Lab 3: Tall Buildings: Columns and Cantilevers

The Eiffel Tower and the Washington Monument

Lab Setup

There are four stations for this lab: The Eiffel Tower full model, and the Eiffel Tower half model, the Washington Monument full model, and the Washington Monument half model. The set up and primary purposes of the lab is explained below.

Part I - 1st Half of Lab

Groups A and B will begin with the Eiffel Tower, for which there are two stations, the full model and the partial model. Both groups will carry out a theoretical evaluation of the real structure before measuring the dimensions of the full model. They will then split up, with group A continuing to work on the full model and group B working on the partial model. Once each group is finished on its station, the two will switch.

Groups C and D will begin with the Washington Monument, for which there are two stations, the full model and the partial model. Both groups will carry out a theoretical evaluation of the real structure before measuring the dimensions of the full model. They will then split up, with group C continuing to work on the full model and group D working on the partial model. Once each group is finished on its station, the two will switch.

Part II - 2nd Half of Lab

Part I of the lab will be repeated, however now groups A and B will switch roles with groups C and D respectively.

The Eiffel Tower and the Washington Monument

The laboratory will demonstrate how tall structures need consideration both of their own dead load and the live load of the wind acting on them in their design.

You will work with two models of the Eiffel Tower, one of the complete structure, and one of only the top half of it, and two equivalent models of the Washington Monument. Wind load will be simulated in the experiment through the application of a calculated concentrated load applied at the mid height of each model. Based on the dimensions measured and wind load calculated, you will be able to predict (and then measure experimentally) bending moments and/or their equivalent force couples (tensile and compressive reactions) at the base of each model. An analysis of these values, along with those of the dead load of the structures, will reveal the extent to which each one is specifically designed so as to accommodate wind. Any differences in the form and materiality of the real structures will then be discussed with a particular focus on if and why one takes the wind into greater consideration than the other.

Important Equations

Variables

P = Concentrated load (lbs, kips)
p = Distributed load (lb/ft, kip/ft, lb/in)
h = Length over with p acts (ft, in)
M_o = Bending moment at base (lbs-ft, k-ft, lb-in)
M = Bending moment at different heights (lbs-ft, k-ft, lb-in)
d = Width of structure where M is being evaluated (ft, in)
T = Tensile vertical reaction resisting wind load (lbs, kips)
C = Compressive vertical reaction resisting wind load (lbs, kips)
x = Distance from base to **applied concentrated load**
y = **moment location** from the base

Equations

Concentrated Load (P) = p*h
**Bending Moment (M_o) at base, when concentrated load is at midheight = P*x
**Bending Moment due to distributed load as a function of height, (M) = $\frac{p*(h-y)^2}{2}$
-C = T = M/d
Percent difference = 100% * (experimental - theoretical) / theoretical

** = See Structural Study "Vertical Cantilevers Part I" and "Vertical Cantilevers Part II" for detailed explanation

Wind Load to Dead Load Ratio

Real Total Wind Load / Real Dead Load = Model Total Wind Load / Model Dead Load

Useful Conversions

1 kip = 1000 lbf
1 lbf = 4.448 N
1 inch = 2.54 cm
1 ft = 0.3048 m
100 cm = 1 m
16 ozf = 1 lbf

Notes

1. For most parts of the course, we use historical units, eg. lbs
2. Use consistent units when adding, multiplying, etc.

Lab 3a: The Eiffel Tower

IMPORTANT

For this lab, each group will use (and therefore scale) the following values for wind load on the structure:

Group A: 1.0 kips/ft
Group B: 2.5 kips/ft
Group C: 4.0 kips/ft
Group D: 5.5 kips/ft

Theoretical Evaluation of the Full-Scale Structure

1. The Eiffel Tower stands 984 ft. tall and has a width of 328 ft. at its base. Use these dimensions along with the uniformly distributed wind load specific to your group to calculate the bending moment (M_o) at the base. Input values into tables 2 and 3 as appropriate.
2. Using your M_o value, calculate the vertical tensile (T) and compressive (C) reactions at the base that will result from the wind load only. Input values into table 3.

Parameters of the Full Model

3. Remove the model structure from the base/balance assembly. Ask your TA for help if you are unsure how to do this.
4. Measure the height and base dimensions of the model. What is the approximate scale of the model to the real structure? Consider both height and base dimensions. Input values into table 1.
5. Measure the width of the model at the quarter and three-quarter heights.
6. Open the Capstone worksheet 'Towers.cap' found in the desktop folder 'cee102_262'. There should be seven digital force displays visible. The four displays on the bottom of the screen correspond to loads measured at the four corners of the structure at its base. The display at the top left of the screen shows total vertical force – this is simply the sum of the loads at the four corners. By placing the model on the base/balance assembly and reading the total vertical force, you will be able to determine the dead load of the structure. Before attaching the model, select 'Fast Monitor Mode' from the pull down menu near the bottom left of the Capstone worksheet. Then click the 'Monitor' button to the immediate left of the drop down menu. Tare (zero) the force sensors by pushing the 'tare' button on the side of the sensors – you may have to do this multiple times. Now attach the model by connecting the K'nex to the white pegs on the base/balance

assembly. Once the structure has stabilized (the values are fairly constant), record the dead load of the model and its approximate scale to the real structure. Input values into table 1. Stop the computer from monitoring by selecting 'stop.'

7. Write on the board the data obtained from steps 3,4, 5, and 6. Have your AI check that the numbers obtained are sensible.
8. Determine the appropriate concentrated wind load (P) to apply to the full model (See equation sheet for wind load ratio). Solve for the distributed wind load (p). Input values into table 2.

Part I - Evaluation of the Entire Model

9. Using the Ohaus portable scales, select a combination of weights that is approximately equal to your value from step 6. Input measured weight into table 3.
10. Attach the hook that applies the wind load (via pulley and hanging weight) to the structure but do not apply any load yet. Measure the vertical distance from the base of the model to the hook. Is this the correct location to apply the concentrated wind load?
11. Given this distance and the load (P) you will be applying, calculate the theoretical M_o value. Using the base width dimension, calculate the T and C forces that should result – check with your TA to make sure you are using the correct width value. Input values into table 3. Capstone will display the experimental T and C values via the two digital displays in the upper right corner.
12. Before you load the structure, be sure you can answer the following: Which direction is the wind 'blowing'? Which side of the structure will experience increased compression forces and which will experience tension due to wind load? Check with your TA if you have any questions.
13. Now you are ready to apply the wind load. As before, click the 'Monitor' button and tare the force sensors. Attach the load to the string and observe the resulting displacement of the model. Once the model has settled and the numbers are fairly constant, record the Total T and Total C values in table 3 – notice that the total vertical force reading remains at approximately 0.
14. Compare these experimental T and C values to the values you predicted by calculating percent difference. Input values into table 3.
15. Fill in the copy of table 3 on the board with your values. Use correct units.

Part II – Evaluation of the Partial Model

14. Remove the top half model from the base/balance assembly and measure its height and the width at its base. Ask your TA for help if you are unsure how to do this.
15. Use Capstone to determine the dead load in the same manner as Part I.

16. Write on the board the data obtained in the same manner as Part I. Have your AI check that the numbers obtained are sensible.
17. Using your distributed wind load (p) from step 7, calculate the appropriate concentrated load (P) for the partial model by taking into consideration the height of this model section. Input value into table 2.
18. Use the Ohaus portable scales to select a combination of weights that is approximately equal to your value from step 16. Input measured weight into table 3.
19. Attach the hook that applies the wind load to the structure but do not apply any load yet. Measure the vertical distance from the base of this model section to the hook. Is this the correct location to apply the concentrated wind load?
20. Given this distance and the load P you will be applying, calculate the theoretical M_o value. Calculate the T and C forces that should result. Input values into table 3.
21. Now you are ready to apply the wind load. Click the 'Monitor' button, and tare the force sensors. Attach the load to the string and observe the resulting displacement of the model. Once the model has settled and the numbers are fairly constant, record the Total T and Total C values in table 3 – notice that the total vertical force reading remains at approximately 0.
22. Compare these experimental T and C values to the values you predicted by calculating percent difference. Input values into table 3.
23. Fill in the copy of table 3 on the board with your values. Use correct units.
24. Copy down other groups results as the table on the board fills in.

Total/Concentrated Full Model Wind Load

$$P_{MODEL} = DL_{MODEL} \times \ P_{REAL}/DL_{REAL}$$

Total/Concentrated Partial Model Wind Load

$$p_{MODEL} \ = \ P_{MODEL}/h_{MODEL}$$

Total/Concentrated Partial Model Wind Load

$$p_{MODEL} \ = \ P_{MODEL}/h_{MODEL}$$

$$P_{PARTIAL\ MODEL} = p_{MODEL} \ \times \ h_{PARTIAL\ MODEL}$$

Theoretical Moments

$$M = \ P_{MODEL} \ \times \ x_{MODEL}$$

Tension-Compression

$$T = \ -C \ = \ M/d$$

Table 1: Eiffel Tower Comparison of Models & Structure			
	Model	Real	Scale Factor
Height (full)		984 ft	
Width at Base (full)		328 ft	
Width at ¼ Height (full)		N/A	N/A
Width at ¾ Height (full)		N/A	N/A
Dead Load (full)		18,800 kip	
x (full)		492 ft	
Height (partial)		N /A	N /A
Width at Base (partial)		N /A	N /A
Dead Load (partial)		N /A	N /A
x (partial)		N/A	

Table 2: Eiffel Tower Applied Loads			
	Full Model	Partial Model	Actual
Distributed Load (p)			
Concentrated Load (P)			

Table 3: Eiffel Tower Experimental Results

Group A		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								
Group B		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								
Group C		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								
Group D		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								

Lab 3b: The Washington Monument

IMPORTANT

For this lab, each group will use (and therefore scale) the following values for wind load on the real structure:

Group A: 1.0 kips/ft
Group B: 2.5 kips/ft
Group C: 4.0 kips/ft
Group D: 5.5 kips/ft

Theoretical Evaluation of the Full-Scale Structure

1. The shaft of the Washington Monument is 500 ft. tall and has a width of 55 ft. at its base. Use these dimensions along with the uniformly distributed wind load specific to your group to calculate the bending moment (M_o) at the base. Input values into tables 5 and 6 as appropriate.
2. Using your M_o value, calculate the vertical tensile (T) and compressive (C) reactions at the base that will result from the wind load only. Input values into table 6.

Parameters of the Full Model

3. Remove the model structure from the base/balance assembly. Ask your TA for help if you are unsure how to do this.
4. Measure the height and base dimensions of the model. What is the approximate scale of the model to the real structure? Consider both height and base dimensions. Input values into table 4.
5. Measure the width of the model at the quarter and three-quarter heights.
6. Open the Capstone worksheet 'Towers.cap' found in the desktop folder 'cee102_262'. There should be seven digital force displays visible. The four displays on the bottom of the screen correspond to loads measured at the four corners of the structure at its base. The display at the top left of the screen shows total vertical force – this is simply the sum of the loads at the four corners. By placing the model on the base/balance assembly and reading the total vertical force, you will be able to determine the dead load of the structure. Before attaching the model, select 'Fast Monitor Mode' from the pull down menu near the bottom left of the Capstone worksheet. Then click the 'Monitor' button to the immediate left of the drop down menu. Tare (zero) the force sensors by pushing the 'tare' button on the side of the sensors – you may have to do this multiple times. Now attach the model by connecting the K'nex to the white pegs on the base/balance

assembly. Once the structure has stabilized (the values are fairly constant), record the dead load of the model and its approximate scale to the real structure. Input values into table 4. Stop the computer from monitoring by selecting 'stop.'

7. Write on the board the data obtained from steps 3,4, and 5. Have your AI check that the numbers obtained are sensible.
8. Determine the appropriate concentrated wind load (P) to apply to the full model (See equation sheet for wind load ratio). Solve for the distributed wind load (p). Input values into table 5.

Part I - Evaluation of the Entire Model

9. Using the Ohaus portable scales, select a combination of weights that is approximately equal to your value from step 6. Input measured weight into table 6.
10. Attach the hook that applies the wind load (via pulley and hanging weight) to the structure but do not apply any load yet. Measure the vertical distance from the base of the model to the hook. Is this the correct location to apply the concentrated wind load?
11. Given this distance and the load (P) you will be applying, calculate the theoretical M_o value. Using the base width dimension, calculate the T and C forces that should result – check with your TA to make sure you are using the correct width value. Input values into table 6. Capstone will display the experimental T and C values via the two digital displays in the upper right corner.
12. Before you load the structure, be sure you can answer the following: Which direction is the wind 'blowing'? Which side of the structure will experience increased compression forces and which will experience tension due to wind load? Check with your TA if you have any questions.
13. Now you are ready to apply the wind load. As before, click the 'Monitor' button and tare the force sensors. Attach the load to the string and observe the resulting displacement of the model. Once the model has settled and the numbers are fairly constant, record the Total T and Total C values in table 6 – notice that the total vertical force reading remains at approximately 0.
14. Compare these experimental T and C values to the values you predicted by calculating percent difference.
15. Fill in the copy of table 6 on the board with your values. Use correct units.

Part II – Evaluation of the Partial Model

14. Remove the top half model from the base/balance assembly and measure its height and the width at its base. Ask your TA for help if you are unsure how to do this.
15. Use Capstone to determine the dead load in the same manner as Part I.

16. Write on the board the data obtained in the same manner as Part I. Have your AI check that the numbers obtained are sensible.
17. Using your distributed wind load (p) from step 6, calculate the appropriate concentrated load (P) for the partial model by taking into consideration the height of this model section. Input value into table 5.
18. Use the Ohaus portable scales to select a combination of weights that is approximately equal to your value from step 16. Input measured weight into table 6.
19. Attach the hook that applies the wind load to the structure but do not apply any load yet. Measure the vertical distance from the base of this model section to the hook. Is this the correct location to apply the concentrated wind load?
20. Given this distance and the load P you will be applying, calculate the theoretical M_o value. Calculate the T and C forces that should result. Input values into table 6.
21. Now you are ready to apply the wind load. Click the 'Monitor' button, and tare the force sensors. Attach the load to the string and observe the resulting displacement of the model. Once the model has settled and the numbers are fairly constant, record the Total T and Total C values – notice that the total vertical force reading remains at approximately 0.
22. Compare these experimental T and C values to the values you predicted by calculating percent difference.
23. Fill in the copy of table 6 on the board with your values. Use correct units.
24. Copy down other groups results as the table on the board fills in.

Table 4: Washington Monument Comparison of Models & Structure

	Model	Real	Scale Factor
Height (full)		500 ft	
Width at Base (full)		55 ft	
Width at ¼ Height (full)		N/A	
Width at ¾ Height (full)		N/A	
Dead Load (full)		89,600 kip	
x (full)		250 ft	
Height (partial)		N /A	N /A
Width at Base (partial)		N /A	N /A
Dead Load (partial)		N /A	N /A
x (partial)		N/A	

Total/Concentrated Full Model Wind Load

$$P_{MODEL} = DL_{MODEL} \times \; P_{REAL}/DL_{REAL}$$

Total/Concentrated Partial Model Wind Load

$$p_{MODEL} \; = \; P_{MODEL}/h_{MODEL}$$

Total/Concentrated Partial Model Wind Load

$$p_{MODEL} \; = \; P_{MODEL}/h_{MODEL}$$

$$P_{PARTIAL\ MODEL} = p_{MODEL} \; \times \; h_{PARTIAL\ MODEL}$$

Table 5: Washington Monument Applied Loads

	Full Model	Partial Model	Actual
Distributed Load (p)			
Concentrated Load (P)			

Theoretical Moments

$$M = \; P_{MODEL} \; \times \; x_{MODEL}$$

Tension-Compression

$$\boldsymbol{T = \; -C \; = \; M/d}$$

Table 6: Washington Monument Experimental Results								
Group A		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								
Group B		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								
Group C		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								
Group D		Theoretical			Experimental		Percent Difference	
	Load "P" (lb)	Moment (lb-ft)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)	Tension (lb)	Compression (lb)
Actual Structure					N /A	N /A	N /A	N /A
Full Model								
Partial Model								