Distributed Engineering

190 m (663 ft) Flag Pole

Baku, Azerbaijan

Introduction

Distributed Engineering

Florin Arsene
He is a Principal with Distributed Engineering Group of Companies, based in London, UK. Florin holds Professional Engineering licenses in the USA, Canada and Australia. Florin was the Engineering of record of the tallest flagpole in the USA, 125 m in Sheboygan, WI, USA. He was the Engineer of record for the top three tallest flagpoles in the world, 171 m in Jeddah, Saudi Arabia, 202.5 m in New Cairo, Egypt and 190 m in Baku, Azerbaijan.

MULTITECH
DAMPER SOLUTIONS

Gilles Oudin is the President and founder of Multitech.
Multitech is operating on a worldwide basis to design and manufacture different types of anti-vibration dampers to solve any issue regarding vibration of structures especially slender structures.

Nina Ifaninnah –Oudin is in charge of the Asian Market and is also a very efficient assistant in the vibration testing laboratories of Multitech (South of France and Jakarta)

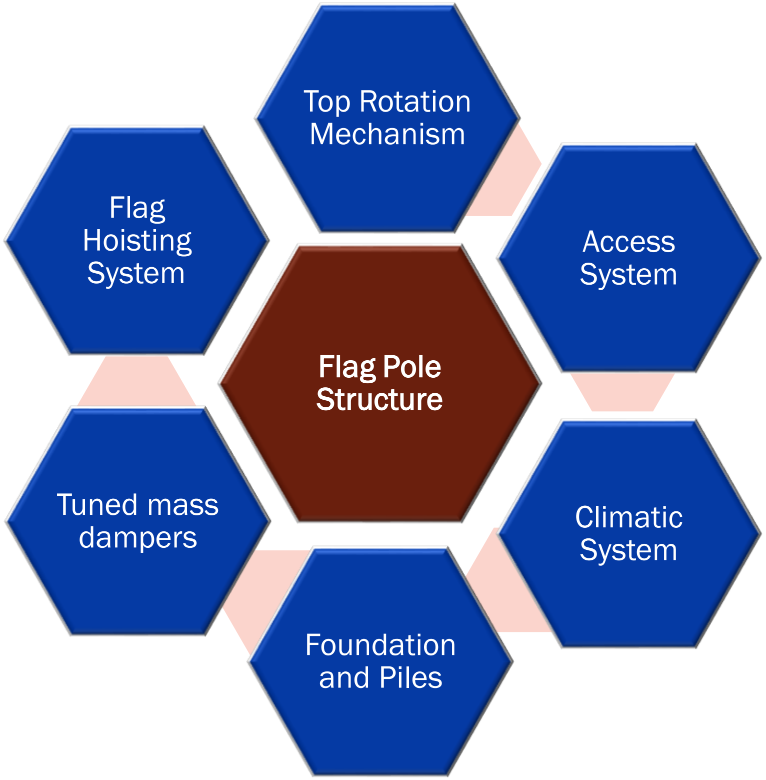
Tallest Flag Poles

#	Height	Location	Flag Size	Year	Engineer
1	190 m 623 ft	Baku, Azerbaijan	35 m × 70 m 115 ft x 229 ft	2022 Under construction	Distributed Engineering
2	202.5 m 664 ft	New Cairo, Egypt	40 m × 60 m 131 ft x 197 ft	2021	Distributed Engineerg
3	171 m 561 fr	Jeddah, Saudi Arabia	30 m × 60 m 98 ft x 197 ft	2014	Distributed Engineering
4	165 m 541 ft	Dusanbe, Tajikistan	30 m × 60 m 98 ft x 197 ft	2011	Trident

Very often installed in front or the Residence of the President of the country.

It is some kind of internationnal competition !!! I have the biggest one !!!

Design System



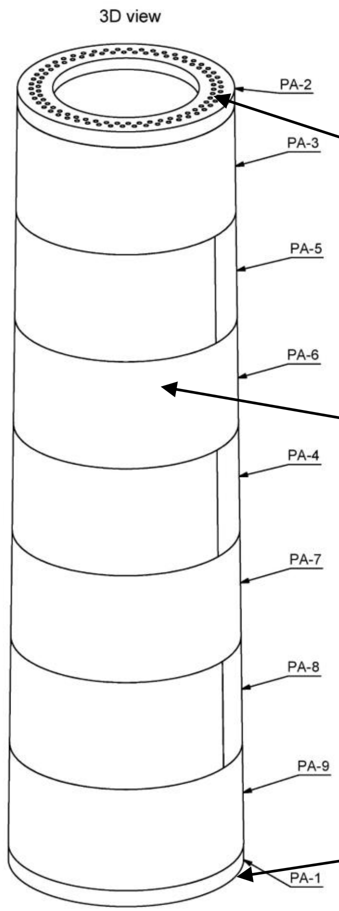
Design Data

Location:	Baku, Azerbaijan
Design Standard:	Az DTN 2.1-1
Basic Wind Pressure:	1000 Pa at 10 m elevation
Wind Pressure at Top:	3740 Pa
Seismic Loads	
Flag Size	35 m x 70 m
Design Method:	Wind Power Spectral Analysis
Dampers	Temporary and Permanent

Flag Pole Configuration

Top Truck Assembly:	5 m (16.4 f)
Pole Height:	185 m (607 ft)
Number Of Sections:	8
Top Diameter:	2060 mm (6.76 ft)
Bottom Diameter:	5700 mm (18,7 ft)
Total Mass	1400 t (3 860 000 Pounds)
Steel:	EN 10025-3 S460NL
Bolts:	10.9-HV-T2N EN 14399-4 up to M100

Flag Pole Configuration



Typical Section

Top Flange

Cans

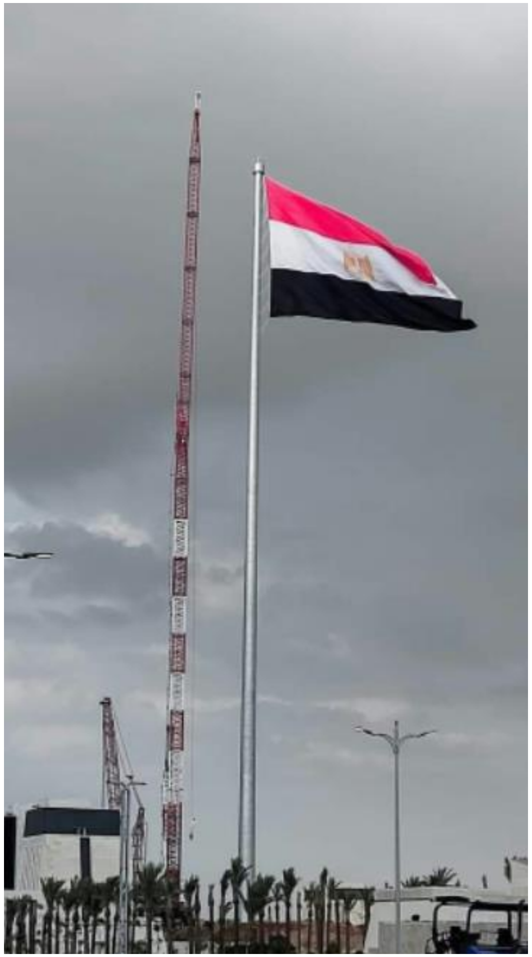
Bottom Flange

Flag Pole Fabrication

Flanges with double row of bolting

Flag Pole Fabrication

New Cairo flagpole during erection 202 m (663 ft)



New Cairo flagpole during erection 202 m (663 ft)

The pole is installed section by section.
It may take a few days between two sections because of the two rows of bolts to be installed with tensioning equipment.
During installation we still have to consider a very high wind velocity which may general vibration issue

Why dampers are requested ?

This flagpole starts to vibrate once the flag was under replacement. The flag so far was acting as a Vortex breaker. Apparently second mode of vibration

Wind to be considered during instalation

For erection time of more than 3 days and less than 3 months, EN 1991-1-6 recommends a 5-year return wind speed (10-minute average).

Based on the wind study carried out by RWDI, the 1700-year return period 10-minute average wind speed for scenario F installation height is 57.5 m/s.

The corresponding 50-year return is 57.5 x 0.86 = 49.45 m/s. The 5-year return period wind speed is 49.45 x 0.85 = 42.03 m/s.

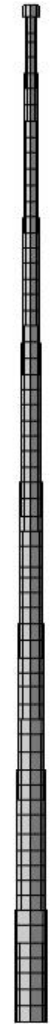
1.25 V_m = 1.25 x 42.033 = 52.54 m/s (117.6 Mile/hr or 189 km/hr) . The calculated critical wind speed limit of 52.54 m/s is much higher than the previously specified 30 m/s

During construction we had to consider these extreme design wind speed

Finite Element Modeling of Baku Flagpole

Finite Element Model

65 different sections



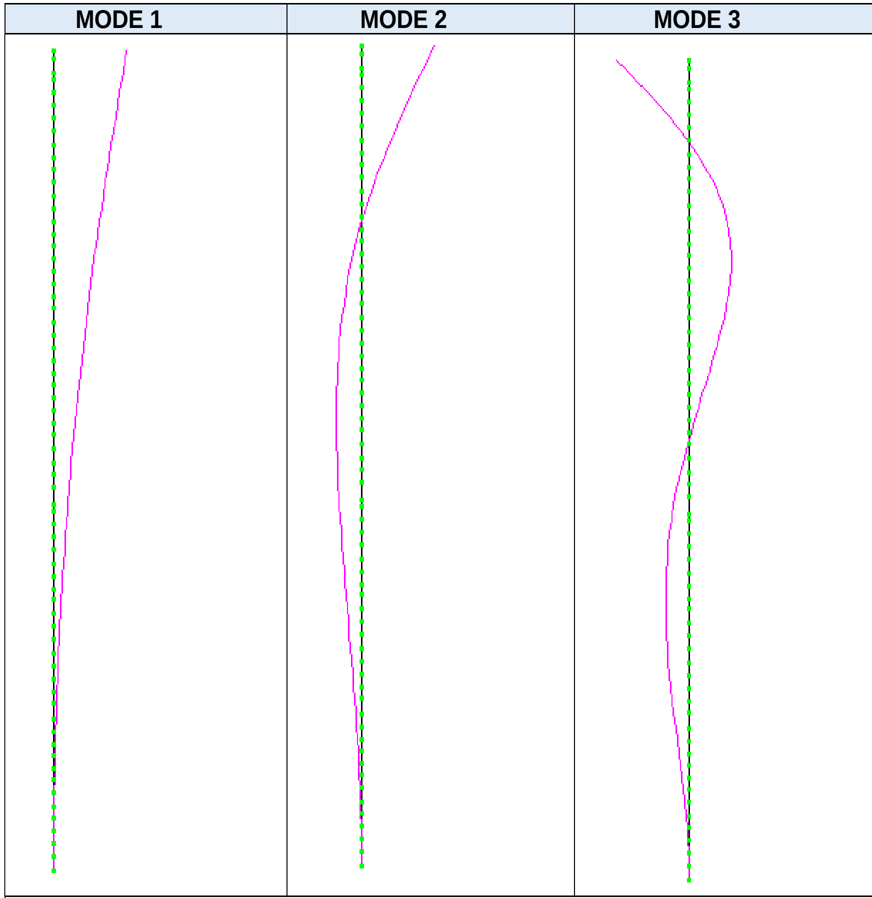
1. Ring 570 X 556 (1)
2. Ring 570 X 556 (2)
3. Ring 570 X 556 (3)
4. Ring 570 X 556 (4)
5. Ring 570 X 556 (5)
6. Ring 563 X 549 (6)
7. Ring 560 X 547 (7)
8. Ring 554 X 541 (8)
9. Ring 548 X 535 (9)
10. Ring 542 X 529 (10)
11. Ring 535 X 522 (11)
12. Ring 529 X 516 (12)
13. Ring 523 X 510 (13)
14. Ring 517 X 504 (14)
15. Ring 510 X 497 (15)
16. Ring 504 X 491 (16)
17. Ring 498 X 485 (17)
18. Ring 497 X 492 (18)
19. Ring 485 X 472 (19)
20. Ring 479 X 466 (20)
21. Ring 473 X 460 (21)
22. Ring 467 X 454 (22)
23. Ring 460 X 447 (23)
24. Ring 454 X 441 (24)
25. Ring 448 X 435 (25)
26. Ring 442 X 430 (26)
27. Ring 435 X 423 (27)
28. Ring 429 X 417 (28)
29. Ring 423 X 411 (29)
30. Ring 416 X 405 (30)
31. Ring 410 X 399 (31)
32. Ring 404 X 393 (32)
33. Ring 397 X 386 (33)
34. Ring 391 X 380 (34)
35. Ring 385 X 375 (35)
36. Ring 379 X 369 (36)
37. Ring 372 X 362 (37)
38. Ring 366 X 356 (38)
39. Ring 360 X 351 (39)
40. Ring 353 X 344 (40)
41. Ring 347 X 339 (41)
42. Ring 341 X 333 (42)
43. Ring 334 X 326 (43)
44. Ring 328 X 320 (44)
45. Ring 322 X 314 (45)
46. Ring 315 X 307 (46)
47. Ring 309 X 301 (47)
48. Ring 302 X 294 (48)
49. Ring 296 X 290 (49)
50. Ring 290 X 284 (50)
51. Ring 283 X 277 (51)
52. Ring 277 X 271 (52)
53. Ring 271 X 265 (53)
54. Ring 264 X 258 (54)
55. Ring 264 X 258 (55)
56. Ring 253 X 247 (56)
57. Ring 245 X 239 (57)
58. Ring 239 X 233 (58)
59. Ring 232 X 226 (59)
60. Ring 226 X 221 (60)
61. Ring 219 X 214 (61)
62. Ring 212 X 207 (62)
63. Ring 207 X 202 (63)
64. Ring 206 X 201 (64)
65. Ring 300 X 295 (65)

Frequency and Critical Wind Speeds

When the flagpole is fully installed the first frequencies are :

1st:0.221 Hz
2nd:0.723 Hz
3rd:1.692 Hz

The corresponding critical wind speed are :
1st:3.63 m/s (11.91 ft/s)
2nd:12.04 m/s (39.5 ft/s)and 15.21 m/s (49.90 ft/s)
3rd:24.37 m/s (79.95 ft/s),23.59 m/s (77.39 ft/s) and 37.94 m/s (124.48 ft/s)



Multitech Results		
f1=0.221 Hz	f2=0.723 Hz	**f3=1.692 Hz**
21-EVC-001 190 m Flagpole Baku Azerbaijan Structural Report Rev. 0 02-07-2021 Results		
f1=0.226 Hz	f2=0.724 Hz	f3=1.696 Hz

Safe choice of the structural damping

Eurocode for a mast/tower , fully welded and without any liner, recommend a log damping of 0.012 (damping=0.191%).

Due to our experience, having done damping measurement on fully welded structures, we recommend to be on the safe side to consider a smaller log damping δ=0.005 (damping 0.08 %) – 2.40 times smaller than the Code Recommendation

EN 1991-1-4:2005 (E)

Table F.2 —Approximate values of logarithmic decrement of structural damping in the fundamental mode, δ_s

Structural type		structural damping, δ_s
reinforced concrete buildings		0,10
steel buildings		0,05
mixed structures concrete + steel		0,08
reinforced concrete towers and chimneys		0,03
unlined welded steel stacks without external thermal insulation		0,012
unlined welded steel stack with external thermal insulation		0,020
steel stack with one liner with external thermal insulation[a]	$h/b < 18$	0,020
	$20 \le h/b < 24$	0,040
	$h/b \ge 26$	0,014
steel stack with two or more liners with external thermal insulation [a]	$h/b < 18$	0,020
	$20 \le h/b < 24$	0,040
	$h/b \ge 26$	0,025
steel stack with internal brick liner		0,070
steel stack with internal gunite		0,030
coupled stacks without liner		0,015
guyed steel stack without liner		0,04
steel bridges + lattice steel towers	welded	0,02
	high resistance bolts	0,03
	ordinary bolts	0,05
composite bridges		0,04
concrete bridges	prestressed without cracks	0,04
	with cracks	0,10
Timber bridges		0,06 - 0,12
Bridges, aluminium alloys		0,02
Bridges, glass or fibre reinforced plastic		0,04 - 0,08
cables	parallel cables	0,006
	spiral cables	0,020

NOTE 1 The values for timber and plastic composites are indicative only. In cases where aerodynamic effects are found to be significant in the design, more refinded figures are needed through specialist advice (agreed if appropriate with the competent Authority.

NOTE 2 For cable supported bridges the values given in Table F.2 need to be factored by 0,75

[a] For intermediate values of h/b, linear interpolation may be used

Vibration Amplitude prediction

Once the flagpole is fully installed, the second mode is the worst case with vibration amplitude of 1.08 m (3.54 ft) (first approach of Eurocode)

Most of the time on this type of extreme slender structures the second mode of vibration is prevailing

Log damping	0.005 0.08%	Eurocode 1 - method 1
1ier mode	0.221 Hz	
	critical wind speed =	3.69 m/s
		vortex shedding to be considered for the first mode
	Scrution NumnerSc =	**2.55**
	/Reynolds Number $Re(V_{crit})$ =	**7.38E+05**
	lateral force coefficient C_{lat} =	**0.20**
	Max displacment $y_{F,max}$ =	**0.556 m**
	Ratio displacment/diameter = $y_{F,max}$ / b =	**0.185**
		too large displacment for any reliability class
	Max fatige stress amplitude $\Delta\sigma$ =	58.3 Mpa
	number of vibration cycles N =	**8.51E+06**
	correlation lenght L_j =	21.070 m

Log damping	0.005 0.08%	Eurocode 1 - méthod 1
2nd mode	0.723 Hz	
critical wind speed V_{crit} =		**12.04 m/s**
		15.21 m/s
		vortex shedding to be considered for the second mode
Nombre de Scruton Sc =		**3.637**
		2.279
Nombre de Reynolds $Re(V_{crit})$ =		**2.41E+06**
		3.84E+06
Coefficient de force latérale C_{lat} =		**0.20**
		0.20
	déplacement maximal $y_{F,max}$ =	**1.082 m**
	$y_{F,max}$ / b =	0.286
		too large displacement for all class of reliability
	Amplitude de contraintes maximale $\Delta\sigma$ =	**368.0 Mpa**
	nombre de cycle N =	**1.48E+08**
ngueur de corrélation L_j =		20.840 m
		13.699 m

Criterion for the design of temporary dampers

DESIGN CRITERIA FOR THE TEMPORARY DAMPERS

A temporary damper will be needed if:

- The vibration amplitude >0.15 m
- The tensile stress during vibration>60% of the shell yield stress

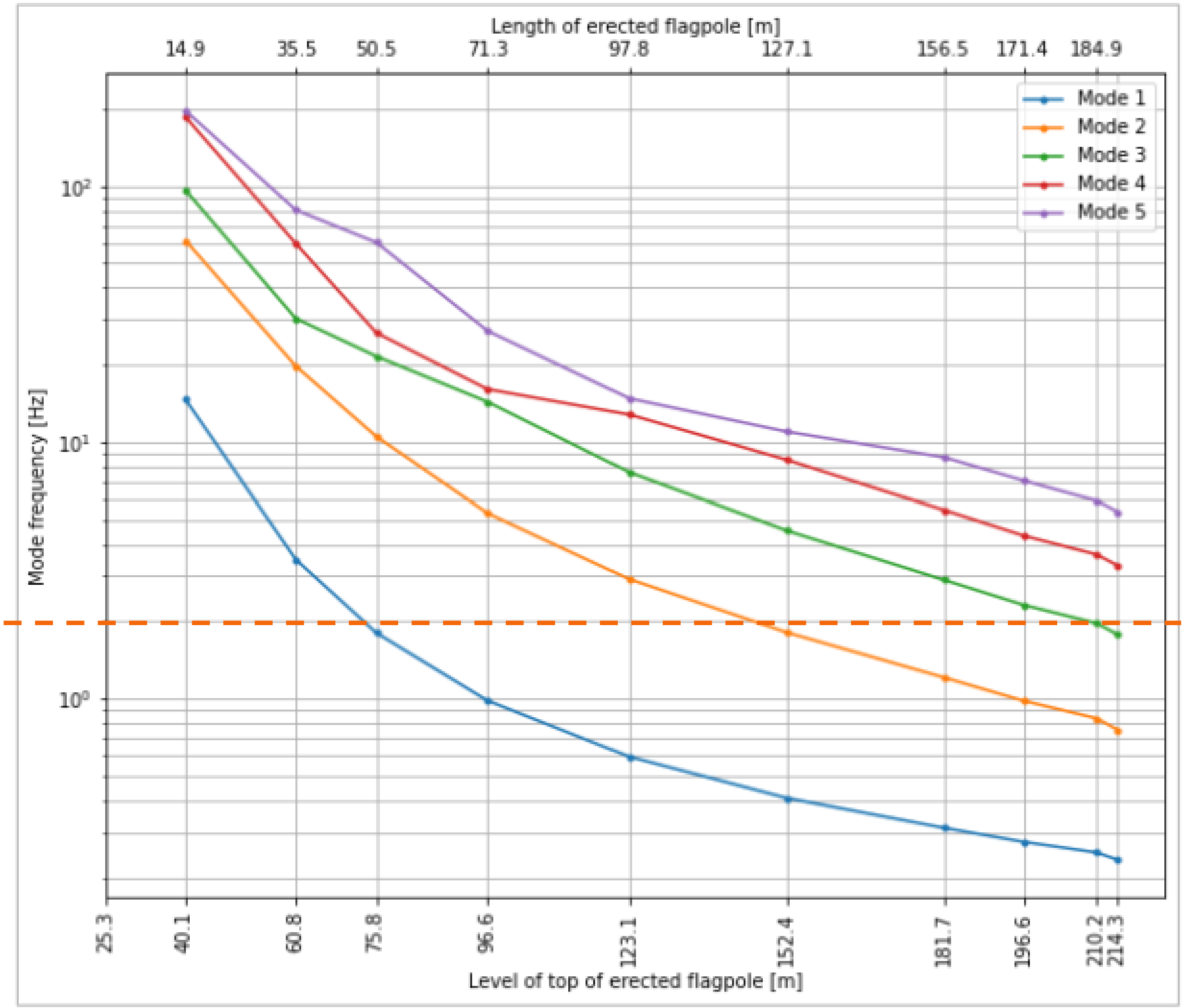
Steel grade	Minimum yield strength Reh MPa							Tensile strength Rm MPa	
	Nominal thickness mm							Nominal thickness mm	
	≤16	>16 ≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤150	>150 ≤200	≤100	>100 ≤200
S460NL	460	440	430	410	400	380	370	540-720	530-710

We consider that the tensile strength is 540 Mpa.

The construction stage is supposed to occurred in a short period of time of less than one month. The maximum critical speed is calculated in Distributed Engineering Memo 21-EVC-001 EM-007 and it has a value of 52.54 m/s

Frequencies Modes during construction

This graph represents the evolution of the frequency's mode during the various height of installation.
During erection stage, only the two first vibration mode may generate vibration



1.925 Hz

First Mode of Vibration

TABLE OF DAMPER TYPE WITH FILLING LEVELS AT EACH STEP OF CONSTRCUTION		1	2	3	4	5	6
		Erection Stage G	Erection Stage F	Erection Stage E	Erection Stage D	Erection Stage C	Erection Stage B
		Top Elevation 202.35 m seg 10 to 3	Top Elevation 187.46 m seg 10 to 4	Top Elevation 158.123 m seg 10 to 5	Top Elevation 128.78 m seg 10 to 6	Top Elevation 102.28 m seg 10 to 7	Top Elevation 81.51 m seg 10 to 8
FIRST MODE							
First Mode f1	Hz	0.257	0.293	0.390	0.584	1.047	1.925
Elevation	m	171.36	156.22	127.11	97.78	71.28	50.51
Diameter b=	b=	2.360	2.647	3.224	3.917	4.484	4.922
Critical Wind Speed-Vcr 1	m/s	3.37	4.31	6.99	12.71	26.09	53.38
Number of vibration cycles on 30 years		8.50E+06	1.55E+07	4.72E+07	1.24E+08	3.33E+07	5.80E+01
Number of critical cycle for 1 months		23,611	43,056	131,111	343,611	92,500	0
Max displacement	m	0.215	0.271	0.347	0.395	0.621	0.691
ratio =displ/b		0.091	0.102	0.108	0.101	0.138	0.140
max fatigue stress amplitude	Mpa	32	47.1	93.5	199.5	647.5	1473.000
Max stress	Mpa	16	23.55	46.75	99.75	323.75	647.5
ratio (stress/540 Mpa)		2.96%	4.36%	8.66%	18.47%	59.95%	119.91%
Modal Mass	kg	127,208	136,153	175,326	193,854	176,543	153,625
	kg (cross check with model)	114,000	130,000	165,000	187,000	153,625	**Vc>52.54 m/s**
		0.90	0.95	0.94	0.96		
Mini requested LOG Damping for 0.150 m displact		0.0072	0.0090	0.0116	0.0132	0.0207	
Mini LOG Damping to have stress<60%		0.0002	0.0004	0.0007	0.0015	0.0050	
Mini requested log decrement damping		0.0072	0.0090	0.0116	0.0132	0.0207	
Min damping		0.114%	0.144%	0.184%	0.210%	0.329%	

The cases in the green cases must be considered because the corresponding critical wind speed is smaller that the max to be considered. Stage B, to be ignored because critical wind speed 53.38 m/s>52.54 m/s

Second Mode of Vibration

		1	2	3	4	5	6
		Erection Stage G	**Erection Stage F**	**Erection Stage E**	**Erection Stage D**	**Erection Stage C**	**Erection Stage B**
		Top Elevation 202.35 m	Top Elevation 187.46 m	Top Elevation 158.123 m	Top Elevation 128.78 m	Top Elevation 102.28 m	Top Elevation 81.51 m
		seg 10 to 3	seg 10 to 4	seg 10 to 5	seg 10 to 6	seg 10 to 7	seg 10 to 8
SECOND MODE			**Zone 2 ignored**				
Second Mode f2	Hz	0.922	1.114	1.733	3.063	5.828	11.150
Elevation first zone	m	171.36	156.22	127.11	97.78	71.28	50.51
Diameter first zone b1=	b1=	2.36	2.647	3.224	3.917	3.384	4.922
Number of vibration cycles on 30 years		1.90E+08	2.17E+08	3.32E+07	6	0	0.00E+00
Number of critical cycle for 1 month		527,778	602,500	92,222	0	0	0
Critical wind speed zone 1-Vrc 2,1	m/s	12.09	16.79	31.04	61.21	145.19	304.89
Elevation second zone	m	88.84	77.4	59.46	47.25	35.07	23.75
Diameter second zone b2=	m	4.106	4.358	4.734	4.984	5.234	5.483
Critical wind speed zone 1-Vrc 2,2	m/s	21.03	27.25	44.97	79.92	169.48	339.64
Max displacement	m	0.262	0.316	0.429			
max fatigue stress amplitude	Mpa	563.1	127.6	1638	**both Vcr**	**both Vcr**	**both Vcr**
Max stress	Mpa	281.55	63.8	819	**>52.4m/s**	**>52.4 m/s**	**>52.4 m/s**
ratio (stress/540 Mpa)		52.1%	11.8%	151.7%	**second mode**	**second mode**	**second mode**
Modal Mass	kg	127,208	136,153	175,326	**ignored**	**ignored**	**ignored**
Mini requested damper for 0.150 m displact		0.0087	0.0105	0.0143			
Mini requested displacment to have stress<60%		0.0043	0.0010	0.0126			
Mini requested log decrement damping		0.0087	0.0105	0.0143			
Min damping		0.139%	0.168%	0.228%			

Stages B to D are ignored with critical wind speed above 61 m/s (136 Miles/hr)

Dampers Configuration

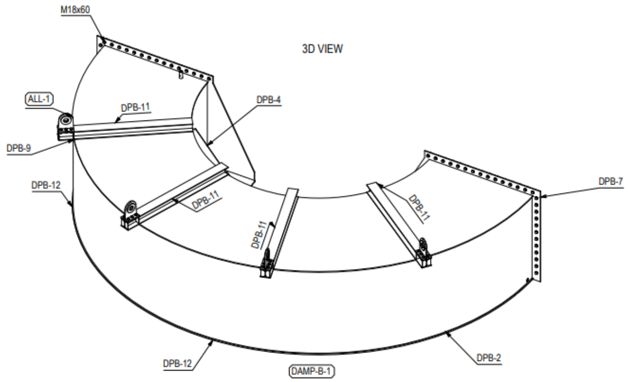
To cover all theses cases, we have design 3 different adjustable dampers
Type A and B are units 180° wide (1 or 2 unit per case, A can be mixed with B)
Type C is a square based damper

TABLE OF REQUESTED DAMPERS AT EACH STEP OF CONSTRCUTION	1	2	3	4	5	6
	Erection Stage G	Erection Stage F	Erection Stage E	Erection Stage D	Erection Stage C	Erection Stage B
	Top Elevation 202.35 m seg 10 to 3	Top Elevation 187.46 m seg 10 to 4	Top Elevation 158.123 m seg 10 to 5	Top Elevation 128.78 m seg 10 to 6	Top Elevation 102.28 m seg 10 to 7	Top Elevation 81.51 m seg 10 to 8
UNIT TYPE A Quantity requested	1XA	1XA	2 X A	2XA		
UNIT TYPE B Quantity requested	1XB	1XB			2XB	
UNIT TYPE C Quantity requested			1 X C			

Damper type A: will be used 4 times for frequencies varying from 0.257 Hz to 0.584 Hz (first mode only)
Damper type B:will be used 3 times for frequencies varying from 0.922 Hz to 1.047 Hz (first and second mode)
Damper type C:will be used 1 time for 1.733 Hz (second mode)

Dampers Shape

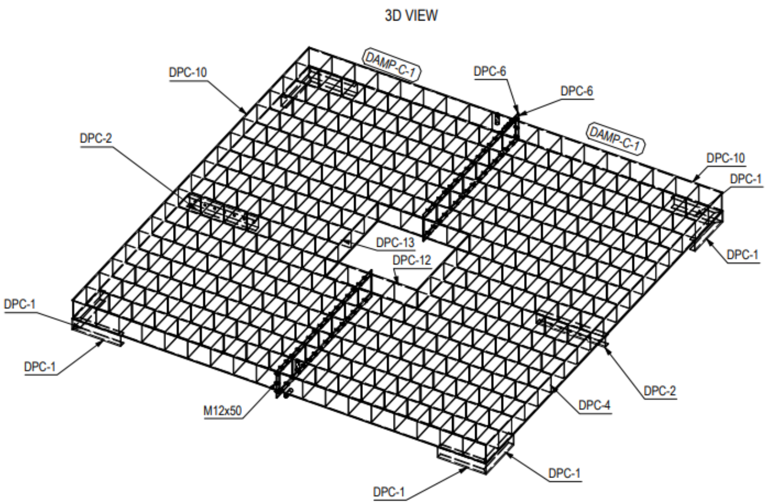
Type A or B shape



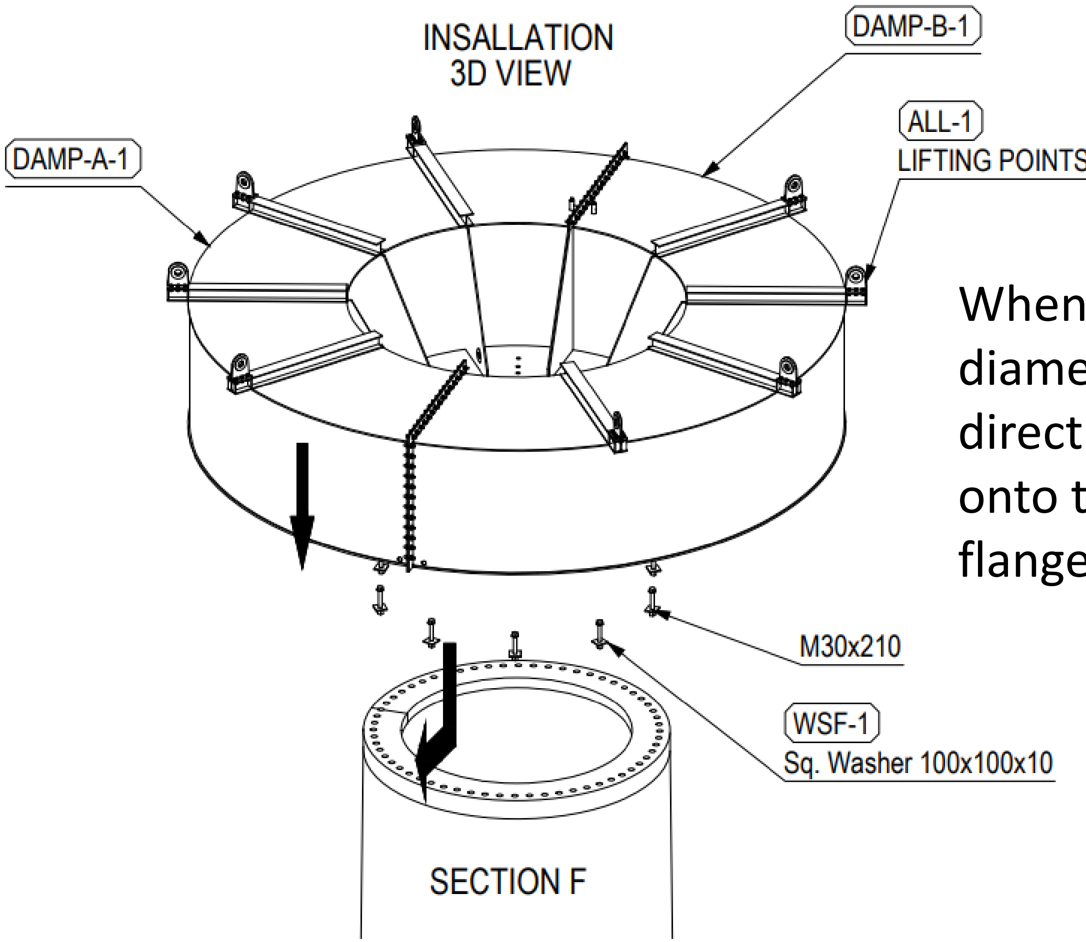
We have 2 dampers A and 2 damper B
Depending on the cases we can have

- A+A
- A+B
- B+B

Type C shape

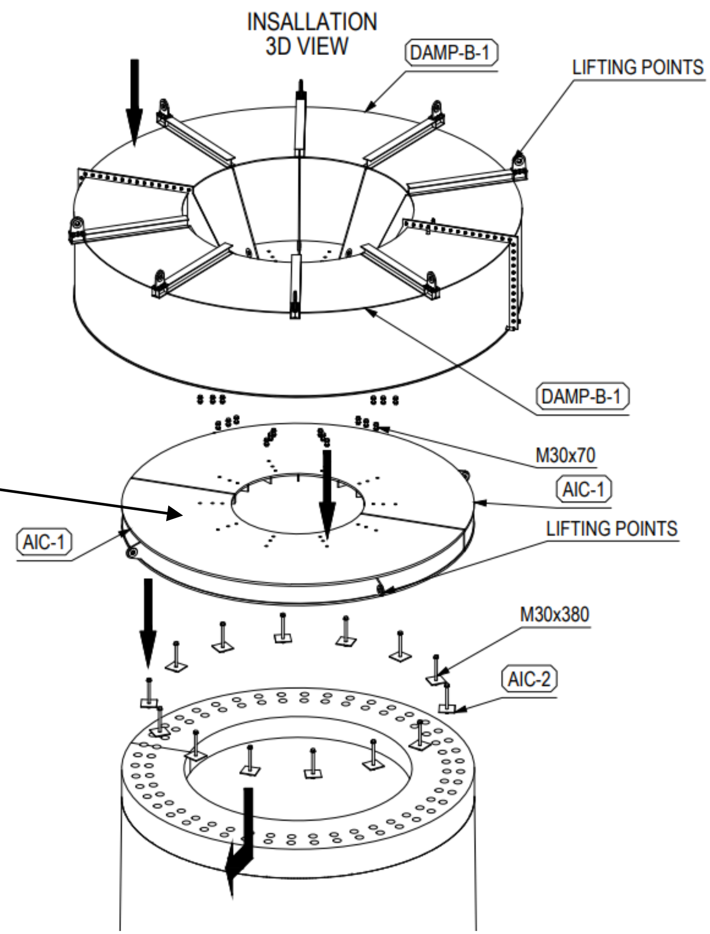


Dampers Installation during Construction



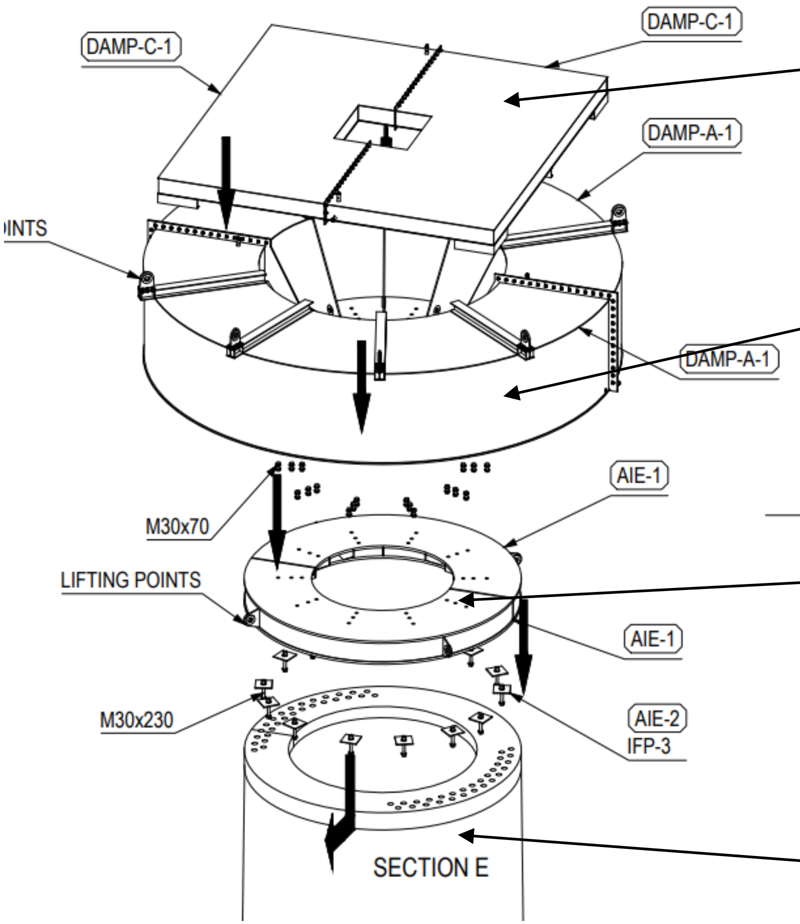
When the flagpole top diameter is small, we can directly bolt the dampers onto the flagpole top flange

Dampers Installation during Construction



Intermediate piece to connect the damper to the flagpole when the top diameter of flagpole is too big

Dampers Installation during Construction



Damper type C

Dampers type A x 2

Intermediate connecting piece

Flagpole

Conclusion

Flagpoles are very sensitive to vibration since the structural damping is extremely small. This small structural damping result from very strong flanges with pre tensioned bolts. This type of connection is so strong that the flagpole behave as a fully welded structure with no energy dissipation at the flanges.

During construction vibration can occur and consequently temporary and permanent dampers must be installed.

Thanks for your attention