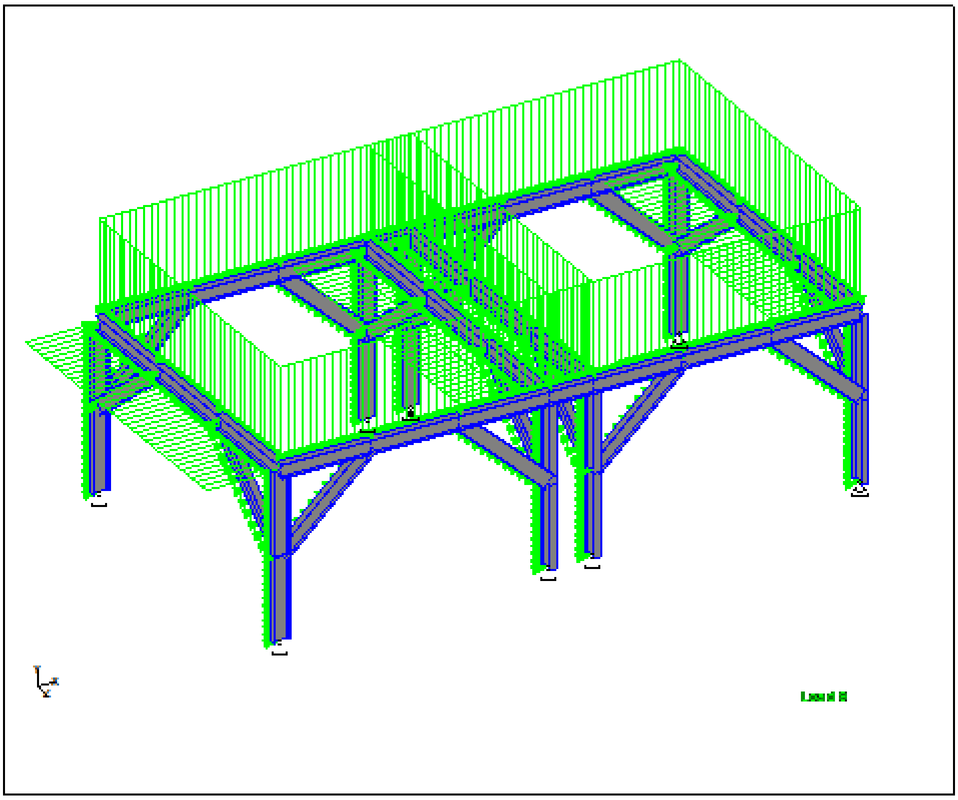


Figure 15: Steel Frame Final Model Full Sections

Successful completion of the steel frame design enabled our design team to develop a design for the appropriate concrete footing.

4.2.2 Concrete Footing

To ensure that the design footing was sized properly to bear all the associated loads, the steel support columns were inspected. It was identified, that the columns on the edges of the steel structure are exposed to a larger load combination. Thus, the footing is designed for the largest load case scenario, and no separate calculations were made on the middle columns. The footing size was initially assumed to be 1500 mm by 1500 mm, and further adjusted to satisfy the design loads. The final size measurements were identified by trial and error method. Detailed calculations are included in section 3.2.2.3 and the final size measurements are included in Table 13.

Table 13: Concrete Footing Design Dimensions

	Dimension	**Units**
Height of the footing	0.3	m
Depth to reinforcement	0.215	m
Width of the footing	1.5	m
Length of the footing	1.5	m
Height of the pedestal	1.1	m
Width of the pedestal	0.47	m
Anchor bolts diameter	19.05	mm

It was important to keep in mind that even though concrete has good compressive properties, it needs reinforcement to resist the tensile forces. It is a common practice to insert steel bars on the top and the bottom of the concrete footing, to strengthen it and prevent fracture. For the size of the footing and then loads it is exposed to, it was decided that 20 steel bars will be inserted on the top and the bottom of the footing, 250 mm apart from each other. The isolated type of footing was chosen for this particular project.

After the optimal size of the footing was determined, anchor bolts were selected for the footing and the pedestal was designed in Hilti PROFIS Anchor software. The final anchor bolts and pedestal design can be viewed in Figure 16. Also, a full report of the design can be found in Appendix I. Cast in cocnrete anchor bolts were used in the project, with a rectangular anchor pattern and a rectangular base plate.

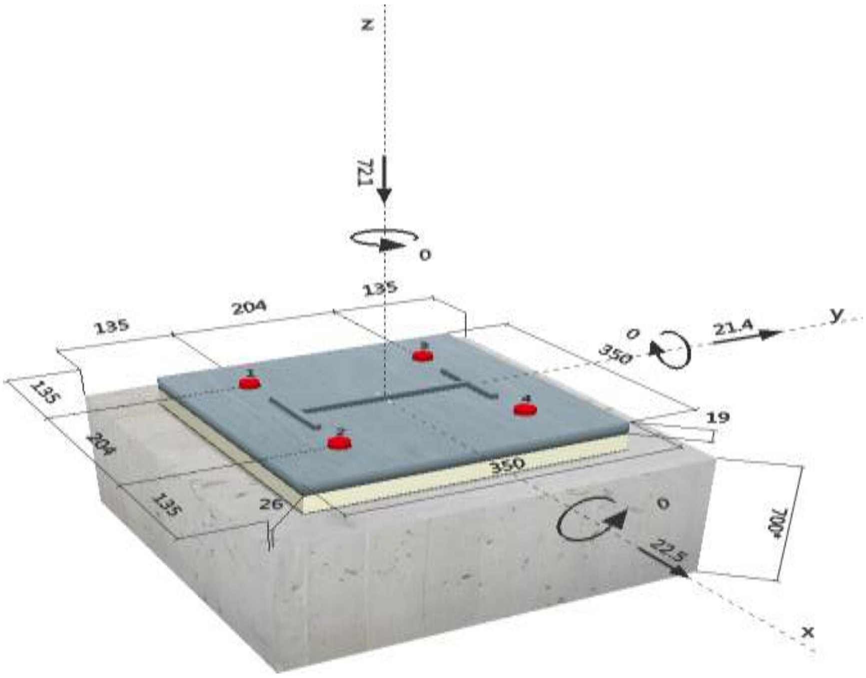


Figure 16: Anchor Bolts Design

Lastly, the concrete pedestal was sized appropriately for the footing. The final design of the pedestal is illustrated in Table 14. A grid of 12 steel bars was selected for this pedestal, to reinforce the concrete and increase pedestal's bearing properties.

Table 14: Final Pedestal Design

Parameter	Value	Unit
Width of the pedestal	457	mm
Height of the pedestal	457	mm
Height of the pedestal	1100	mm
Number of Steel Bars	12	
Bar Designation No.	25	mm
Bar Nominal Mass	3.925	kg/m

4.3 Recommendations

The final design of the cooler foundation complies with the National Building Code of Canada. Throughout the project, it was ensured that the load and size calculations were correctly performed, and the design was effective.

However, there are 2 adjustments for this foundation design that our design team wasn't able to perform due to the lack of time. Both of those adjustments are discussed further here, and are referred to as Recommendation 1 and Recommendation 2.

Recommendation 1 – The final design of the steel structure includes a 0.6 m gap in the middle of the frame. It was initially inserted for easier access for maintenance, to allow workers to walk under the structure without health hazards (bumping their heads). However, it was later identified that the cooler top is expected to be leveled with the top of the frame as opposed to sitting on top of the frame. Thus, having a gap in the middle of the structure was not anymore feasible. The Stantec design team is recommended to return to the original steel frame design that was created in week 2 of the project and can be viewed in Figure 12: Preliminary Design Week 2. This would allow the design team to create a smaller footing in the middle and avoid costs associated with materials and construction tools.

Recommendation 2 – check the uplift caused by the wind load. Our design team identified a fairly large uplift load – pressures from wind flow which cause lifting effects. For this project, it was assumed that the downward vertical loads are significantly larger than the uplift load. However, in order to avoid the uplift, the structure could have been checked with the software published by the National Research Council of Canada (the same publisher of the 2005 NBCC), specifically developed for the calculations of roof specified design wind uplift pressures.

Both of these recommendations require further work on the design, to ensure a safe and stable foundation structure.

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Appendix A: Proposal

Design and evaluation of a cooler foundation at an oil refinery

MQP Proposal

Sponsored by Stantec

Shakhizada Issagaliyeva

Professor Susan LePage, Co-Advisor
Professor Frederick Hart, Co-Advisor

December 19, 2013

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Chapter 1: Introduction

Stantec is an international professional services company in the design and consulting industry that provides professional consulting services in planning, engineering, architecture, interior design, environmental sciences, and many other sustainable community design aspects. It is seeking to develop design recommendations for an oil refinery compressor foundation in Newfoundland, Canada.

To assist Stantec in achieving this goal, the specific needs of the company for a compressor facility foundation and information regarding different types of compressors and their applications will be identified. Additionally, economic, infrastructural, environmental, and effectiveness constraints particular to that facility will be identified by the design team. Using these data, a preliminary design of a compressor foundation will be developed, satisfying constraints mentioned above. Laboratory experiments will be conducted in the lab to test the feasibility of the preliminary design. Finally, recommendations outlining a proposed design will be developed.

Chapter 2: Background

In this chapter, the concept of an industrial gas compressor is introduced along with detailed information on major compressor and appropriate foundation types.

2.1 Industrial Gas Compressors

A gas compressor is a mechanical device that increases the pressure of a gas by reducing its volume. It is capable of converting electrical power into kinetic energy, specifically by utilizing compressed air. When this air is released in a quick burst, it releases an amount of kinetic energy that can be harnessed for a number of purposes, including pneumatic device activation, air transfer, and cleaning operations (Air Compressors, n.d.).

2.1.1 Types Of Compressors In An Oil Refinery

Compressors constitute an important part of the mechanical equipment in oil and gas refineries and petrochemical plants. They are separated in two main groups – positive displacement and dynamic – according to the mechanism by which they generate compressed air (Air Compressors, n.d.). Compressor types and subcategories are shown in Figure 1below.

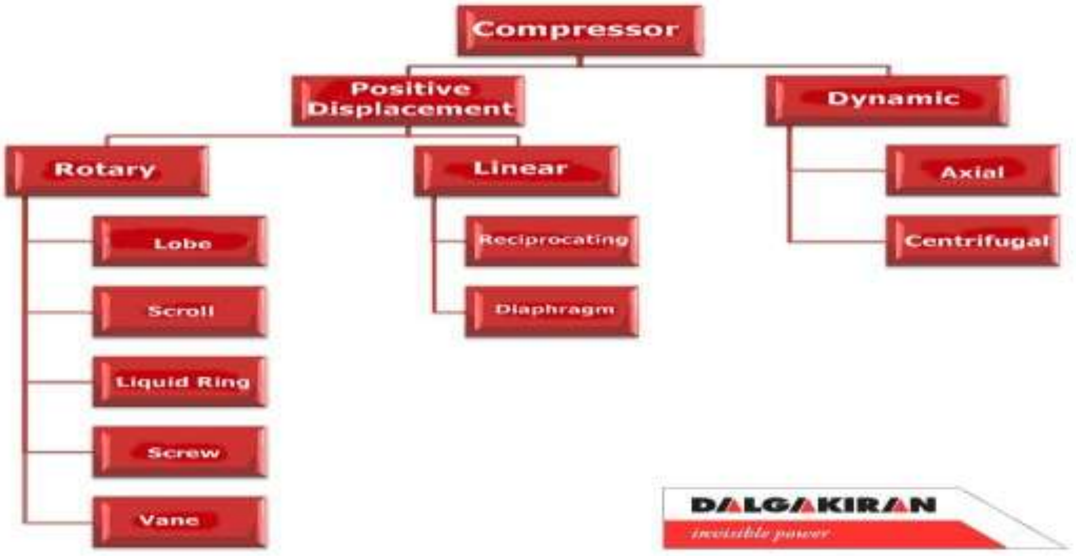


Figure 17: Types of Compressors

Electrically-driven reciprocating, centrifugal and screw compressors are most commonly used in oil and gas refining facilities and are further discussed below.

2.1.1.1 Reciprocating Compressors

Reciprocating compressors are used for oil and oil free compression. For high-pressure hydrogen service, such as hydrocracking, reciprocating compressors are used for make-up gas service (Dalgakiran Air Compressors, n.d.). A reciprocating compressor uses the reciprocating action of a piston inside a cylinder to compress refrigerant.

2.1.1.2 Centrifugal Compressors

Centrifugal compressors are typically employed for recycle gas service in high pressure hydrogen service. Centrifugal compressors use the rotating action of an impeller wheel to exert centrifugal force on refrigerant inside a round chamber. Centrifugal compressors are well suited to compressing large volumes of refrigerant to relatively low pressures. Centrifugal compressors are desirable for their simple design and few moving parts (Dalgakiran Air Compressors, n.d.).

2.1.1.3 Screw Compressors

Screw compressors are used throughout oil refineries in applications ranging from vapor recovery to gas-processing operations. They use two reciprocal screws to compress gases (Brown, 2005). Gas is fed into the compressor by suction and moved through the threads by the rotating screws. Compression takes place as the clearance between the threads decreases, forcing the compressed gas to exit at the end of the screws (Dalgakiran Air Compressors, n.d.).

2.2 Industrial Gas Compressor Foundation Design

Heavy machinery with reciprocating, impacting, or rotating masses requires a support system that can resist dynamic forces and the resulting vibrations (Foundations for Dynamic Equipment, n.d.). When excessive, such vibrations may damage the machinery and its support system. Thus, design of an appropriate compressor foundation is an important step in compressor installation.

2.2.1. Reciprocating Compressor Foundation Specifications

In reciprocating compressors, a piston moving in a cylinder interacts with a fluid through the kinematics, producing vibration that must be taken into account when designing a foundation. To absorb the vibration, it is advised to install the compressor on a concrete block foundation (Kuly, 2010). Concrete absorbs vibration more easily than a steel frame or skid because its internal molecular structure absorbs vibration energy. The optimal weight of the foundation is 4 to 8 times the weight of the compressor, and the width is at least 1.5 times its height. If a skid was chosen as a foundation, the steel is stiffened by either running the anchor bolts to the top of the skid or filling the void spaces inside the skid with epoxy grout (Kuly, 2010).

2.2.2. Centrifugal Compressor Foundation Specifications

The heavy compressor vibrating machines are typically supported on concrete table top pedestal that includes a mat foundation and supports two units (Kuly, 2010). A typical centrifugal compressor, including all of its rotating elements, is usually balanced to a minimum of four times the weight of the rotor, which leads to very small residual unbalance. Low unbalance force also results in a smaller foundation size, compared to a reciprocating compressor station. However, the dynamic load is very high on the foundation of the reciprocating machines, translating to higher civil engineering costs (Energy-Tech Magazine, 2005).

2.2.3 Screw Compressor Foundation Specifications

Screw compressors typically work with a positive displacement rotary design. Therefore, they have the characteristics of reciprocating compressors but have lower vibrations and a reduced physical size (Rotary Twin Screw Compressors, 2007). Under most conditions, no elaborate foundation is necessary. However, a proper foundation is necessary to maintain motor alignment and proper elevation (Emerson Climate Technologies, 2012). The foundation needs to be permanently exposed against the earth. If it is to be installed indoors, the floor has to be broken up to get to the earth. Additionally, if the installation will take place on the upper floors of the building, rubber or spring isolators should be used to prevent package vibration transferring directly to the building structure. (Rotary Screw Compressor Units with Microprocessor Control, 2000)

Chapter 3: Methodology

Stantec's client requires a design for installing a new compressor foundation. Information to develop a design of a new compressor foundation for the facility is therefore needed. The goal of this project will be to investigate different compressor foundation options and provide a design for the most feasible one. This foundation will have to conform to API 686 and GMRC recommended practices for reciprocating compressor foundations.

The first step will be to obtain and analyze data to explore various compressor foundation options. Using these data, the benefits and disadvantages of these options for the client's plant will be identified. This information will be used to develop recommendations for an appropriate compressor.

The objectives of the project are to:

1) Characterize the scope of the project and existing compressor foundation options

2) Identify evaluative criteria to compare possible solutions based on economic, infrastructural, environmental, and constructability factors applicable to this plant.

3) Evaluate and determine preliminary design alternatives based on Stantec-approved criteria

4) Specify design requirements and appropriate modeling materials and tools for the compressor foundation

5) Create an engineering presentation of the design feasibility, societal impact and tradeoffs

The below sections describe methods that will be used to achieve each of these objectives.

3.1. Characterizing the scope of the project and existing compressor foundation options

Through background research, different types of compressor foundations installed at modern oil refinery plants will be identified. The next step will be to outline the project scope, which will involve Stantec staff and the client plant managers. Gathering and investigating this information will identify potential foundation design options.

Various methods will be used to gather the required information. It will be important to consult with Stantec to identify their view on the compressor foundation design for the plant. A site visit to the plant will be an excellent source of information. Interview guides will be developed to organize the data acquired in interviews with Stantec and the plant staff. Necessary lab experiments will be identified and developed for testing the foundation design feasibility.

3.2. Identifying evaluative criteria to compare possible solutions based on economic, infrastructural, environmental, and constructability constraints applicable to the client plant

Next objective is to identify and evaluative criteria to Stantec for the compressor options. Most relevant constraints specific to the client plant, including economic, infrastructural, environmental, and constructability will be considered when identifying which criteria will affect the design decision.

The proposed compressor facility design has to satisfy a number of different constraints to be considered feasible. To ensure that, many different sources will be consulted to collect information on each of the constraints specifically to Canada. Gathering and analyzing this information will generate a list of selected criteria to further assist in determining the most feasible compressor design.

Below is the preliminary evaluative criteria table, subject to change as more information is obtained.

Table 15: Preliminary Evaluative Criteria

	Criteria			
Factors	Economic	Infrastructural	Environmental	Constructability
	Price of construction materials	Building structure	Noise	Vibration elimination
	Price of installation	Water table under the building	Industrial standards	Operation speed
	Maintenance frequency and price	Soil conditions		Duration of life
		Floor thickness		power rating of motor

	Intake air		Size and weight of the foundation

3.3. Evaluating preliminary design alternatives

The third objective is to use the criteria determined in Section 3.2, to evaluate and compare each of the potential compressor options. It will allow the Stantec team to determine which of the compressor foundation options is most feasible for the client plant. It is also important to consider the API 686 and GMRC recommended practices in evaluating preliminary designs. Finalizing this objective will assist us in moving on to the next objective.

3.4. Specifying design requirements and appropriate modeling materials and tools for the compressor foundation

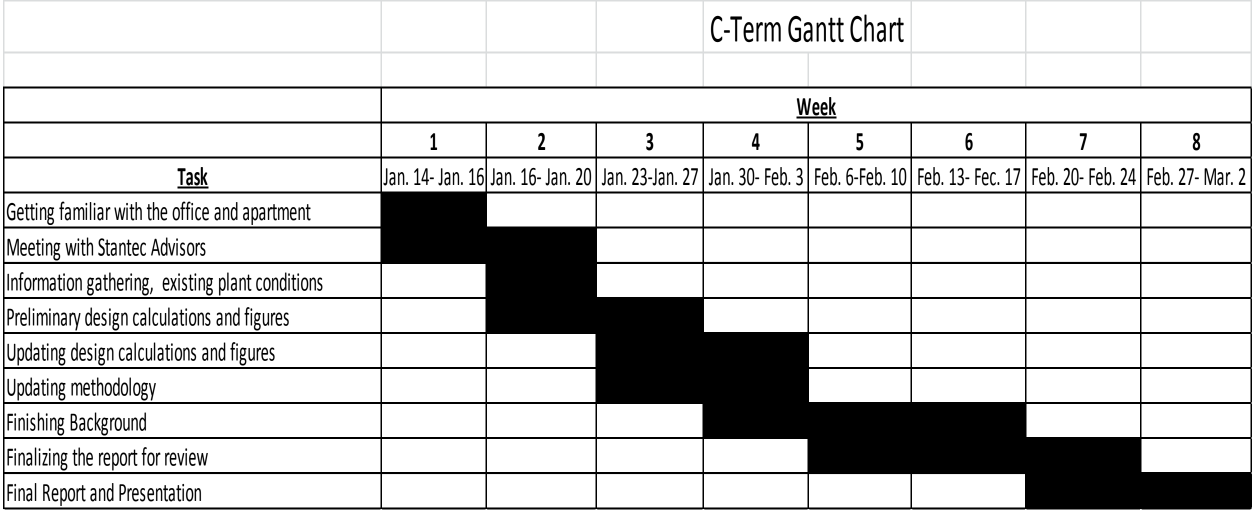
The fourth objective is to define the overall system configuration and provide schematics, diagrams, and layouts of the project. To define the general framework and operating parameters, external dimensions, material and reliability requirements, as well as maintenance requirements will be fixed. Multiple compressor foundation installation manuals will be consulted to fulfill this objective. Lab experiments at the Stantec geotechnical lab will be conducted to examine different foundation properties.

3.5 Creating an engineering presentation of the design feasibility, societal impact and tradeoffs

The final objective of the project is to examine the preliminary design based on the 4 criteria developed in Section 3.2. This will allow us to review the design solution and help identify problems to be fixed. This objective will discuss how the new foundation design fulfills the economic, infrastructural, environmental and constructability criteria and a conclusion will be included in the final report. In addition, it will discuss how the foundation meets API 686 and GMRC guidelines for reciprocating compressor foundation.

3.6 Methodology Conclusion

Completion of these five objectives will result in a design of the most feasible compressor type specific to the client plant. Below is a tentative schedule for onsite research to be conducted between January 1, 2013 and March 3, 2013.



C-Term Gantt Chart

	Week							
	1	2	3	4	5	6	7	8
Task	Jan. 14- Jan. 16	Jan. 16- Jan. 20	Jan. 23-Jan. 27	Jan. 30- Feb. 3	Feb. 6-Feb. 10	Feb. 13- Fec. 17	Feb. 20- Feb. 24	Feb. 27- Mar. 2
Getting familiar with the office and apartment	■							
Meeting with Stantec Advisors	■	■						
Information gathering, existing plant conditions		■						
Preliminary design calculations and figures		■	■					
Updating design calculations and figures			■	■				
Updating methodology			■	■				
Finishing Background				■	■	■		
Finalizing the report for review					■	■	■	
Final Report and Presentation							■	■

Figure 18: Tentative Schedule

Deliverables

The final deliverable of this project will be a report on the proposed design of a compressor foundation at the client plant, which will include design requirements for the compressor facility and appropriate modeling materials and tools. Design development will also include a close look on economic, infrastructural, environmental, and constructability criteria approved by Stantec. In addition, 2 lab reports will be produced as a result of foundation testing experiments at the geotechnical lab at Stantec.

The capstone design component of the project, which is the final design for the foundation improvements we recommend, will be presented in a report that will be submitted to both Stantec and WPI.

Capstone Design

The Accreditation Board for Engineering and Technology (ABET) requires that all accredited engineering programs include a capstone design experience. This requirement is met at WPI through the Major Qualifying Project (MQP). The following report considered 8 constraints relevant to the project. They are as follows:

- Economic – the cost of the project will be evaluated, including capital investment for technology and maintenance costs.
- Infrastructural – the project is feasible when produced with as few resources possible, including parts, labor, and maintenance. Constructability of the new compressor will be examined by the existing infrastructure at the plant.
- Environmental and Sustainability – the foundation design will consider important environmental aspects, including pollution, health and safety, and sustainability. More aspects may be discovered in the process, to ensure that impacts and mitigation of the compressor project are minimized.
- Constructability – the foundation design will be examined based off a number of interdependent project-related factors, including effectiveness of the foundation and the extent to which the design of the building facilitates ease of construction.
- Ethical – the project should not interfere with the code of ethics followed by Stantec employees, including considerations for the public, clients, employers, and the profession.
- Political – foundation design's political aspect will be taken into account, including political impact of the project. However, due to the nature of the project, political impact will be marginal.
- Health and Safety – the foundation design will ensure that routine operations will not present a risk of hazardous exposure to the plant workers and satisfies proper industry standards for design, construction, and operation.

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Appendix B: Importance Category Table for Buildings

(National Building Code of Canada, 2005)

Table 4.1.2.1.
Importance Categories for Buildings
Forming part of Sentence 4.1.2.1.(3)

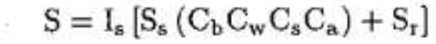
Use and *Occupancy*	**Importance Category**
Buildings that represent a low direct or indirect hazard to human life in the event of failure, including: • low human-*occupancy buildings*, where it can be shown that collapse is not likely to cause injury or other serious consequences • minor storage *buildings*	Low
All *buildings* except those listed in Importance Categories Low, High and Post-disaster	Normal
Buildings that are likely to be used as post-disaster shelters, including *buildings* whose primary use is: • as an elementary, middle or secondary school • as a community centre Manufacturing and storage facilities containing toxic, explosive or other hazardous substances in sufficient quantities to be dangerous to the public if released.	High
Post-disaster buildings are *buildings* that are essential to the provision of services in the event of a disaster, and include: • hospitals, emergency treatment facilities and blood banks	Post-disaster

Table 4.1.2.1.
Importance Categories for Buildings
Forming part of Sentence 4.1.2.1.(3)

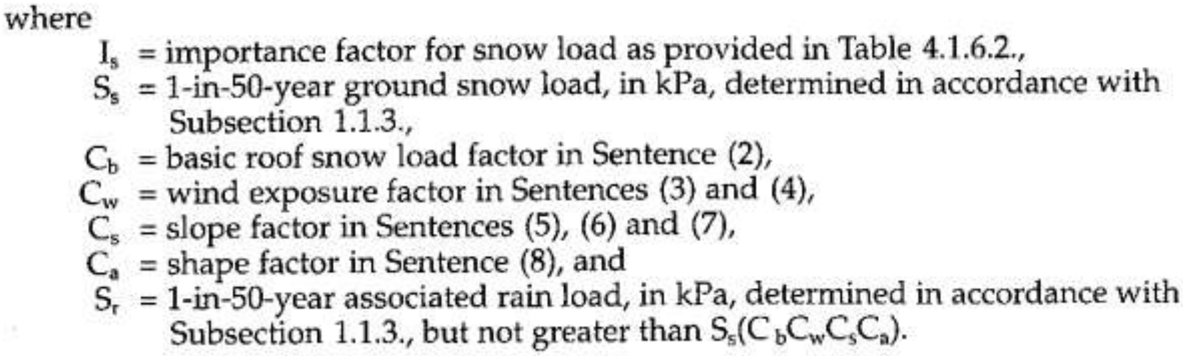
Use and *Occupancy*	Importance Category

• telephone exchanges
• power generating stations and electrical substations
• control centres for air, land and marine transportation
• public water treatment and storage facilities, and pumping stations
• sewage treatment facilities and *buildings* having critical national defence functions
• *buildings* of the following types, unless exempted from this designation by the *authority having jurisdiction*: EXISTING PROVISION Table 4.1.2.1. Footnote (2)
    • emergency response facilities
    • fire, rescue and police stations, and housing for vehicles, aircraft or boats used for such purposes
    • communications facilities, including radio and television stations	

Appendix C: Snow Load Calculations



$$S = I_s [S_s (C_b C_w C_s C_a) + S_r]$$



where

I_s = importance factor for snow load as provided in Table 4.1.6.2.,

S_s = 1-in-50-year ground snow load, in kPa, determined in accordance with Subsection 1.1.3.,

C_b = basic roof snow load factor in Sentence (2),

C_w = wind exposure factor in Sentences (3) and (4),

C_s = slope factor in Sentences (5), (6) and (7),

C_a = shape factor in Sentence (8), and

S_r = 1-in-50-year associated rain load, in kPa, determined in accordance with Subsection 1.1.3., but not greater than $S_s(C_b C_w C_s C_a)$.

Ss = 2.4 kPa

Cb = 0.8

Cw = 1.0

Cs = 1.0

Ca = 1.0

Sr = 0.7 kPa

S = Is (Ss (CbCwCsCa)+Sr.

A = l*h = (3.66*4.27) m2 = 15.63 m2

P = (2*3.66 + 2*4.27) m = 15.86 m

S ultimate = 1.15*(2.4 (0.8*1.0*1.0*1.0))kPa + (0.7)kPa = 2908 Pa = 2.9 kPa = 2.9 kN/m2 (strength).

S ultimate = 2.9 kN/m2 * (15.63 m2)/15.86 m = 2.86 kN/m

S deflection = 1.0*(2.4 (0.8*1.0*1.0*1.0))kPa + (0.7) kPa = 2.6 kPa = 2.6 kN/m2 = S ultimate*1.116

S deflection = 2.6 kN/m2 * (15.63 m2)/15.86 m = 2.56 kN/m

S serviceability = 0.9*(2.4 (0.8*1.0*1.0*1.0))kPa + (0.7)kPa = 2428 Pa = 2.4 kPa = 2.4 kN/m2

(overturning) = S ultimate*1.207

S serviceability = 2.4 kN/m2 * (15.63 m2)/15.86 m = 2.37 kN/m

Appendix D: Wind Load Calculations

Load on the frame Columns

$Fn = I_w\ k\ C_f\ C_n\ q\ C_g\ C_e\ h\ l$ = 1.15*0.6*1.15*1.6*0.75kPa*2.0*1.0*1.0m*0.2m = 0.38 kN/m

$I_w = 1.15$

K = 0.6

$C_e = 1.0$ (standard)

l = 0.2 m

h = 1.0 m

$C_n = 1.6$, $C_t = 1.9$ (Figure I-29, NBC of Canada, 2005)

q -From Table C-2 c-36 division b, hourly wind pressures q are 0. 58 kPa for 1/10 and 0.75 kPa for 1/50 in Newfoundland. 10 year and 50 year return periods, use 0.75 kPa.

C_f for walls above ground = 1.15 from figure I-23, Commentary I, Part 4 of Divison B.

To obtain gust effect factor, C_g, section 4.1.7.1, division B, volume 2 of the national building code of Canada was referred to, and $C_g = 2.0$ for the building as a whole and main structural members was assumed.

Load on the cooler

$Fn = I_w$ Cf Cn q Cg Ce h l_1 = 1.15*1.15*1.0*0.75kPa*2.0*1.0*2.67m*4.57m = 24.2 kN

Fn = 21.0 kN/4.27 m*2 = 2.83 kN/m (in ± Z direction)

$Fn = I_w$ Cf Cn q Cg Ce h l_2 = 1.15*1.15*1.0*0.75kPa*2.0*1.0*2.67m*3.66m = 19.4 kN (in)

Fn = 16.9 kN/4.27 m*2 = 2.27 kN/m (in ± X direction)

Where l_1= 4.27 m + (0.6 m/2) = 4.57 m

L_2 = 3.66 m

h = 2.67 m

Cf (when l/h) = 1.15

Appendix E: Steel Frame Dimensions Table

	Dimension	Units
Height of the frame	2.44	m
Width of the frame	4.27	m
Length of the frame	7.92	m
Beam Thickness	8 by 15	in
Brace Thickness	8 by 15	in

Appendix F: STAAD Pro Load Combinations

Type	L/C	Name
Primary	1	DEAD LOAD
Primary	2	LIVE LOAD
Primary	4	SNOW LOAD
Primary	13	WIND LC1
Primary	3	WIND LC2
Primary	15	WIND LC3
Primary	7	WIND LOAD COOLER
Combination	5	1.4DEAD
Combination	6	1.25D + 1.5L + 0.5S
Combination	8	1.25D + 1.5S + 0.5L
Combination	9	1.25D + 1.4WIND X + 0.5L
Combination	10	1.25D + 1.4WIND Z + 0.5L
Combination	11	0.9D + 1.4WIND X
Combination	12	0.9D + 1.4WIND Z
Combination	14	1.25D + 1.4WIND X + 0.5S
Combination	16	1.25D + 1.4WIND Z + 0.5S
Combination	17	0.75 WIND X + 0.75 WIND Z

Appendix G: Footing Shear and Moment Calculations

Calculations:

Vertical Load on Footing

Load	Ps (KN)	Pf (KN)
Pv (vertical load)	57.70	72.10
W1 (column)	4.32	5.40
W2 (slab)	3.00	3.75
W3 (soil)	18.71	23.38
W4 (footing)	10.15	12.69
Total	93.87	117.32

Ground Water at Grade

Load	Ps (KN)	Pf (KN)
Pv (vertical load)	57.70	72.10
W1 (column)	2.81	3.51
W2 (slab)	1.72	2.15
W3 (soil)	8.31	10.39
W4 (footing)	5.83	7.29
Total	76.38	95.45

	Specified	Factored
Base Pressure, Q (KN/m^2)	65.19	81.47

Allowable bearing pressure not exceeded

Shear Calculations:

One-Way Shear

Vc = 0.18*landa*Fc*sqrt(fc')*bw*d =	152.62	KN	cl 11.3.4
landa =	1		
Fc =	0.6		
fc' =	30	MPa	
bw =	1200	mm	
d = tk-db/2-cover =	215	mm	
Vf = Qf*fftw*(ftl/2-cw/2-d) =	17.79	KN	OK, Vc >= Vf

Two-Way Shear

Vc1 = 0.38*l*Fc*Sqrt(fc')*bo*d =	666.94	KN	cl 13.3.4.1
Vc2 = (1+2/Bc)*Vc1/2	1053.06	KN	
landa =	1		
Qc =	0.6		
fc' =	30	MPa	
bo	2484	mm	
Bc	1.00		
d = tk-db/2-cover =	215	mm	

Vf = Qf*(ftl*ftw-((cw+d)*(cl+d))) = 85.90 KN OK, Vc >= Vf

Moment Calculations:

X Direction

Mf = w*l^2/2 = 7.70 KNm

w = Qf* width = 97.77 KN/m
l = length/2-column length/2 = 397.00 mm

As, min (x dir) = 0.002Ag = 720 mm^2
As,min (x dir) = 0.2*sqrt(fc')*bt*h/fy = 986 mm^2

Z Direction

Mf = w*l^2/2 = 7.70 KNm

w = Qf* width = 97.77 KN/m
l = length/2-colum length/2 = 397.00 mm

As, min (z dir) = 0.002Ag = 720 mm^2
As,min (z dir) = 0.2*sqrt(fc')*bt*h/fy = 986 mm^2

Bearing Pressure including Moment from Eccentricities - Foundation and Soil Weight NOT Included

Hs =	16.10	kN	Horizontal Force (X Direction) at Top of Pedestal						
hp =	1.415	m	Distance between Bottom of Footing and Top of Pedestal						
e = M/Rv =	0.395	m	L/6 =	0.200		e > L/6, Therefore No Good			
Qmaxs =	254.19	kPa	Qmaxf =	317.67	kPa	Allowable Soil Bearing Capacity :		29500	kPa
Qmins =	0.00	kPa	Qminf =	0.00	kPa	% Difference =	-99.14%		OK

Moment

Mfx = w*l^2/2 =	25.07	KNm	% Diff =	-83.98%
w_eqivl = Qf* width =	318.14	KN/m		
l = length/2-column length/2 =	397.00	mm		
Mr =	156	KNm		
Mfz = w*l^2/2 =	15.02	KNm	% Diff =	-90.40%
w_eqivl = Qf* width =	190.60	KN/m		
l = length/2-column length/2 =	397.00	mm		
Mr =	156	KNm		

Shear

Vc = 0.2*l*Fc*sqrt(fc')*bw*d =	152.62	KN
Vf = w_equ*l =	64.12	KN
w_eqivl = Qf* width =	352.29	KN/m
l = length/2-column length/2 -d=	182.00	mm

Bearing Pressure including Moment from Eccentricities - Foundation and Soil Weight Included

Hs = 16.10 kN Horizontal Force (X Direction) at Top of Pedestal
hp = 1.415 m Distance between Bottom of Footing and Top of Pedestal
e = M/Rv = 0.243 m L/6 = 0.200 e > L/6, Therefore No Good
Qmaxs = 145.95 kPa Qmaxf = 182.40 kPa Allowable Soil Bearing Capacity : 29500 kPa
Qmins = 0.00 kPa Qminf = 0.00 kPa % Difference = -99.51% OK

Overturning

FOS = Mr/Mh = 0.95 Without Applied Vertical Load X-dir No Good, FOS<2
FOS = Mr/Mh = 2.47 With Applied Vertical Load X-dir OK

Sliding

FOS = Rv*Tan d/(Rh) = 1.89 Without Applied Vertical Load OK
FOS = Rv*Tan d/(Rh) = 4.89 With Applied Vertical Load OK

Moment

Mfx = w*l^2/2 = 14.40 KNm % Diff = -90.80%

w_eqivl = Qf* width = 182.68 KN/m
l = length/2-column length/2 = 397.00 mm

Mr = 156 KNm

Mfz = w*l^2/2 = 8.62 KNm % Diff = -94.49%

w_eqivl = Qf* width = 109.44 KN/m
l = length/2-column length/2 = 397.00 mm

Mr = 156 KNm

Shear

Vc = 0.2*l*Fc*sqrt(fc')*bw*d = 152.62 KN

Vf = w_equ*l = 36.82 KN

w_eqivl = Qf* width = 202.29 KN/m
l = length/2-column length/2 -d= 182.00 mm

Bearing Pressure including Moment from Eccentricities - Foundation and Soil Weight Included with Ground Water at Grade

Hs = 16.10 kN Horizontal Force (X Direction) at Top of Pedestal
hp = 1.415 m Distance between Bottom of Footing and Top of Pedestal
e = M/Rv = 0.298 m L/6 = 0.200 e > L/6, Therefore No Good
Qmaxs = 140.63 kPa Qmaxf = 175.74 kPa Allowable Soil Bearing Capacity 29500 kPa
Qmins = 0 kPa Qminf = 0.00 kPa % Difference = -99.52% OK

Overturning

FOS = Mr/Mh = 0.49 Without Applied Vertical Load X-dir No Good, FOS<2
FOS = Mr/Mh = 2.01 With Applied Vertical Load X-dir OK

Sliding

FOS = Rv*Tan d/(Rh) = 0.97 Without Applied Vertical Load No Good, FOS<1.5
FOS = Rv*Tan d/(Rh) = 3.98 With Applied Vertical Load OK

Moment

Mfx = w*l^2/2 = 13.87 KNm % Diff = -91.14%

w_eqivl = Qf* width = 176.01 KN/m
l = length/2-column length/2 = 397.00 mm

Mr = 156 KNm

Mfz = w*l^2/2 = 8.31 KNm % Diff = -94.69%

w_eqivl = Qf* width = 105.45 KN/m
l = length/2-column length/2 = 397.00 mm

Mr = 156 KNm

Shear

Vc = 0.2*l*Fc*sqrt(fc')*bw*d = 152.62 KN

Vf = w_equ*l = 35.47 KN

w_eqivl = Qf* width = 194.90 KN/m
l = length/2-column length/2 -d= 182.00 mm

Appendix H: Beam with Tension Reinforcing in the Footing

Loads	Value	Units
Factored Moment (Mf) =	25.1	kNm
Specified Moment (Ms) =	20.1	kNm

Beam	Value	Units
Depth (h) =	300	mm
Width (b) =	1200	mm

Reinforcing			20 M bars @ 150 mm =	2000	mm^2/m	2400	mm^2
Bottom Reinforcing (As) =	2400	mm^2	As, min (x dir) = 0.002Ag =	720	mm^2		
Dist. Top of Beam to Bottom Rebar (d) =	214	mm	As,min (x dir) = 0.2*sqrt(fc')*bt*h/fy =	986	mm^2		

Concrete		
Compressive strength footing (fc') =	30.0	MPa
Density of concrete =	23.5	KN/m^3
Qc =	0.6	

Reinforcement		
Yield strength (fy) =	400	MPa
Qs =	0.85	

Calculations:

Mr = As*Qs*fy*(d-(As*Qs*fy/(1.7*Qc*fc'*b))) =	156.5	kNm

Appendix I: Anchor Bolts Design Report

www.hilti.us **Profis Anchor 2.4.6**

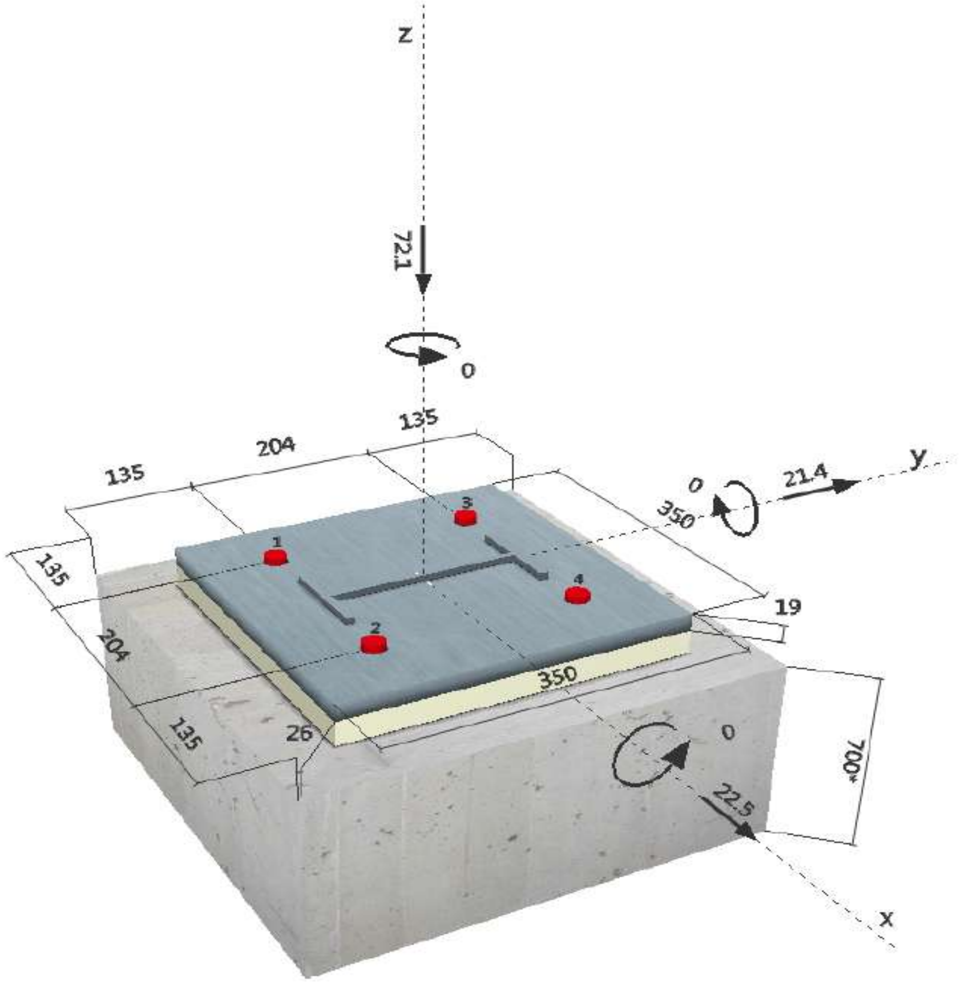
Company:		Page:	1
Specifier:		Project:	Cooler Anchor Bolts
Address:		Sub-Project I Pos. No.:	
Phone I Fax:	|	Date:	2/28/2014
E-Mail:			

Specifier's comments:

1 Input data

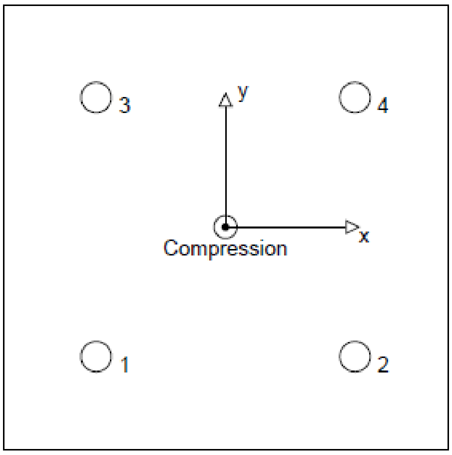
Anchor type and diameter:	**Hex Head ASTM F 1554 GR. 36 7/8**
Effective embedment depth:	h_{ef} = 635 mm
Material:	ASTM F 1554
Proof:	design method ACI 318-11 / CIP
Stand-off installation:	without clamping (anchor); restraint level (anchor plate): 2.00; e_b = 26 mm; t = 19 mm
	Hilti Grout: CB-G EG, epoxy, $f_{c,Grout}$ = 103.00 N/mm^2
Anchor plate:	l_x x l_y x t = 350 mm x 350 mm x 19 mm; (Recommended plate thickness: not calculated)
Profile:	W shape (AISC); (L x W x T x FT) = 206 mm x 102 mm x 6 mm x 8 mm
Base material:	uncracked concrete, 4000, f_c' = 4000 psi; h = 700 mm
Reinforcement:	tension: condition B, shear: condition B; edge reinforcement: > No. 4 bar

Geometry [mm] & Loading [kN, kNm]



Company:		Page:	2
Specifier:		Project:	Cooler Anchor Bolts
Address:		Sub-Project I Pos. No.:	
Phone I Fax:	|	Date:	2/28/2014
E-Mail:			

2 Load case/Resulting anchor forces



Load case: Design loads

Anchor reactions [kN]
Tension force: (+Tension, -Compression)

Anchor	Tension force	Shear force	Shear force x	Shear force y
1	0.000	7.763	5.625	5.350
2	0.000	7.763	5.625	5.350
3	0.000	7.763	5.625	5.350
4	0.000	7.763	5.625	5.350

max. concrete compressive strain: 0.02 [‰]
max. concrete compressive stress: 0.59 [N/mm^2]
resulting tension force in (x/y)=(0/0): 0.000 [kN]
resulting compression force in (x/y)=(0/0): 72.100 [kN]

3 Tension load

	Load N_{ua} [kN]	**Capacity ϕN_n [kN]**	**Utilization $\beta_N = N_{ua}/\phi N_n$**	**Status**
Steel Strength*	N/A	N/A	N/A	N/A
Pullout Strength*	N/A	N/A	N/A	N/A
Concrete Breakout Strength**	N/A	N/A	N/A	N/A
Concrete Side-Face Blowout, direction **	N/A	N/A	N/A	N/A

* anchor having the highest loading **anchor group (anchors in tension)

4 Shear load

	Load V_{ua} [kN]	Capacity ϕV_n [kN]	Utilization $\beta_V = V_{ua}/\phi V_n$	Status
Steel Strength*	7.763	37.189	21	OK
Steel failure (with lever arm)*	7.763	14.424	54	OK
Pryout Strength**	31.052	242.889	13	OK
Concrete edge failure in direction x+**	31.052	32.026	97	OK

* anchor having the highest loading **anchor group (relevant anchors)

4.1 Steel Strength

$V_{sa} = n\ 0.6\ A_{se,V}\ f_{uta}$ ACI 318-11 Eq. (D-29)

$\phi\ V_{steel} \geq V_{ua}$ ACI 318-11 Table D.4.1.1

Variables

n	$A_{se,V}$ [mm^2]	f_{uta} [N/mm^2]
1	298	399.90

Calculations

V_{sa} [kN]
71.517

Results

V_{sa} [kN]	ϕ_{steel}	ϕ_{eb}	$\phi\ V_{sa}$ [kN]	V_{ua} [kN]
71.517	0.650	0.800	37.189	7.763

4.2 Steel failure (with lever arm)

$V_s^M = \frac{\alpha_M \cdot M_s}{L_b}$ bending equation for stand-off

$M_s = M_s^0 \left(1 - \frac{N_{ua}}{\phi N_{sa}}\right)$ resultant flexural resistance of anchor

$M_s^0 = (1.2)\ (S)\ (f_{u,min})$ characteristic flexural resistance of anchor

$\left(1 - \frac{N_{ua}}{\phi N_{sa}}\right)$ reduction for tensile force acting simultaneously with a shear force on the anchor

$S = \frac{\pi (d)^3}{32}$ elastic section modulus of anchor bolt at concrete surface

$L_b = z + (n)(d_0)$ internal lever arm adjusted for spalling of the surface concrete

$\phi V_s^M \geq V_{ua}$ ACI 318-11 Table D.4.1.1

Variables

α_M	$f_{u,min}$ [N/mm^2]	N_{ua} [kN]	ϕN_{sa} [kN]	z [mm]	n	d_0 [mm]
2.00	399.90	0.000	89.396	36	0.500	22

Calculations

M_s^0 [kNm]	$\left(1 - \frac{N_{ua}}{\phi N_{sa}}\right)$	M_s [kNm]	L_b [mm]
0.517	1.000	0.517	47

Results

V_s^M [kN]	ϕ_{steel}	ϕV_s^M [kN]	V_{ua} [kN]
22.191	0.650	14.424	7.763

4.3 Pryout Strength

$V_{cpg} = k_{cp} \left[\left(\frac{A_{Nc}}{A_{Nc0}} \right) \psi_{ec,N}\, \psi_{ed,N}\, \psi_{c,N}\, \psi_{cp,N}\, N_b \right]$ ACI 318-11 Eq. (D-41)

$\phi\, V_{cpg} \geq V_{ua}$ ACI 318-11 Table D.4.1.1

A_{Nc} see ACI 318-11, Part D.5.2.1, Fig. RD.5.2.1(b)

$A_{Nc0} = 9\, h_{ef}^2$ ACI 318-11 Eq. (D-5)

$\psi_{ec,N} = \left(\frac{1}{1 + \frac{2\, e_N}{3\, h_{ef}}} \right) \leq 1.0$ ACI 318-11 Eq. (D-8)

$\psi_{ed,N} = 0.7 + 0.3 \left(\frac{c_{a,min}}{1.5 h_{ef}} \right) \leq 1.0$ ACI 318-11 Eq. (D-10)

$\psi_{cp,N} = \mathrm{MAX}\left(\frac{c_{a,min}}{c_{ac}}, \frac{1.5 h_{ef}}{c_{ac}} \right) \leq 1.0$ ACI 318-11 Eq. (D-12)

$N_b = k_c\, \lambda_a \sqrt{f'_c}\, h_{ef}^{1.5}$ ACI 318-11 Eq. (D-6)

Variables

k_{cp}	h_{ef} [mm]	$e_{c1,N}$ [mm]	$e_{c2,N}$ [mm]	$c_{a,min}$ [mm]
2	90	0	0	135

$\psi_{c,N}$	c_{ac} [mm]	k_c	λ_a	f'_c [psi]
1.250	-	24	1.000	4000

Calculations

A_{Nc} [mm^2]	A_{Nc0} [mm^2]	$\psi_{ec1,N}$	$\psi_{ec2,N}$	$\psi_{ed,N}$	$\psi_{cp,N}$	N_b [kN]
224676	72900	1.000	1.000	1.000	1.000	45.034

Results

V_{cpg} [kN]	$\phi_{concrete}$	$\phi\, V_{cpg}$ [kN]	V_{ua} [kN]
346.984	0.700	242.889	31.052

4.4 Concrete edge failure in direction x+

$V_{cbg} = \left(\frac{A_{Vc}}{A_{Vc0}} \right) \psi_{ec,V}\, \psi_{ed,V}\, \psi_{c,V}\, \psi_{h,V}\, \psi_{parallel,V}\, V_b$ ACI 318-11 Eq. (D-31)

$\phi\, V_{cbg} \geq V_{ua}$ ACI 318-11 Table D.4.1.1

A_{Vc} see ACI 318-11, Part D.6.2.1, Fig. RD.6.2.1(b)

$A_{Vc0} = 4.5\, c_{a1}^2$ ACI 318-11 Eq. (D-32)

$\psi_{ec,V} = \left(\frac{1}{1 + \frac{2 e_V}{3 c_{a1}}} \right) \leq 1.0$ ACI 318-11 Eq. (D-36)

$\psi_{ed,V} = 0.7 + 0.3 \left(\frac{c_{a2}}{1.5 c_{a1}} \right) \leq 1.0$ ACI 318-11 Eq. (D-38)

$\psi_{h,V} = \sqrt{\frac{1.5 c_{a1}}{h_a}} \geq 1.0$ ACI 318-11 Eq. (D-39)

$V_b = 9\, \lambda_a \sqrt{f'_c}\, c_{a1}^{1.5}$ ACI 318-11 Eq. (D-34)

Variables

c_{a1} [mm]	c_{a2} [mm]	e_{cV} [mm]	$\psi_{c,V}$	h_a [mm]
135	135	0	1.400	700

l_e [mm]	λ_a	d_a [mm]	f'_c [psi]	$\psi_{parallel,V}$
178	1.000	22	4000	1.000

Calculations

A_{Vc} [mm^2]	A_{Vc0} [mm^2]	$\psi_{ec,V}$	$\psi_{ed,V}$	$\psi_{h,V}$	V_b [kN]
95985	82013	1.000	0.900	1.000	31.025

Results

V_{cbg} [kN]	$\phi_{concrete}$	$\phi\, V_{cbg}$ [kN]	V_{ua} [kN]
45.751	0.700	32.026	31.052

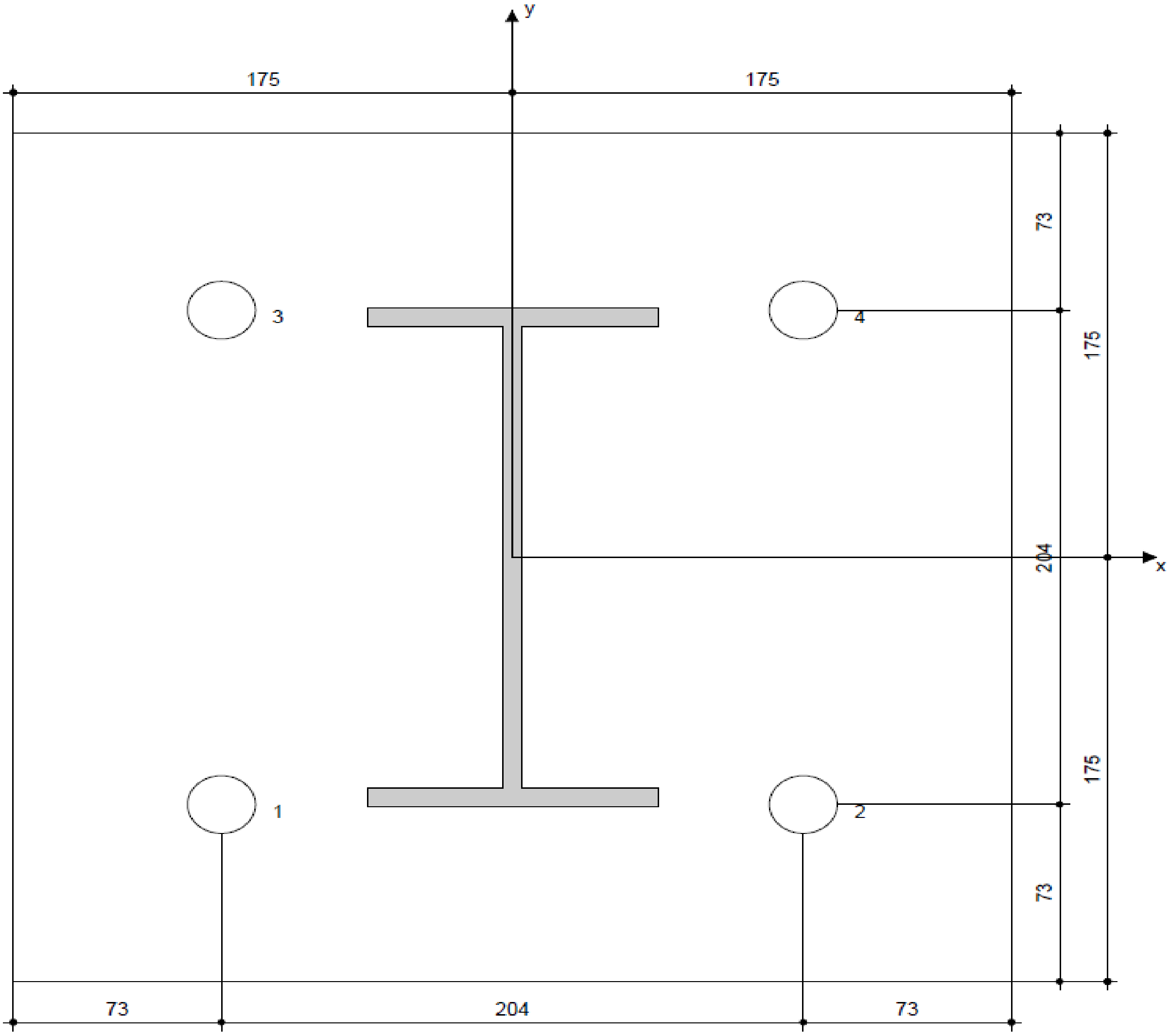
www.hilti.us **Profis Anchor 2.4.6**

Company:		Page:	6
Specifier:		Project:	Cooler Anchor Bolts
Address:		Sub-Project I Pos. No.:	
Phone I Fax:	|	Date:	2/28/2014
E-Mail:			

6 Installation data

Anchor plate, steel: -
Profile: W shape (AISC); 206 x 102 x 6 x 8 mm
Hole diameter in the fixture: d_f = 24 mm
Plate thickness (input): 19 mm
Recommended plate thickness: not calculated
Cleaning: No cleaning of the drilled hole is required

Anchor type and diameter: Hex Head ASTM F 1554 GR. 36, 7/8
Installation torque: 0.000 kNm
Hole diameter in the base material: - mm
Hole depth in the base material: 635 mm
Minimum thickness of the base material: 687 mm



Coordinates Anchor mm

Anchor	x	y	c_{-x}	c_{+x}	c_{-y}	c_{+y}
1	-102	-102	135	339	135	339
2	102	-102	339	135	135	339
3	-102	102	135	339	339	135
4	102	102	339	135	339	135

Results

V_s^M [kN]	ϕ_{steel}	ϕV_s^M [kN]	V_{ua} [kN]
22.191	0.650	14.424	7.763

Appendix J: Concrete Pedestal Design Calculations

Compression Failure	Example 15.2, pg 524			
x =	230.3817	mm	Change "x" until M-pr = 0	
Cc*((w/2-e)-0.85*x/2)+C's*((w/2-e)-cr)+T*(d-(w/2-e))	3.39E-05			M_pr = 0,
% Area of reinforcement in Compression A's =	50%			
% Area of reinforcement in Tension Ast =	50%			
Cc=0.85*Qc*f'c*b*(0.85*x) =	1369.224	kN		
C's=A's(Qs*f's-0.85*Qc*f'c) =	709.1773	kN		
T = As*Qs*fy =	558.3562	kN		
Ey = fy/E =	0.002			
E's = Ec*(x-cr)/x =	0.002023		O.K. f's = fy	
Pr = Cc + C's - T =	1520.0	kN		
Mr = Cc(d^-a/2) + C's(d^-d')+T(d-d^) =	373.4	kNm		
e = Pr/Mr =	0.246	m		
Tension Failure	Example 15.3, pg 526			
x =	282.9645	mm	Change "x" until M-pr = 0	
Cc*((e-w/2)+0.85*x/2)+C's*((e-w/2)+cr)-T*((e-w/2)+d)	0.0006			M_pr = 0,
% Area of reinforcement in Compression A's =	50%			
% Area of reinforcement in Tension Ast =	50%			
Cc=0.85*Qc*f'c*b*(0.85*x) =	1681.738	kN		
C's=A's(Qs*f's-0.85*Qc*f'c) =	709.1773	kN		
T = As*Qs*fy =	742.594	kN		
Ey = fy/E =	0.002			
E's = Ec*(x-cr)/x =	0.002205		O.K. f's = fy	
Pr = Cc + C's - T =	1648.3	kN		
Mr = Cc(d^-a/2) + C's(d^-d')+T(d-d^) =	404.9	kNm		
e = Pr/Mr =	0.246	m		
If Compression Steel Does Not Yield				
x =	278.6331	mm	Change "x" until M-pr = 0	
Cc*((e-w/2)+0.85*x/2)+C's*((e-w/2)+cr)-T*((e-w/2)+d)	1.65E-05			M_pr = 0,
f's = 600*(x-cr)/x	438.4973			
Cc=0.85*Qc*f'c*b*(0.85*x) =	1655.996	kN		
C's=A's(Qs*f's-0.85*Qc*f'c) =	780.6469	kN		
T = As*Qs*fy =	742.594	kN		
Ey = fy/E =	0.002			
E's = Ec*(x-cr)/x =	0.002192		O.K. f's = fy	
Pr = Cc + C's - T =	1694.0	kN		
Mr = Cc(d^-a/2) + C's(d^-d')+T(d-d^) =	416.1	kNm		
e = Pr/Mr =	0.246	m		