Development of a Guidelines Document for Aerodynamic Design of Stay Cables

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Outlines

- Background
  - Motivation
  - Objectives
- Introduction to current work
  - Outline of Work
  - Primary References
  - Scope
- Significant Issues
  - Performance requirements
  - Hazard definition
  - Vibration mechanisms
  - Design/Analysis
  - Mitigation
  - Testing
- Summary
  - Impact to the industry
  - Future studies

Motivation

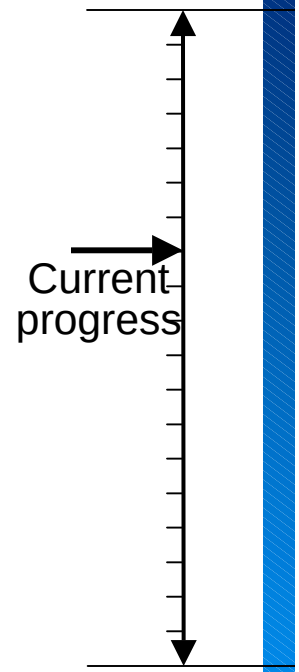
- Growing number of cable-stayed bridges
- Insufficient design provisions for dynamic wind hazard
- FHWA's practical orientation on research
- Academic communication→engineer's language
  - Interpretation of existing knowledge from various types of industry
  - Identifying and resolving technical issues in conveying research products to practice
- Abundant results from pooled fund study since 1999—SPR-3(078)

Objectives

- Making use of available research products
  - Tailoring the practices in various industry (bridge, building, power transmission, offshore structure,…) into suitable forms for stay cables
  - Identifying missing connections among research products that impede their implementation
  - Developing practical resolution to bridge the identified gaps when possible
  - Proposing necessary studies
- Developing design procedures that fit into state-of-the-art design and retrofitting methodology
- Implementing simple and cost-effective aerodynamic hazard mitigation design schemes
- Clarifying technical terms

Outline of work

- Reviewing available materials
- Producing scalable documental framework and identifying essential needs for further studies
- Consulting committee
- Developing details of procedures and drafting the document
- Reviewing



•Revising
•Re-reviewing
•Publishing

or

•Publishing
•Preparation for second edition

Primary References

- Wind Induced Vibration of Stay Cables (HNTB)
- Draft-Guidelines for Design and Retrofit (Buckland & Taylor)
- Recommendations for Stay Cable Design, Testing and Installation (PTI Guide Spec)
- AASHTO and other design guides

Scope:
The guidance document includes:

- Performance requirements
- Hazard definition
- Structural/component response and analysis
  - Structural force and deflection
- LRFD design and mitigation methods
  - Limit states
  - Load factors and resistance factors
  - Selection of mitigation methods and recommended design procedures
- Testing

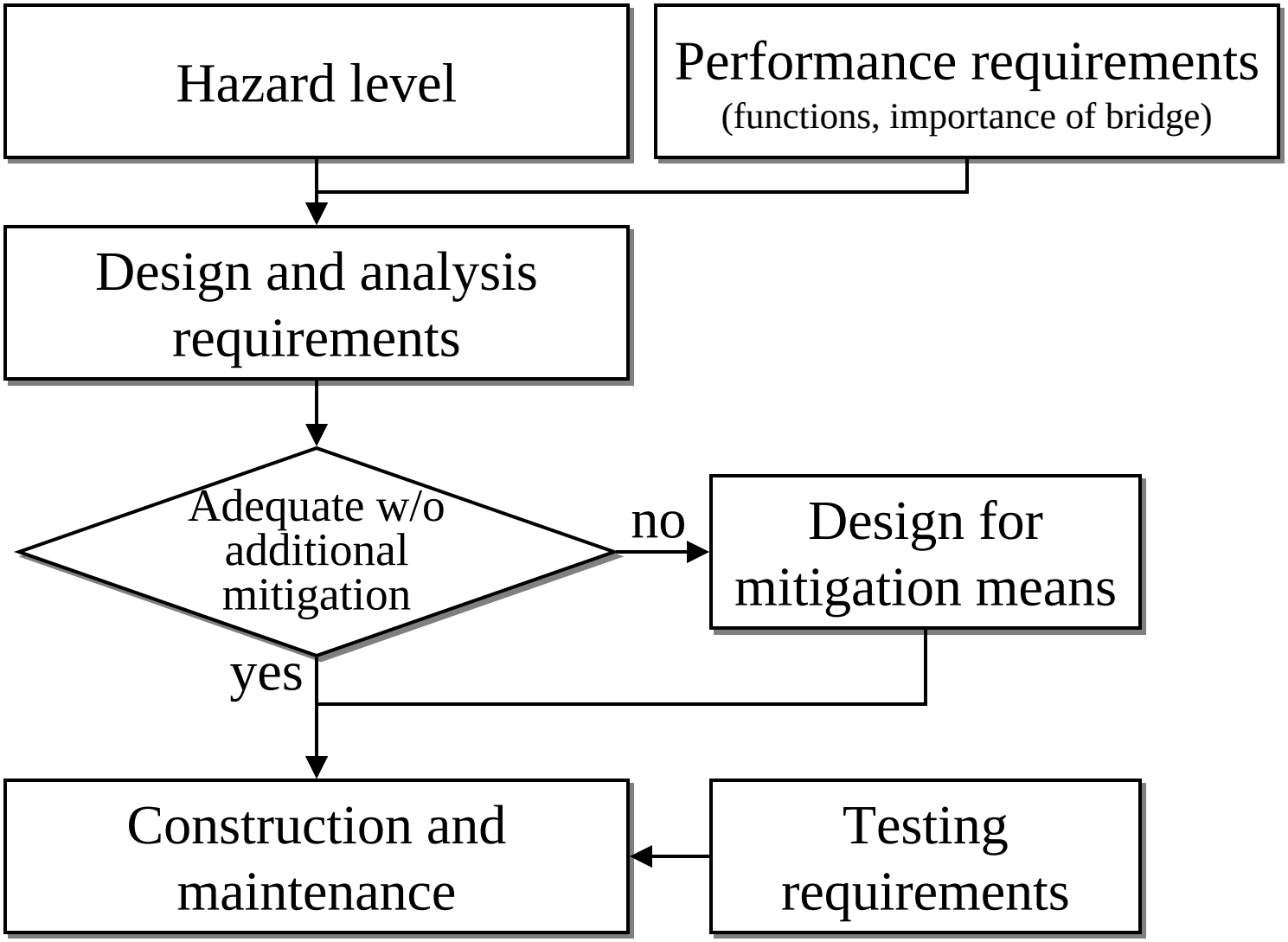
Scope:
The document does not include:

- Detailed derivation
- Untested or rare mitigation methods
- Hybrid mitigation (may be included in the future)
- Design example (will be developed upon completion)

Some significant issues

- Performance requirements
- Hazard definition
- Identification of vibration mechanisms
- Design and Analysis:
  - Strength $\not\propto$ resilience
  - Stress in cables from dynamic response
- Mitigation:
  - Composing practical design scheme with available analysis methods
- Testing

Basic concept of analysis and design



Performance requirements

- Using LRFD: a risk-based approach, and can be made performance-based
- Aerodynamics related limit states
- New extreme limit state
- Performance requirements for extreme limit state
- Assessment of performance

Aerodynamic-related limit states

- Strength V
  - Strength III: High wind, low traffic; Strength V: moderate wind, normal traffic
  - WS in strength V should be modified to reflect the possible maximum response under moderate wind
- Service I
  - Normal operational condition
  - Deflection control and user comfort

Aerodynamic-related limit states

- Fatigue
  - Only concern oscillatory load
- Extreme limit states
  - AASHTO only includes earthquake and ice/collision/hydraulic extreme event
  - Aerodynamic extreme event may not only occur at or above design wind speed
  - Concurrent with static wind load
  - Multi-level performance requirements

Load and resistance factors in PTI guide spec and AASHTO bridge design

Limit state	Resistance factor (PTI 5.3.3)
Strength	0.65
Service	0.85
Fatigue	1
Extreme event	1

Also AASHTO 6.5.5 for steel members

Limit state	Load factor (AASHTO static—WS)
Strength	0.4
Service	0.3
Fatigue	1.05
Extreme event	1
Construction	1.25

Load Combination / Limit State	*DC DD DW EH EV ES EL*	*LL IM CE BR PL LS*	*WA*	*WS*	*WL*	*FR*	*TU CR SH*	*TG*	*SE*	Use One of These at a Time			
										EQ	*IC*	*CT*	*CV*
STRENGTH I (unless noted)	γ_p	1.75	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
STRENGTH II	γ_p	1.35	1.00	—	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
STRENGTH III	γ_p	—	1.00	1.40	—	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
STRENGTH IV *EH, EV, ES, DW DC* ONLY	γ_p 1.5	—	1.00	—	—	1.00	0.50/1.20	—	—	—	—	—	—
STRENGTH V	γ_p	1.35	1.00	0.40	1.0	1.00	0.50/1.20	γ_{TG}	γ_{SE}	—	—	—	—
EXTREME EVENT I	γ_p	γ_{EQ}	1.00	—	—	1.00	—	—	—	1.00	—	—	—
EXTREME EVENT II	γ_p	0.50	1.00	—	—	1.00	—	—	—	—	1.00	1.00	1.00
SERVICE I	1.00	1.00	1.00	0.30	1.0	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—
SERVICE II	1.00	1.30	1.00	—	—	1.00	1.00/1.20	—	—	—	—	—	—
SERVICE III	1.00	0.80	1.00	—	—	1.00	1.00/1.20	γ_{TG}	γ_{SE}	—	—	—	—
SERVICE IV	1.00	—	1.00	0.70	—	1.00	1.00/1.20	—	1.0	—	—	—	—
FATIGUE—*LL, IM & CE* ONLY	—	0.75	—	—	—	—	—	—	—	—	—	—	—

Should be raised

0.75 (by AASHTO)×1.4 (by PTI 5.1.3 for long-span bridges)

Value 1.0 same as other hazard. To be combined with Extreme II of AASHTO

By AASHTO 3.4.2

Possible approach:
A new multi-level extreme limit state

- Multi-level performance-based design
- Combination with loads in normal operation
- Check on fatigue, service, and strength concerns
- Consistent with seismic design but address static and dynamic wind issues

Concerns in aerodynamic extreme event

Wind level		Concerns	Performance objectives
Lower level storm	Moderate wind	Fatigue	Stress produced by vibration is below the level of which the cables and other affected components may develop fatigue crack or fracture in the service life of the bridge.
		Service	The vibration amplitude does not produce visual irritation or rattling noise. Vibration level of the vehicular traffic lanes and sidewalk/bikeway remain the comfortable and safe range for respective usage. Corrosion resistant layers must remain uncracked. Visible movement or damage of cosmetic attachments and coatings should be controlled.
		Strength	Force effects on structural component must be in the adequate range and no yielding and rupture occur. Vibration control devices or fuse devices that are designed to yield or break under extreme wind speed may be allowed to be activated for lower level storm.
			Minimal and repairable damage occurs.
Upper level storm		Instability	Structural failure is prevented under upper level wind storm or loss of cable due to wind or other hazards.

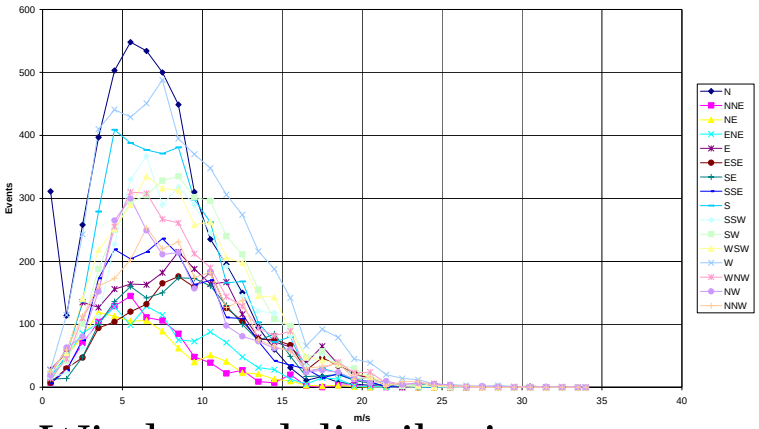
Wind hazard definition

- Design map values: 50 yr fastest-mile (AASHTO) or 3-sec gust (ASCE 7)
- Lower level wind storm: 100 yr return period
- Upper level wind storm: 10,000 yr return period
- Aerodynamic response sometimes peaks at moderate wind speed. The current hazard map does not provide sufficient information on such events.

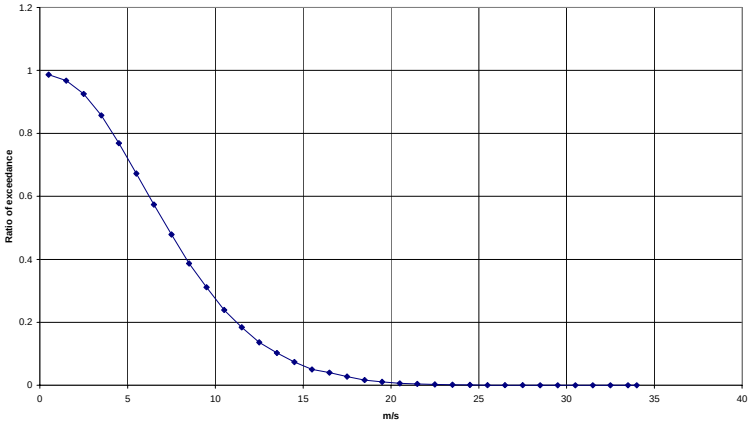
Sample wind speed distribution of 15 yrs record

wind speed bin [m/s]	wind direction in DEG AZIMUTH																Total
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	
0 0.9	311	7	10	11	28	7	13	6	17	15	24	22	28	14	19	25	557
1 1.9	114	29	50	50	55	30	14	27	50	23	42	54	115	45	63	59	820
2 2.9	258	70	81	86	135	47	48	75	136	63	101	141	243	110	80	113	1787
3 3.9	397	104	119	102	127	94	100	173	279	113	188	218	410	154	152	161	2891
4 4.9	503	129	113	128	156	104	136	219	409	227	250	252	441	255	265	173	3760
5 5.9	548	145	105	99	164	120	160	204	388	330	294	290	429	310	300	203	4089
6 6.9	534	111	106	129	163	132	142	215	377	367	305	335	451	308	249	253	4177
7 7.9	500	106	89	115	182	165	150	236	371	290	328	316	488	267	211	220	4034
8 8.9	449	85	62	75	215	176	174	211	381	318	335	313	395	261	214	231	3895
9 9.9	310	48	40	73	188	159	173	163	298	290	302	258	370	212	157	175	3216
10 10.9	235	39	51	88	164	183	161	170	262	245	296	263	348	190	183	182	3060
11 11.9	195	22	41	71	167	126	130	111	166	192	240	206	306	144	98	127	2342
12 12.9	150	27	23	48	116	105	100	109	168	145	211	198	274	129	81	138	2022
13 13.9	95	9	21	31	79	76	74	73	103	121	155	145	216	94	73	75	1440
14 14.9	60	7	13	28	72	76	85	42	72	118	108	143	188	82	62	65	1221
15 15.9	31	20	10	13	64	67	49	35	80	82	97	89	142	89	60	57	985
16 16.9	11	2	3	5	39	27	17	29	25	34	47	48	66	25	24	30	432
17 17.9	17	0	2	15	65	47	18	15	30	52	57	43	92	30	27	33	543
18 18.9	8	3	3	13	36	34	20	21	23	35	36	38	79	40	24	38	451
19 19.9	5	4	1	2	19	24	11	12	12	19	30	23	45	23	13	13	256
20 20.9	3	0	0	1	15	13	6	9	15	12	18	16	39	24	7	16	194
21 21.9	4	0	1	0	4	6	3	0	6	6	5	8	20	6	10	1	80
22 22.9	1	0	1	1	0	3	1	4	5	2	2	4	14	5	4	9	56
23 23.9	1	0	0	0	4	0	5	1	2	4	1	3	12	6	7	9	55
24 24.9	0	0	0	0	1	5	1	0	0	1	1	1	5	6	5	3	29
25 25.9	1	0	0	0	0	0	2	2	1	1	0	3	4	2	4	2	22
26 26.9	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1	2	7
27 27.9	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	3
28 28.9	0	0	0	0	0	0	1	0	0	0	0	0	3	0	1	0	5
29 29.9	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2
30 30.9	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	3
31 31.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
32 32.9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
33 33.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	4741	967	945	1184	2258	1826	1796	2162	3676	3105	3473	3431	5228	2834	2397	2413	42436

Vandiver et al, 1996



Wind speed distribution



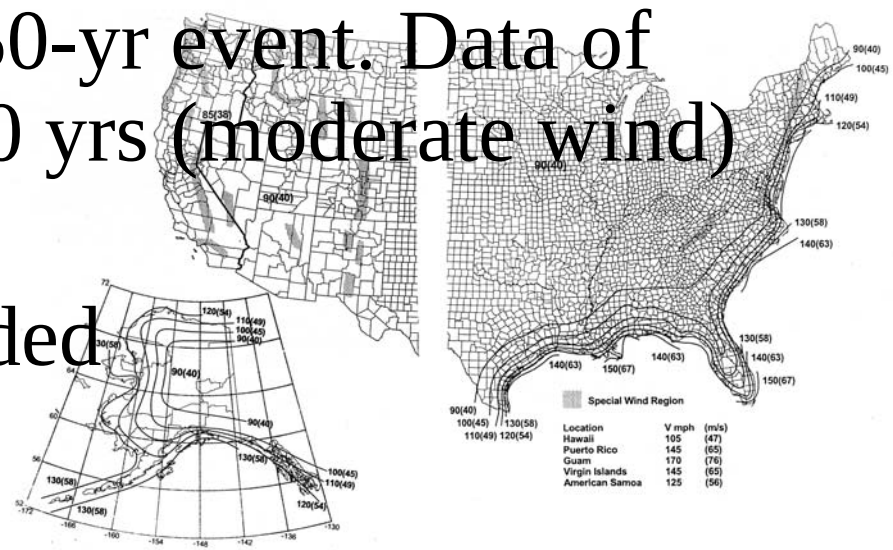
Wind speed and ratio of exceedance

Wind level and probability Of exceedance

Wind level	Probability of exceedance in 75 years
Moderate wind (often occurrence)	To be determined
Lower level storm (Service)	53%
Upper level storm (Life safety)	0.75%

Local hazard level

- AASHTO: ASCE-7(88) map, fastest-mile wind @30 ft above ground
- Logarithm profile above ground $V_{DZ} = 2.5V_0 \frac{V_{30}}{V_B} \ln \frac{Z}{Z_0}$
- Exposure category
- Map is equivalent to 50-yr event. Data of return period below 50 yrs (moderate wind) is not available.
- Rain data may be needed



Identified Mechanisms

- SPR-3(078) report (HNTB)
  - Vortex
  - Rain/wind induced
  - Wake Galloping
  - Inclined Galloping
  - Ice Accumulation Galloping
  - System Vibration
  - Buffeting
  - Cable Tension Fluctuation
- PTI guide spec
  - Buffeting
  - Vortex Shedding in wake
  - Self-induction (galloping)
  - Wake Galloping
  - Wind-rain interaction

Considered significant

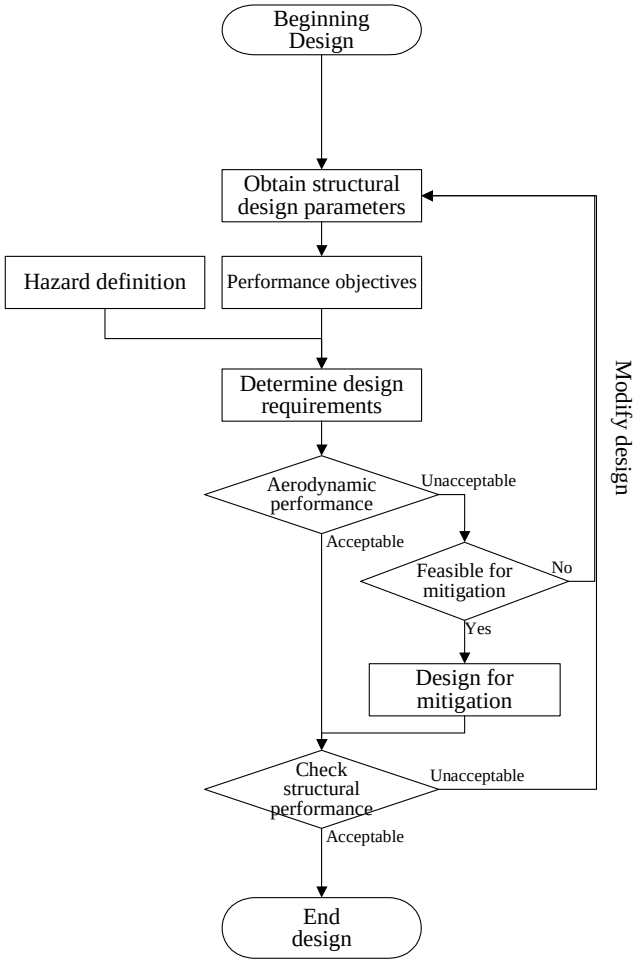
Mechanisms by AASHTO LRFD

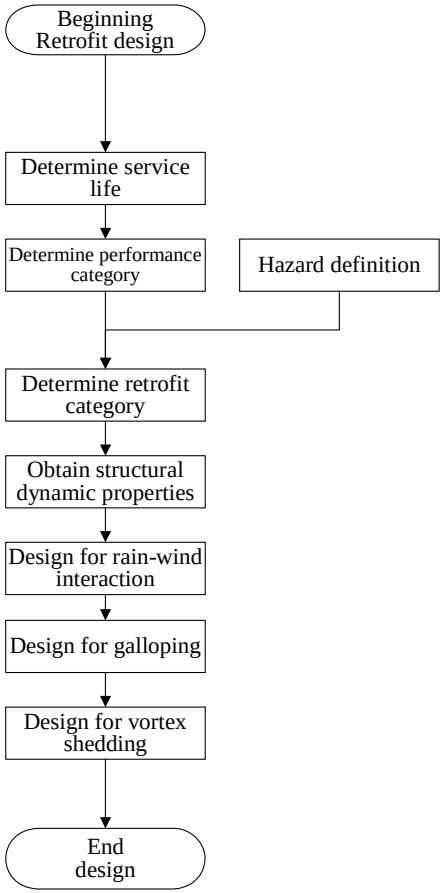
- Vortex Shedding
- Galloping—not considered for circular sections
- Flutter
- Divergence

Identification of vibration mechanisms

- Is it necessary or possible to distinguish vibration mechanisms by engineering practitioners?
- General design criteria may be found to cover most vibration episodes
- Identifying mechanisms may be more important in problem-driven retrofitting

Analysis: Design and analysis procedures





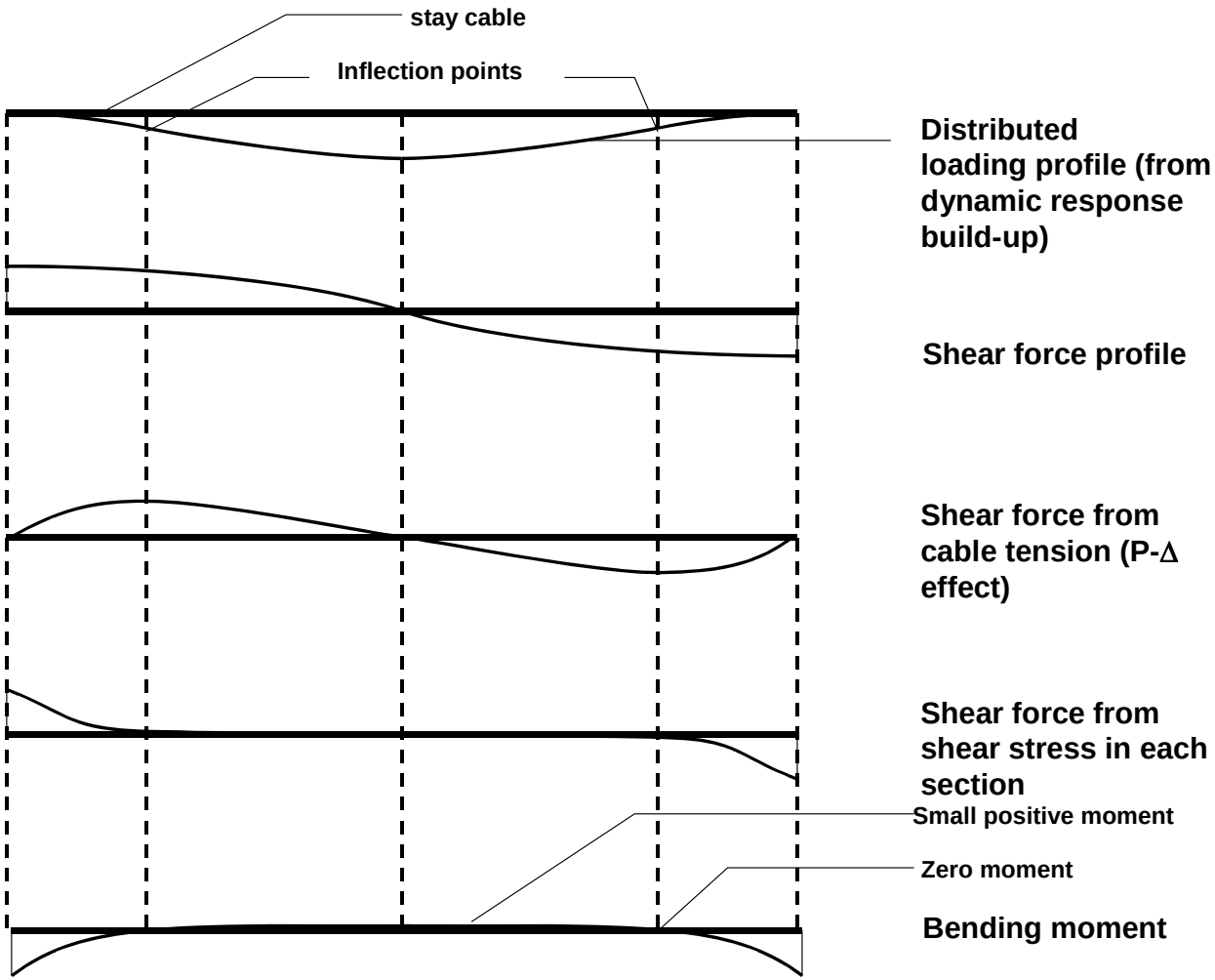
Key parameters for response computation

- Length
- Axial tension
- Linear mass density
- Axial and flexural stiffness
- Anchorage
- Frequency (combined effect of above parameters)
- Shape and surface features
- Damping
- Cables in group

Analysis: Factors in performance and stress profile

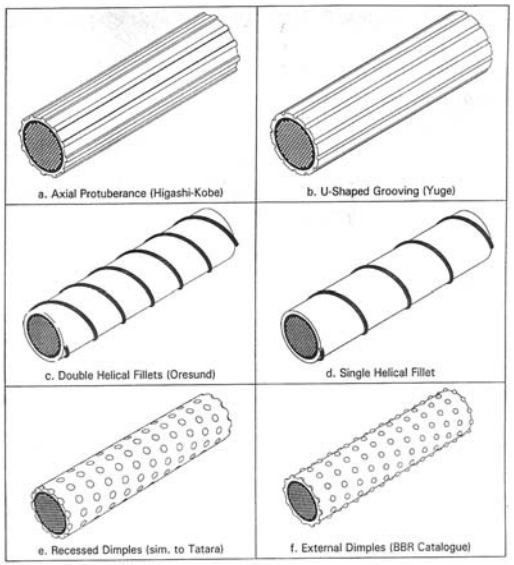
- Functional and mechanical performance
- Analysis model (e.g. taut string vs. beam)
- Equivalent sectional property (section modulus, bending stiffness vs. tension, grouting)
- Boundary conditions (fixity, initial rotation)
- Sag-extensibility
- Transverse bracing (guide-pipe bushing, damper)

Analysis: Response and stress



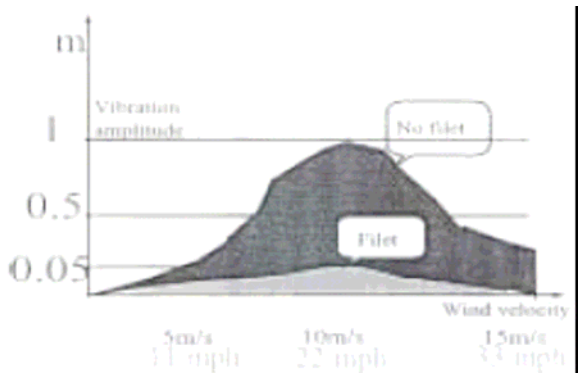
Mitigation methods

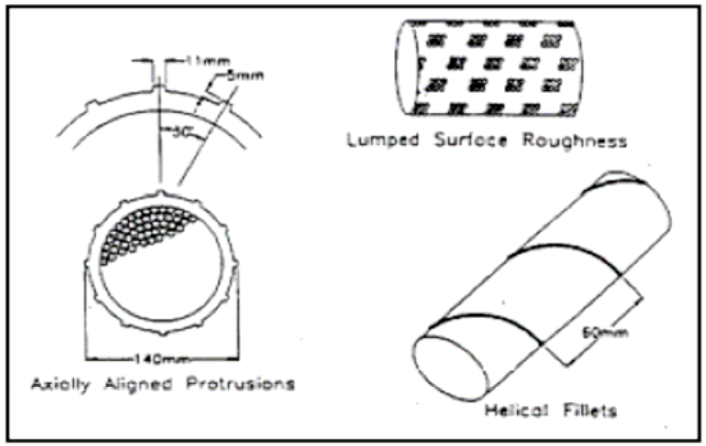
- Aerodynamic mitigation
  - Aerodynamic properties by testing
- Mechanical mitigation
  - Damper design for multiple modes
- Structural mitigation
  - Design procedure for cross-ties
- Hybrid mitigation
  - Insufficient data



Surface treatment

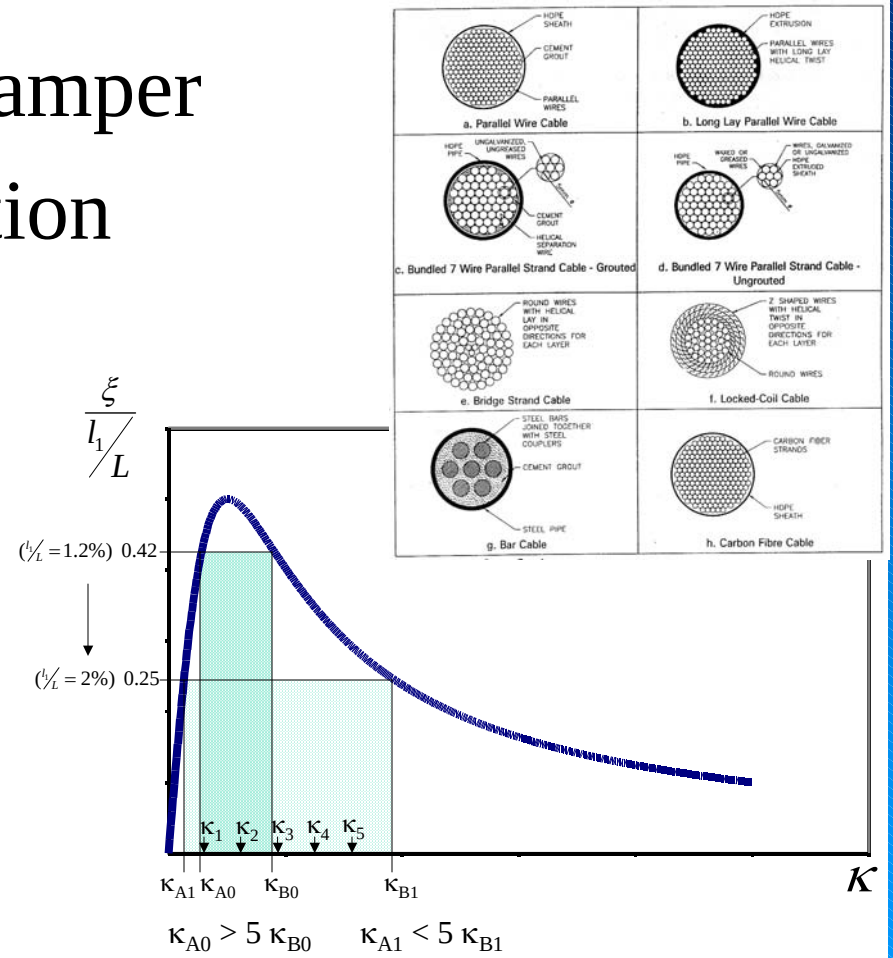
- Surface features to regulate water rivulets
- Force coefficients are changed—influence on static design
- Analytical formulation not available
  - May not be suitable as a stand-alone mitigation





Damper design

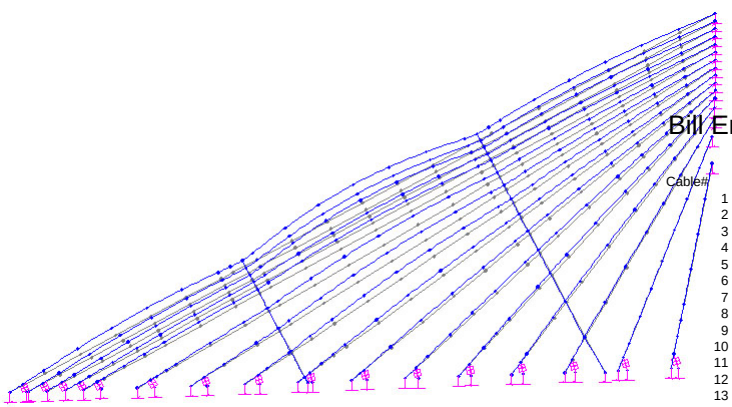
- Choice of the type of damper
- Choice of damper location
- Inherent damping in cables
- Calculation of damping coefficient
- Damper-induced stress



Cross-tie design

- Choice of the number of cross-tie
- Calculation of the size of the cross-tie
- Straightforward design procedure (spread sheet approach)
- Amount of post-tensioning

				E					
				2.00E+08	2.00E+08				
Ct	L	Lc1	Lc2	A1	A2			D1	D2
0.073681	52.4655	26.04924	51.95098	1.53E-04	3.05E-04	1.53E-04	3.05E-04	1.40E-02	1.97E-02
0.098119	51.13055	24.52138	50.51812	1.16E-04	2.40E-04	2.69E-04	5.45E-04	1.85E-02	2.63E-02
0.104985	49.79711	22.98667	49.07875	9.98E-05	2.13E-04	3.69E-04	7.58E-04	2.17E-02	3.11E-02
0.234601	48.46385	21.4531	47.64576	4.11E-05	9.14E-05	4.10E-04	8.49E-04	2.29E-02	3.29E-02
0.245531	47.17254	19.90253	46.20142	3.58E-05	8.31E-05	4.46E-04	9.32E-04	2.38E-02	3.45E-02
0.313817	43.8023	15.95074	43.60712	2.33E-05	6.37E-05	4.69E-04	9.96E-04	2.44E-02	3.56E-02
0.386134	40.47258	11.59136	40.83843	1.41E-05	4.97E-05	4.83E-04	1.05E-03	2.48E-02	3.65E-02
0.506996	37.17537	6.7288	37.85127	6.58E-06	3.70E-05	4.90E-04	1.08E-03	2.50E-02	3.71E-02
0.441595	50.93717	1.214411	34.5899	8.84E-07	2.52E-05	4.91E-04	1.11E-03	2.50E-02	3.76E-02
0.660556	46.20737	5.181996	30.94751	2.54E-06	1.52E-05	4.93E-04	1.12E-03	2.51E-02	3.78E-02
1.374932	41.62477	12.80404	26.78291	3.17E-06	6.63E-06	4.97E-04	1.13E-03	2.51E-02	3.79E-02
6.434273	37.15647	22.15203	21.87847	1.22E-06	1.20E-06	4.98E-04	1.13E-03	2.52E-02	3.79E-02
-1.833561	32.96989	33.98833	15.79637	-7.03E-06	-3.27E-06	4.91E-04	1.13E-03	2.50E-02	3.79E-02
-1.435805	29.01246	49.79542	7.948802	-1.23E-05	-1.97E-06	4.78E-04	1.13E-03	2.47E-02	3.79E-02
-1.01345	24.79501	72.62072	2.910512	-2.63E-05	-1.06E-06	4.52E-04	1.12E-03	2.40E-02	3.78E-02
-0.775838	20.53238	109.2692	19.77741	-5.81E-05	-1.05E-05	3.94E-04	1.11E-03	2.24E-02	3.77E-02



Bill Emerson Memorial Bridge, MO

												XTieConne	YTieConne	XTieConne	YTieConnect2		
												-94.20667	44.95	-47.98333	69.77		
											X2, Y2	-12.32317	22.95	-24.57663	45.77		
Cable#	Xtower	Ytower	Xdeck	Ydeck	Tension	CableFreq	xTieAnchor	yTieAnchor	TargetFreq	X1	Y1					#ofCrossTi	Lumda
1	-1.76	94.59	-140.43	20.13	4537	0.557289	-81.8835	22	1.381788	-138.67	-74.46	-94.20667	44.95	-47.98333	69.77	2	2.596506
2	-1.76	93.07	-136.77	20.26	4759	0.585754	-23.4067	24	RefFreq	-135.01	-72.81	-93.48388	43.60392	-47.30549	68.50762	2	2.470327
3	-1.76	91.54	-133.12	20.39	4537	0.593401			2.786447	-131.36	-71.15	-92.75785	42.25181	-46.62456	67.2395	2	2.438493
4	-1.76	90.02	-129.47	20.53	4359	0.713216				-127.71	-69.49	-92.03236	40.90069	-45.94665	65.97701	2	2.028846
5	-1.76	88.49	-125.93	20.6	4163	0.721553				-124.17	-67.89	-91.29883	39.53461	-45.26337	64.70451	2	2.005404
6	-1.75	86.98	-115.38	20.98	4011	0.768935				-113.63	-66	-89.42935	36.05298	-44.03608	62.41887	2	1.88183
7	-1.73	85.48	-104.83	21.35	3801	0.811754				-103.1	-64.13	-87.36705	32.21226	-42.72628	59.9796	2	1.782566
8	-1.72	83.97	-94.27	21.74	3682	0.870701				-92.55	-62.23	-85.06671	27.92823	-41.31314	57.34784	2	1.661885
9	-1.73	82.46	-83.79	22.09	3272	1.047998				-82.06	-60.37	-82.458	23.06992	-39.77027	54.47449	1	2.071098
10	-1.71	80.97	-73.26	22.48	2992	1.117443				-71.55	-58.49	-79.43204	17.43454	-38.04715	51.26546	1	1.942387
11	-1.71	79.48	-62.74	22.86	2832	1.22414				-61.03	-56.62	-75.82627	10.71934	-36.07699	47.59636	1	1.773088
12	-1.82	77.88	-52.22	23.27	2631	1.340842				-50.4	-54.61	-71.40399	2.483534	-33.75683	43.27543	1	1.618765
13	-1.84	76.05	-41.79	23.59	2498	1.578532				-39.95	-52.46	-65.80457	-7.944528	-30.87955	37.91697	1	1.375017
14	-1.84	73.98	-31.3	23.99	2061	1.655355				-29.46	-49.99	-58.32668	-21.87095	-27.16707	31.00308	1	1.311204
15	-2.35	70.38	-20.85	24.37	1821	1.851166				-18.5	-46.01	-47.52867	-41.98058	-22.02981	21.43577	1	1.172508
16	-2.37	65.08	-10.41	24.81	1692	2.177226				-8.04	-40.27	-30.19131	-74.26875	-14.05053	6.57565	1	0.996914

Testing

- System characterization
- Proof-of-concept
- Quality control

} Base isolation guide spec

- Instrumentation recommendations
  - Construction stage
  - Baseline characterization
  - Long-term monitoring

Summary: Impact to the Industry

- Promoting understanding of dynamic wind hazard
- Stimulating and guiding future studies
  - New hazard definition, etc.
- Requirements for manufacturing and construction
  - Required information on products
  - Instrumentation and measurement requirements

Summary: Future study

- Wind hazard definition
- Hybrid mitigation schemes
- Adequate load and resistance factors
- Remaining vibration amplitude after mitigation

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