Failure of the Tacoma Narrows Bridge: Flutter not Resonance

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What can a mechanical system do?

What really happened to the Tacoma Narrows Bridge?

What dynamic properties could be present in ion channel proteins?

What Didn't Happen

NOT Resonance

Resonance

- excite at a given frequency f_o.
- resonance frequency of the bridge

$$f_b \approx f_o.$$

There was NO driving at fixed frequency f_o .

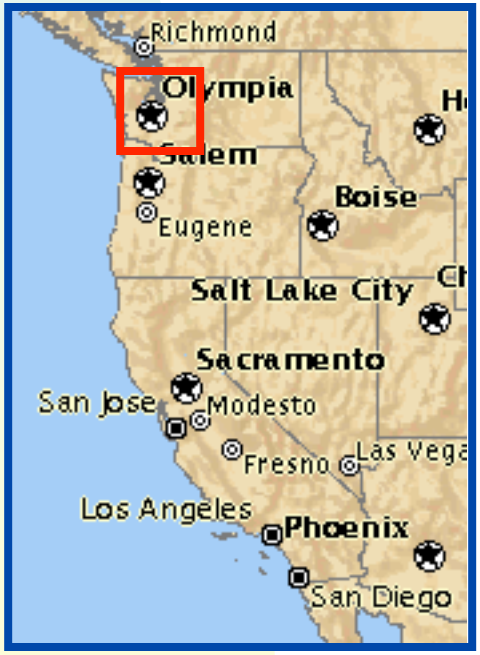
NOT Alternatively shed vortices

- Strouhal frequency ≈ 1 Hz.
- Bridge frequency ≈ 1/5 Hz.

Wind tunnel tests show that:
the bridge controlled the vortices,
NOT that the vortices drove the bridge.

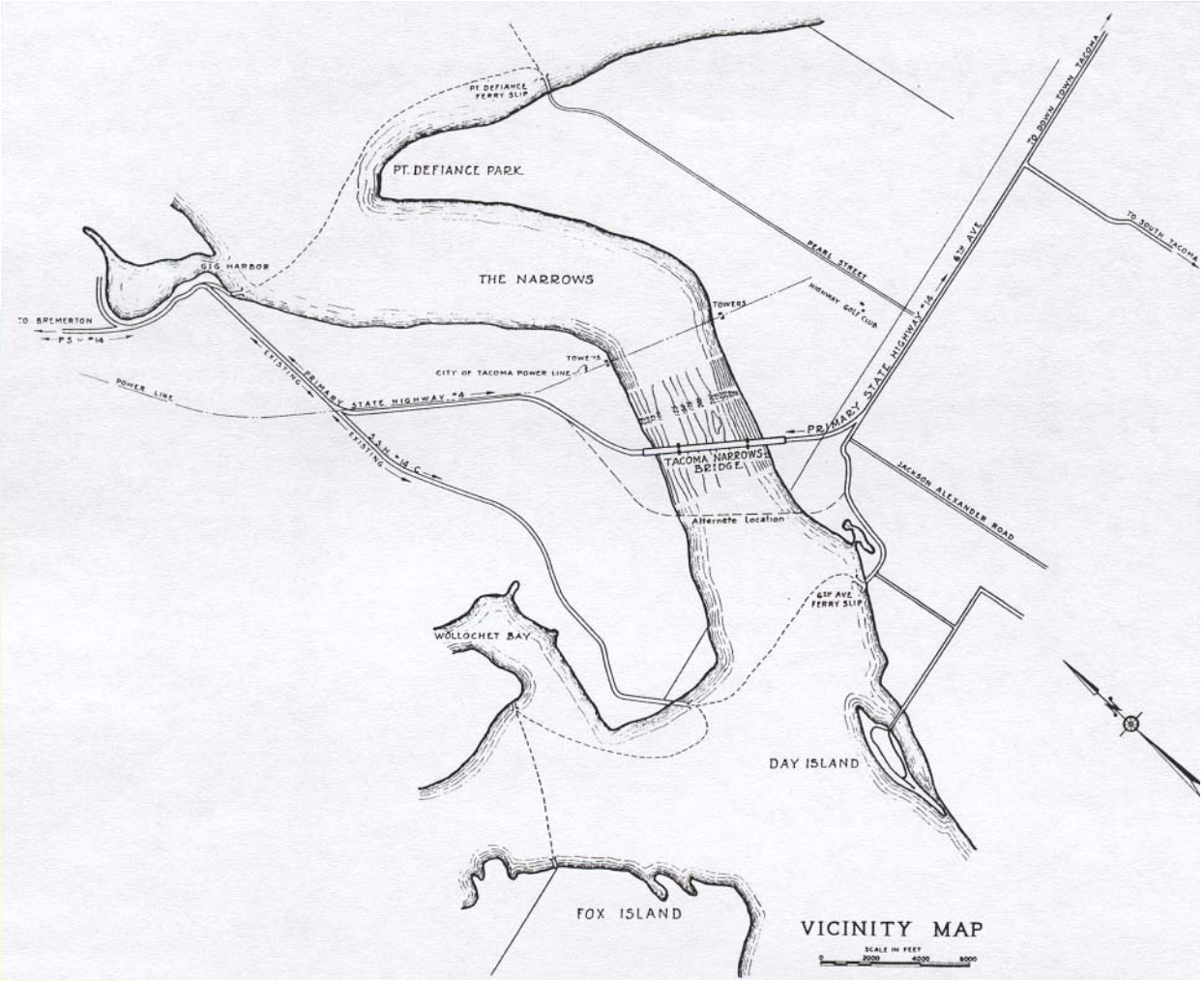
The Area


North
America

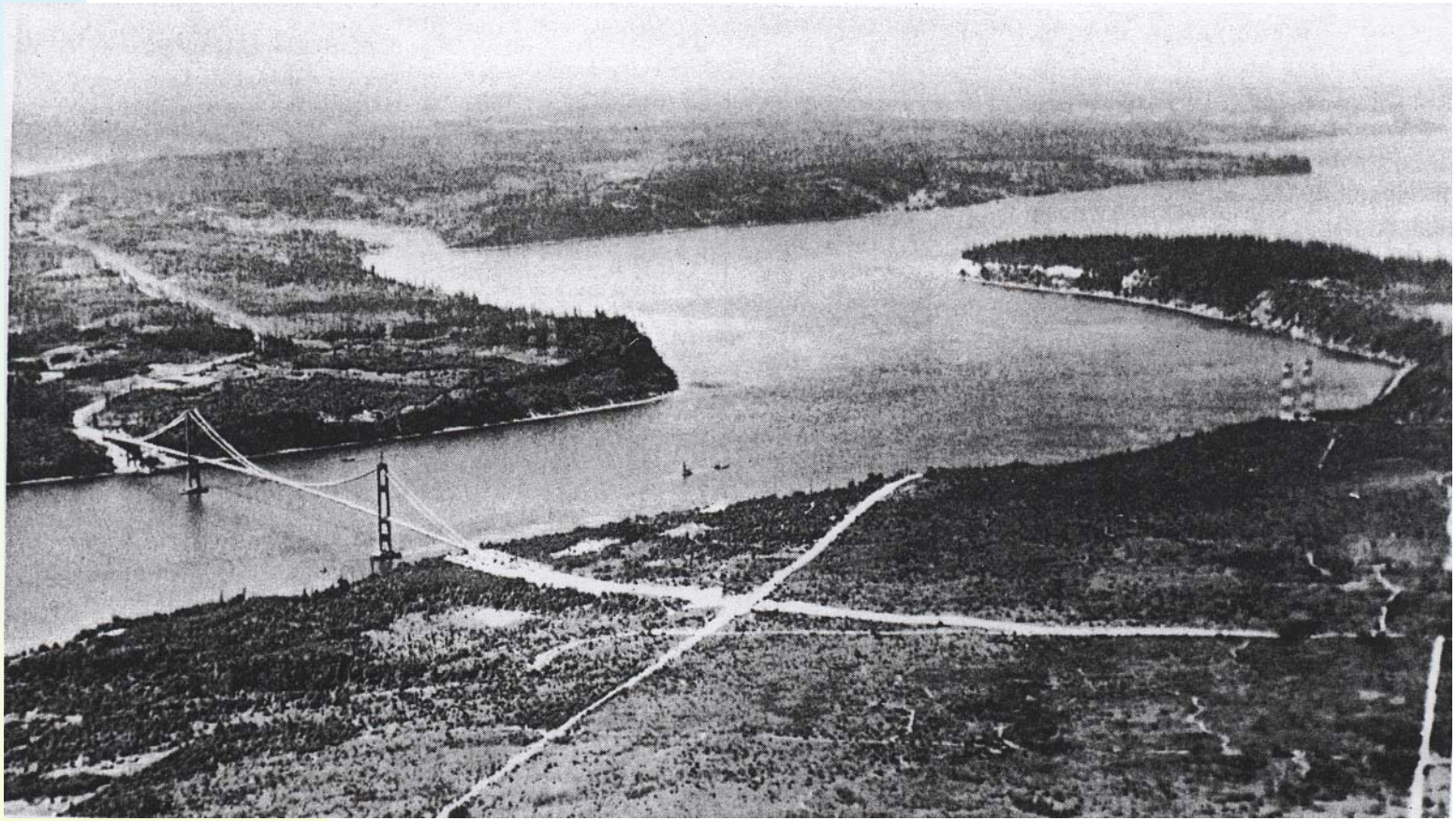

Richmond
Olympia
Salem
Eugene
Boise
Salt Lake City
Sacramento
San Jose
Modesto
Fresno
Las Vega
Los Angeles
Phoenix
San Diego


Clallam
Jefferson
Port Ludlow
Hansville
Quilcene
Edmonds
Poulsbo
Brinnon
Seattle
Bremerton
Eldon
White
Burien
Tahuya St. For.
Allyn
Seatac
Union
Tahuya
Federal Way
Tacoma
Fife
Puyallu
Lakewood
Spanaway
Olympia
Elk Plain
Tumwater
Lacey
Roy
McCleary
104
526
305
3
101
16
512
410
108
119

The Site


PT. DEFIANCE FERRY SLIP
PT. DEFIANCE PARK
THE NARROWS
GIG HARBOR
TO BREMERTON
TOWER 3
TOWER 4
CITY OF TACOMA POWER LINE
POWER LINE
EXISTING
PRIMARY STATE HIGHWAY #4
EXISTING
PRIMARY STATE HIGHWAY #16
TACOMA NARROWS BRIDGE
Alternate Location
PEARL STREET
HIGHWAY GOLF CLUB
6TH AVE
TO DOWN TOWN TACOMA
TO SOUTH TACOMA
JACKSON ALEXANDER ROAD
6TH AVE FERRY SLIP
WOLLOCHET BAY
DAY ISLAND
FOX ISLAND
VICINITY MAP
SCALE IN FEET
0 2000 4000 6000

The Bridge at the Site

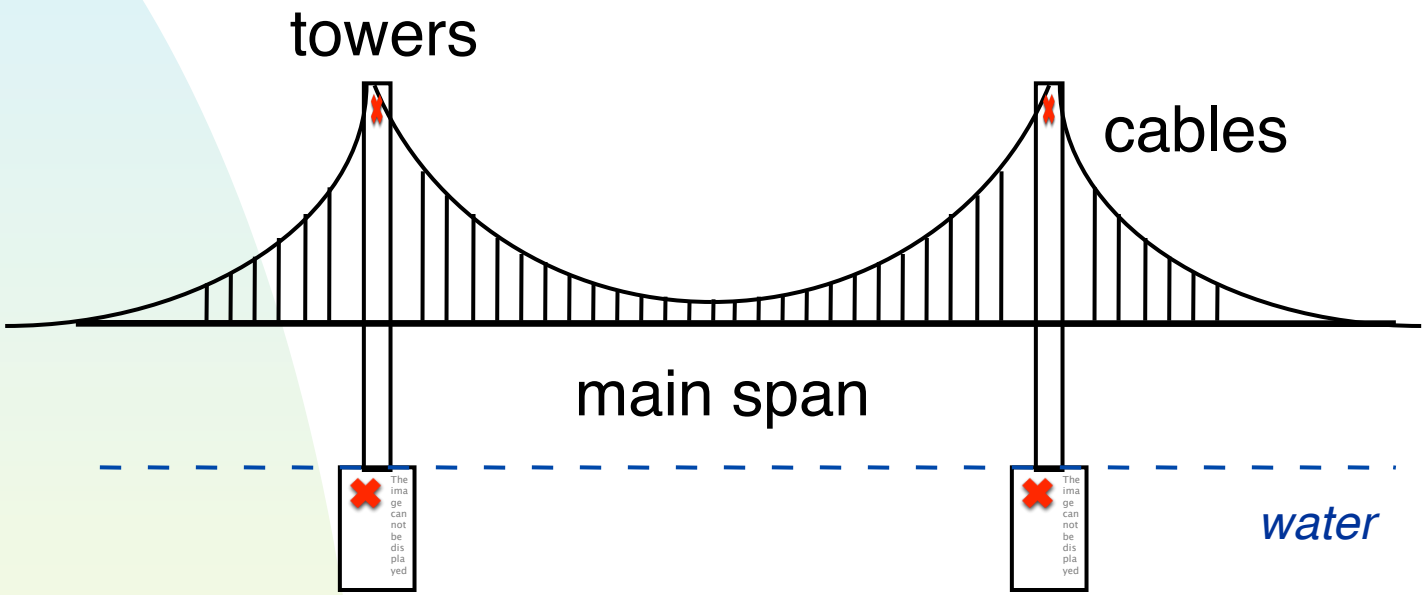


Timetable

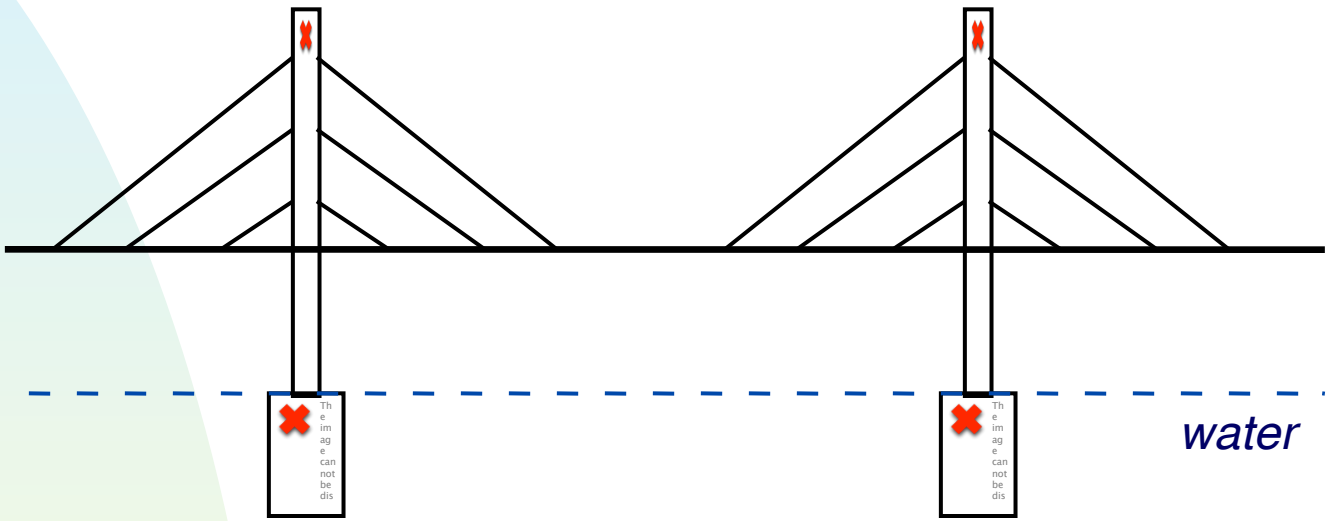
Bids received	Sept. 27, 1938
Contract awarded	Nov. 23, 1938
Construction commenced	Nov. 23, 1938
Main piers completed	Sept. 11, 1939
Towers completed	Jan. 6, 1940
Cables completed	Mar. 9, 1940
Suspended steel completed	May 31, 1940
Concrete roadways completed	June 28, 1940
Bridge opened to traffic	July 1, 1940

The bridge failed on November 7, 1940.

Suspension Bridge



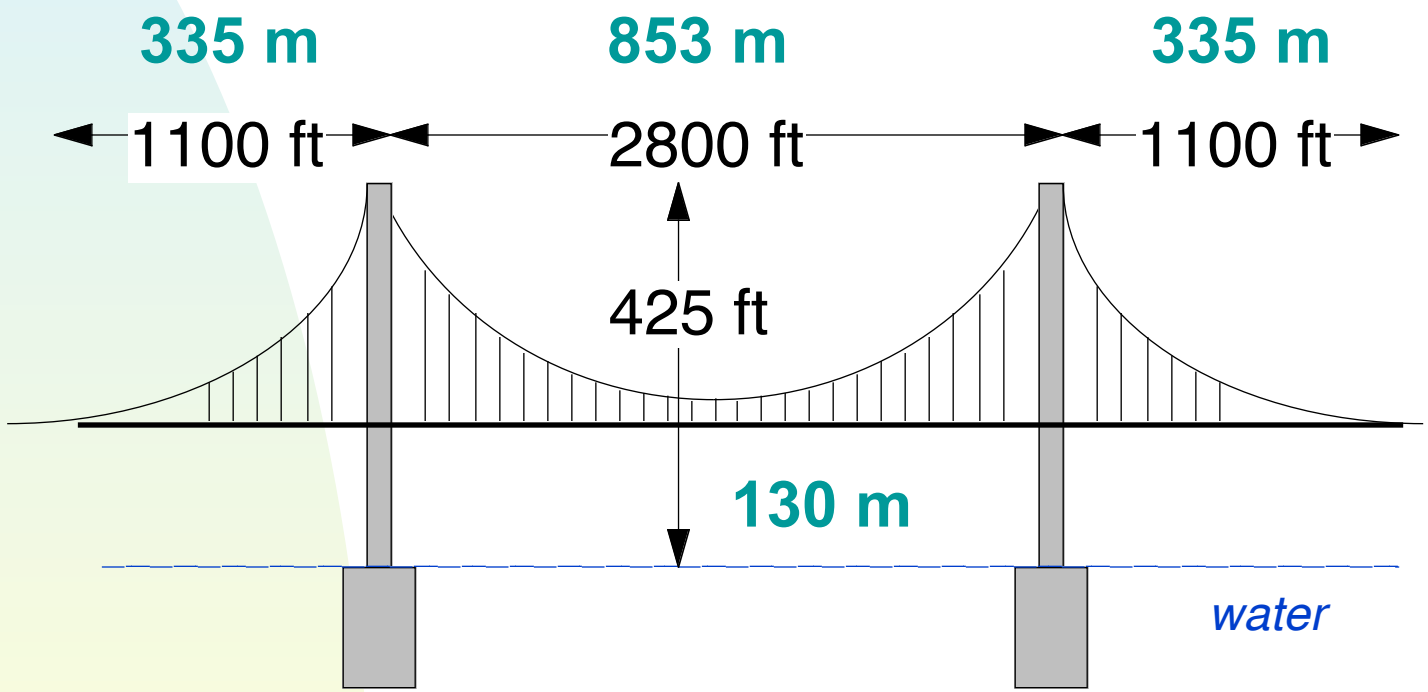
Cable Stay Bridge



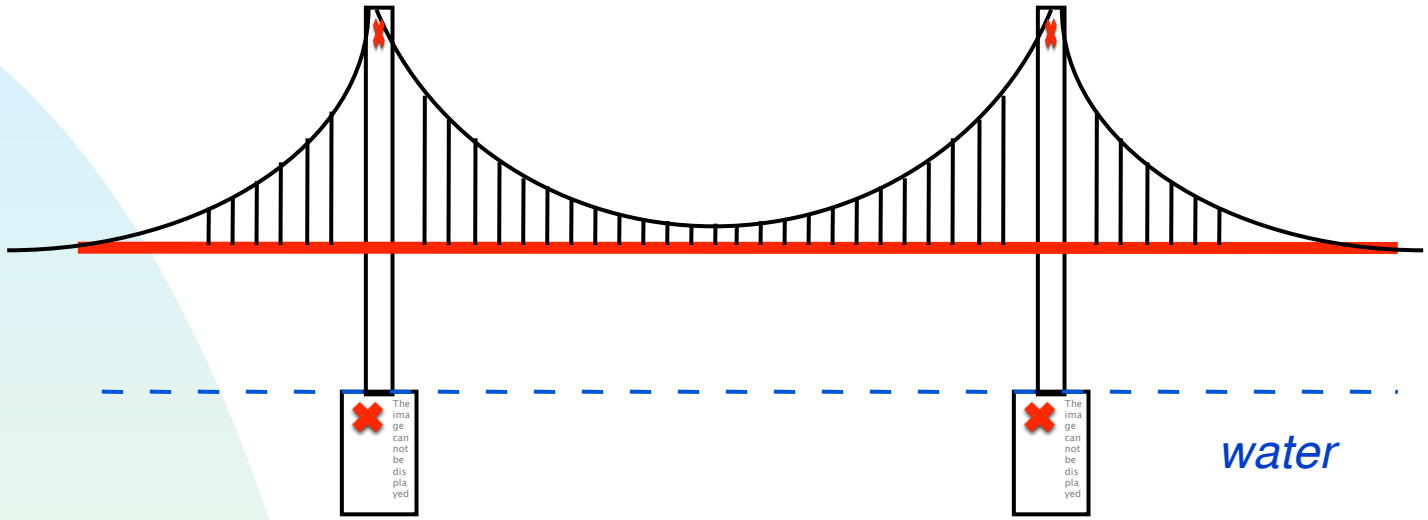
Why?

- **For medium spans, less steel, less money.**
- **Pretty.**

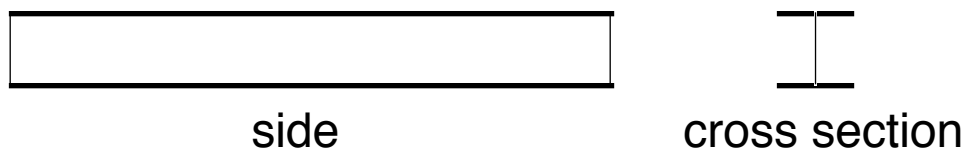
Tacoma Narrows Bridge



Tacoma Narrows



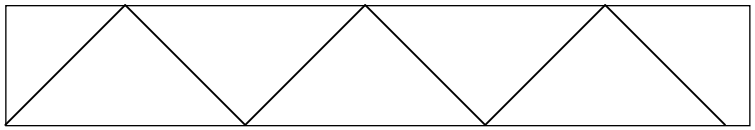
Main span:
Plate Girder.



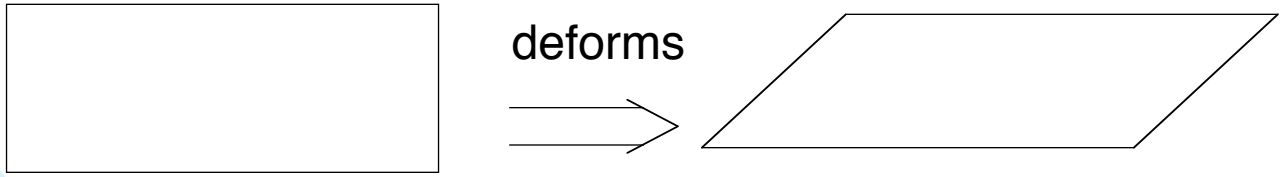
Why? **Because it was beautiful.**

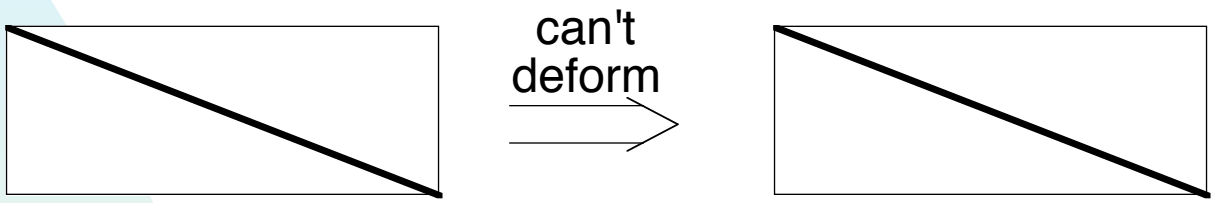
By far, this was the longest, narrowest, bridge with a man span built using a plate girder.

Normally, a Truss, would be used.

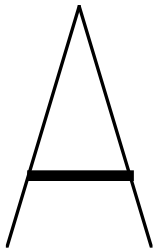


Truss



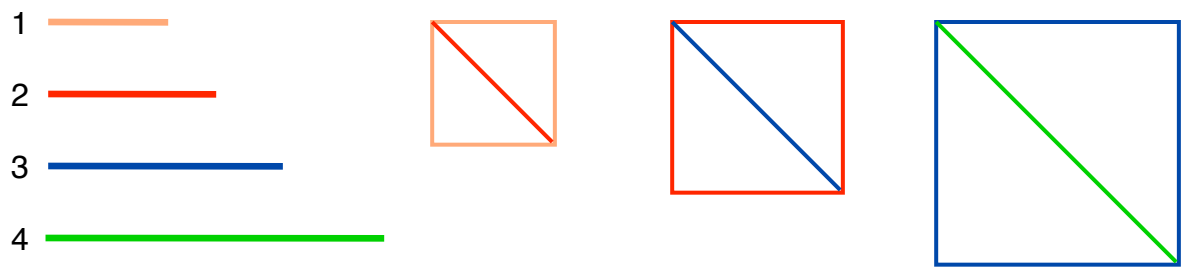


A frame houses:



Tinker Toy:

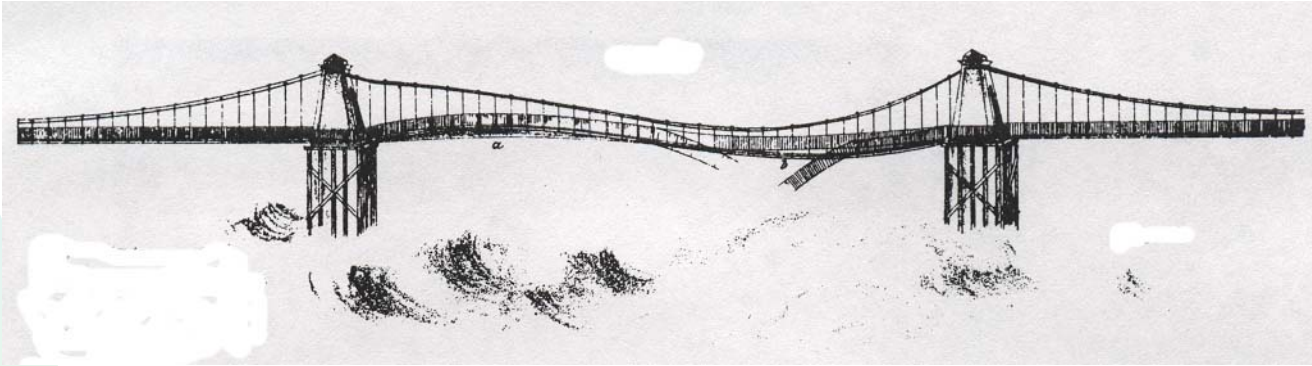
Each piece is $\sqrt{2}$ larger than the next smaller piece.

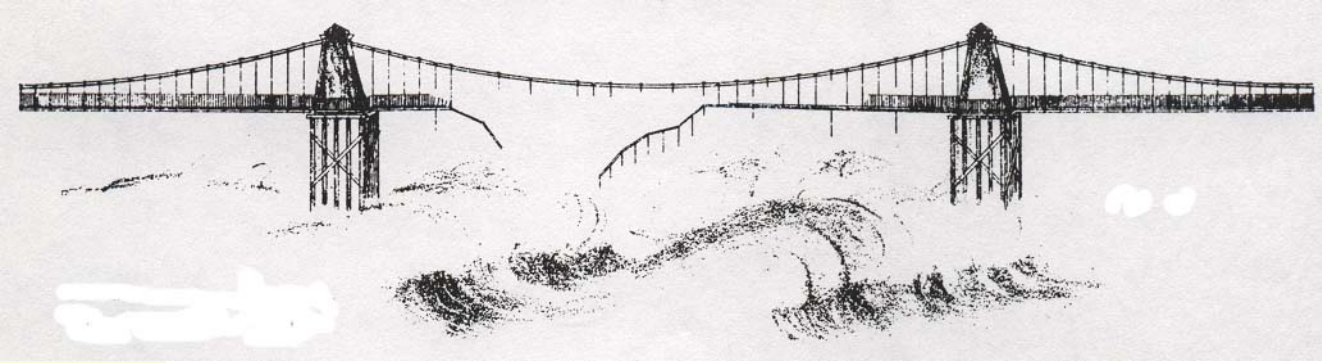


Bridges Damaged or Destroyed by Wind

Dryburgh Abbey	Scotland	260 ft.	1818
Union	England	449 ft.	1821
Nassau	Germany	245 ft.	1834
Brighton Chain Pier	England	255 ft.	1836
Montrose	Scotland	432 ft.	1838
Menai Straights	Wales	580 ft.	1839
Roche-Bernard	France	641 ft.	1852
Wheeling	U.S.A.	1010 ft.	1854
Niagara-Lewiston	U.S.A.	1041 ft.	1864
Niagara-Clifton	U.S.A.	1260 ft.	1889
Tacoma Narrows	U.S.A.	2800 ft.	1940

Chair Pier at Brighton

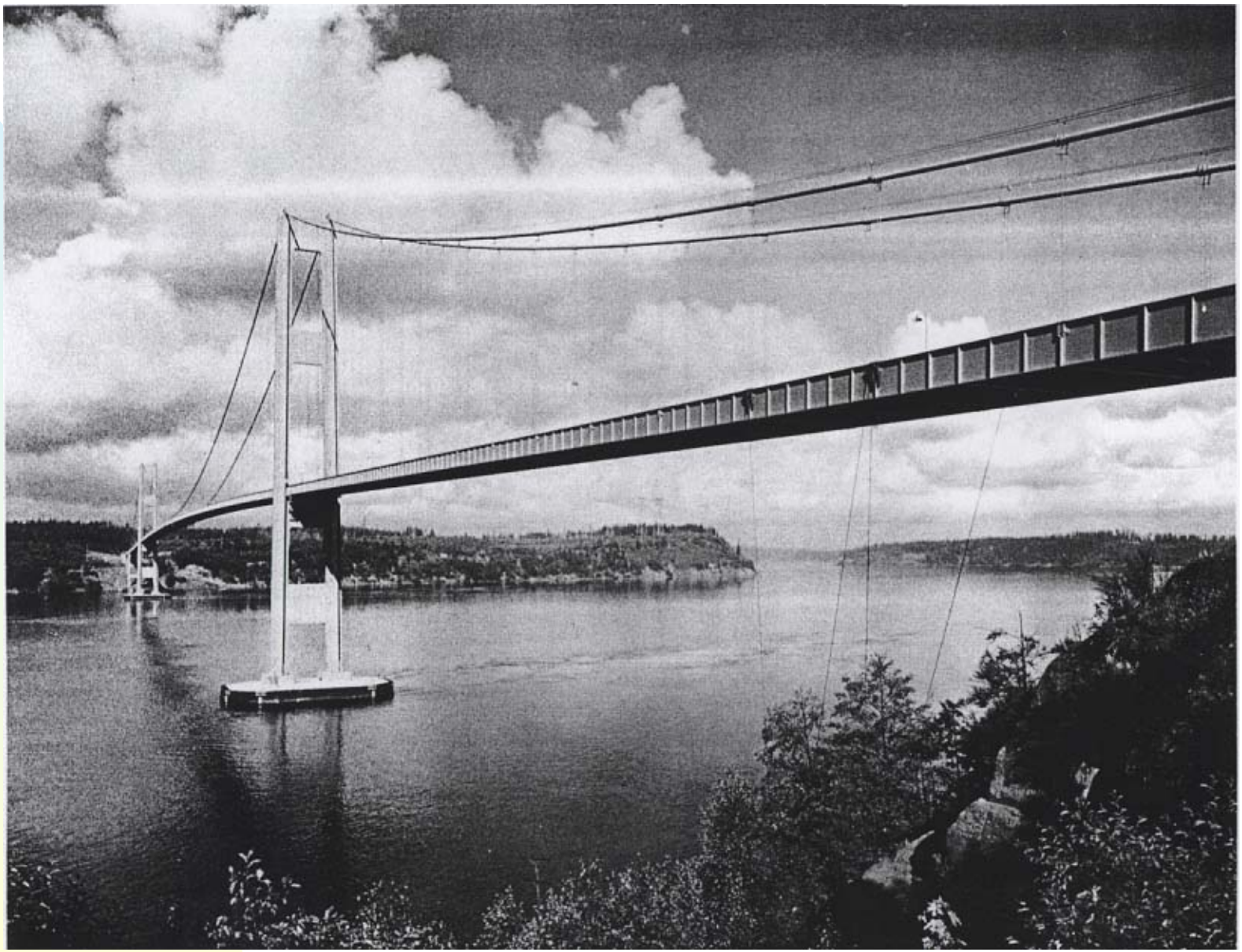




Modern Bridges Active in the Wind

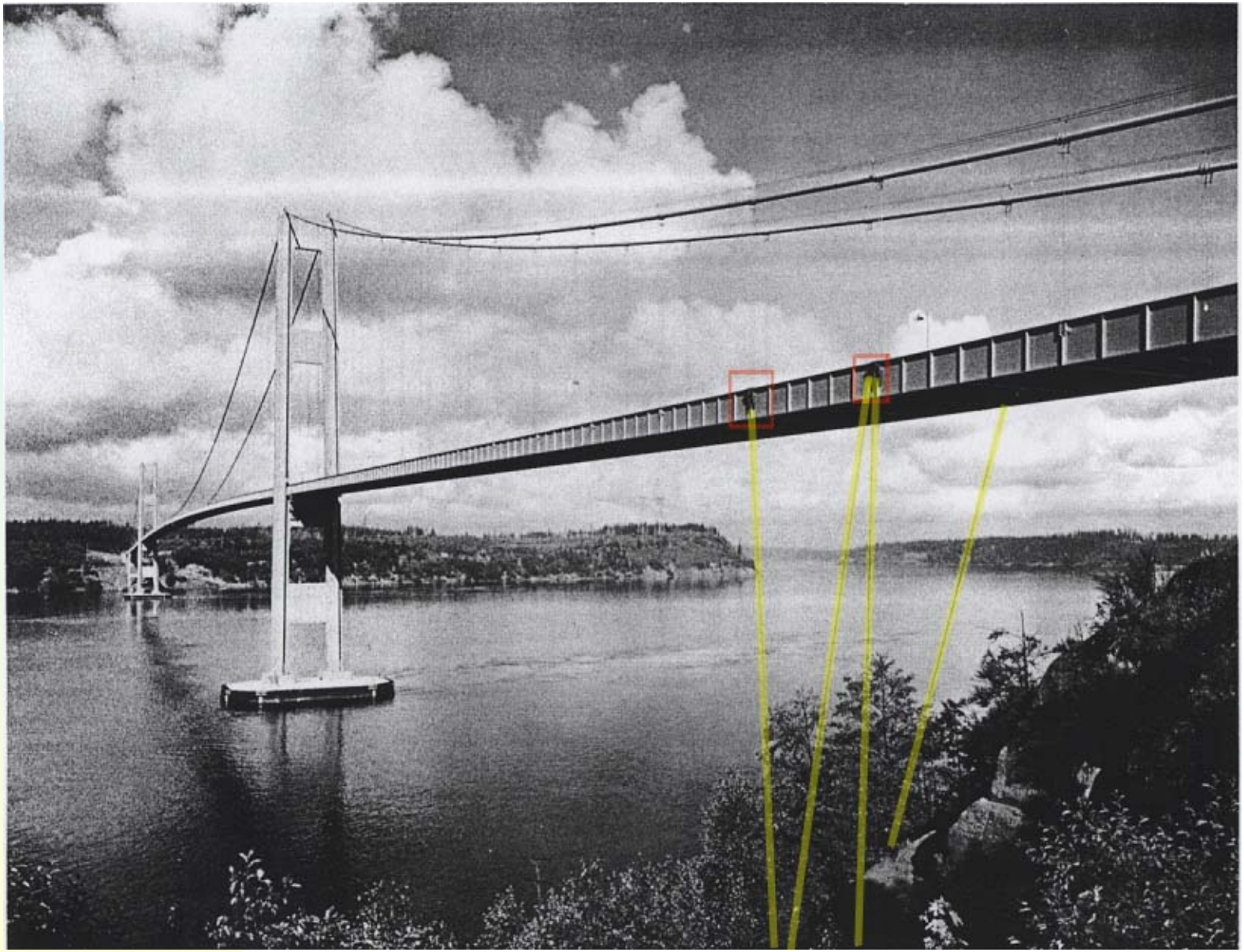
Bridge	Built	Span (ft.)	Stiffened
Fyksesund (Norway)	1937	750	Rolled I-beam
Golden Gate	1937	4200	Truss
Thousand Islands	1938	800	Plate Girder
Deer Isle	1939	1080	Plate Girder
Bronx-Whitestone	1939	2300	Plate Grider

Tacoma Narrows



Tacoma Narrows

Tie down cables.



Events: Before Bridge Was Finished

Static Model

To check the erection sequence.

Dynamic Model

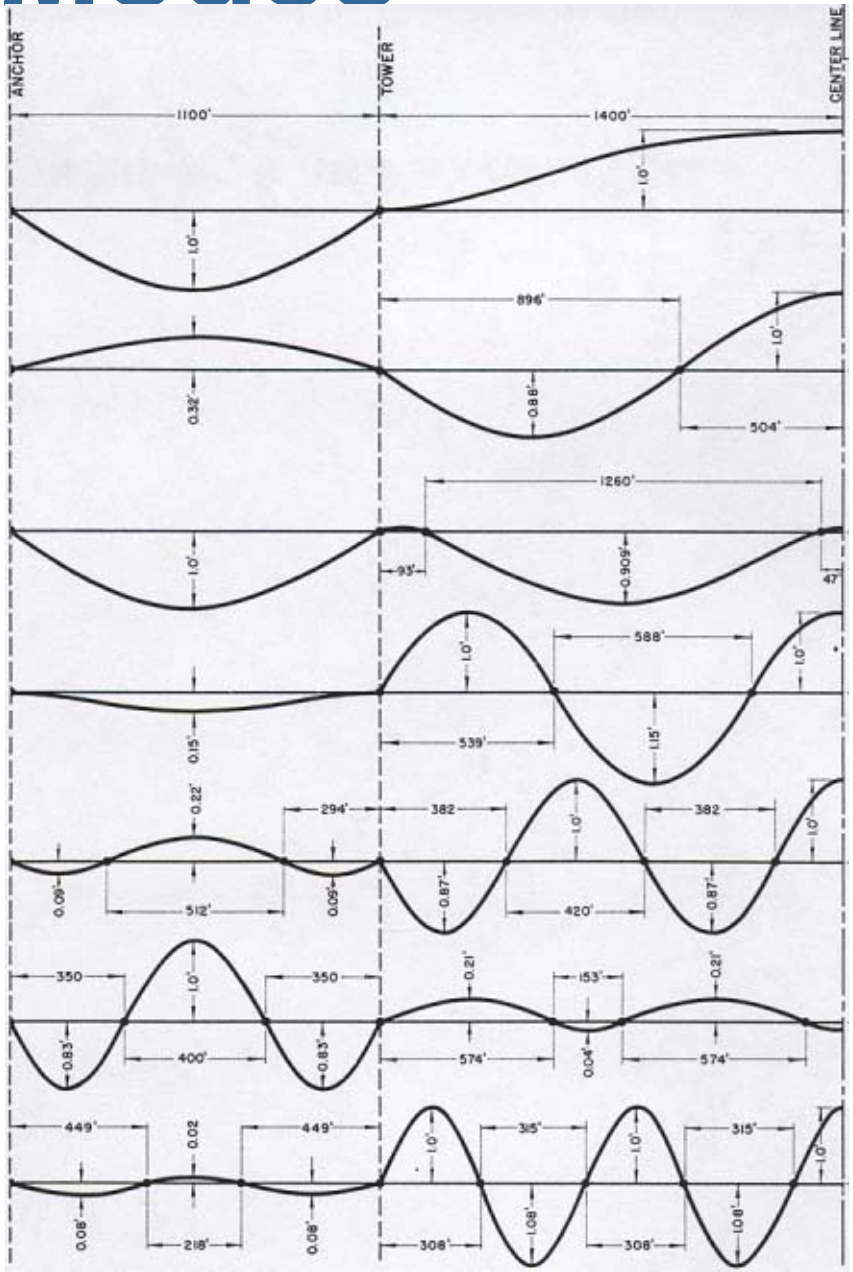
"Unprecedented motion" of the Bronx-Whitestone bridge.

Wind Tunnel Tests

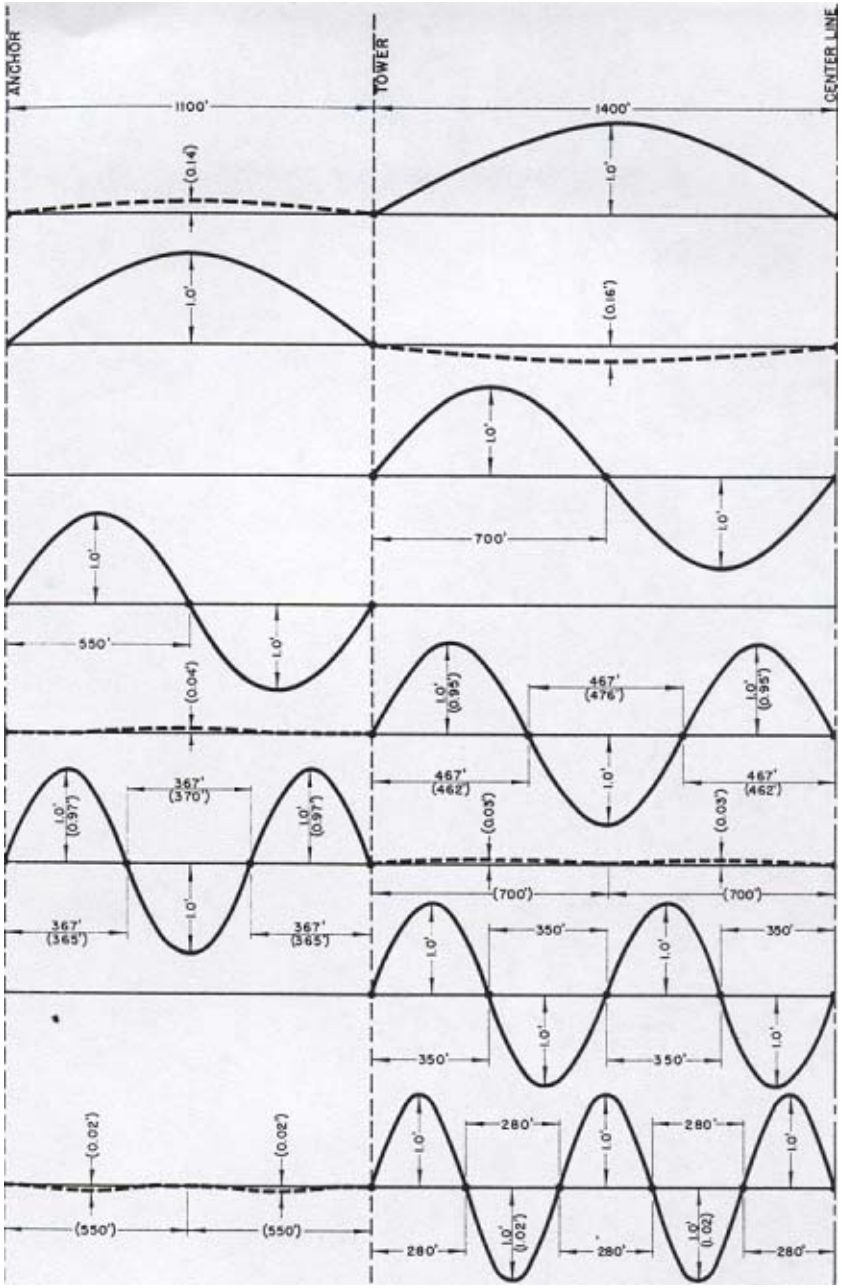
Events

June 1, 1940	**Center ties installed.** Diagonal cables from the span to the main suspending cables.
June 28, 1940	**Hydraulic damping.** Shock absorbers - destroyed by sandblasting the steel.
July 1, 1940	**Bridge opened.**
October 4, 1940	**Side span hold-down cables.**
November 7, 1940	**Maximum wind = 42 mph (68 Km/hr).** Several hours of typical vertical motion. Suddenly, violent TORSION. • 10 minutes - damage • 50 minutes - collapse.

Symmetric Modes



Asymmetric Modes



Eyewitness' Account

"A series of observations and photographs taken just before 10:00 AM showed the bridge to be moving with the usual vertical motion...

Observations of the wind at this time showed 42 mph...

a few minutes later a violent change in motion was noted. This change appeared to take place without any intermediate stages and with such extreme violence that the span appeared to roll completely over.

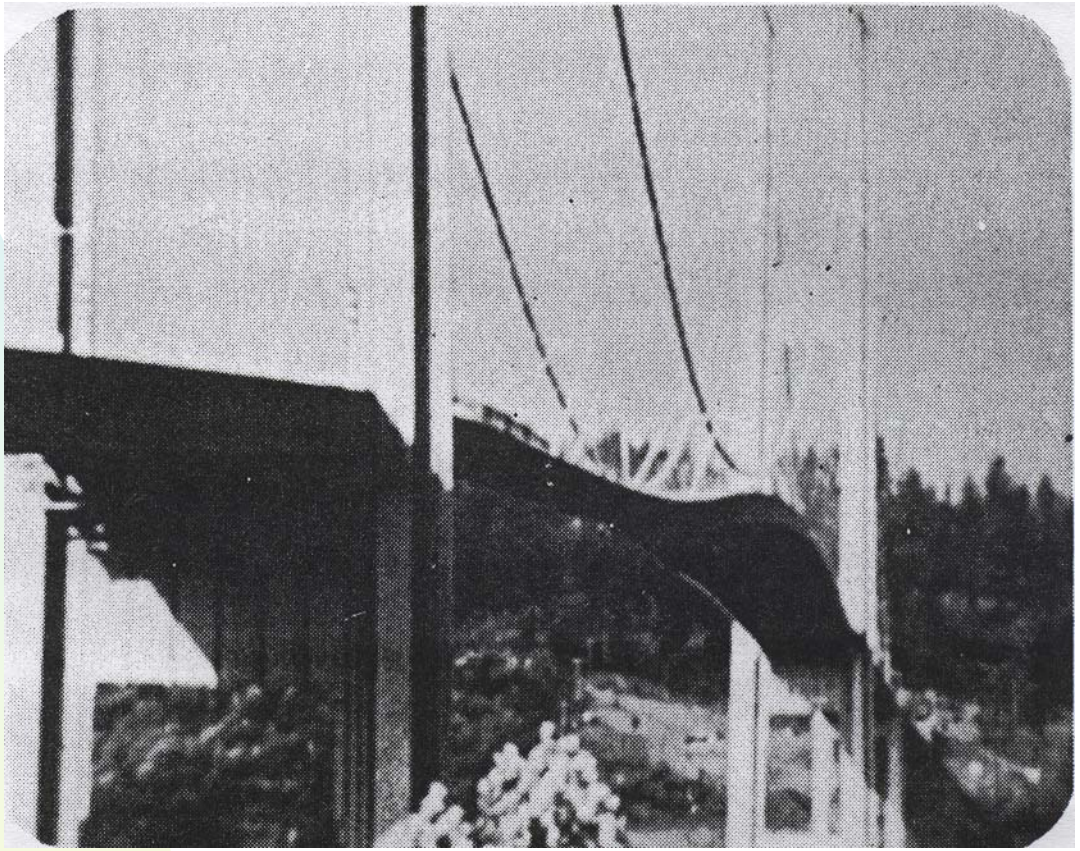
not more than 8 or 10 minutes after the start of this violent motion, a considerable amount of damage had been done to the concrete sidewalks and curbs and several of the lamp posts in the vicinity of the Tacoma towers were already off their bases.

A car was stalled some little distance beyond the quarter point toward the center of the bridge. An effort was made during a momentary decrease in the violence of the motion to drive this car to safety; but shortly after reaching the car, the violence increased to a point where the acceleration must have reached that of gravity, since the car began to shift around in a most alarming manner. While out on this position of the span, opportunity was taken to examine the state of the bridge...the double amplitude of approximately 28 feet was causing no distress in the girder.

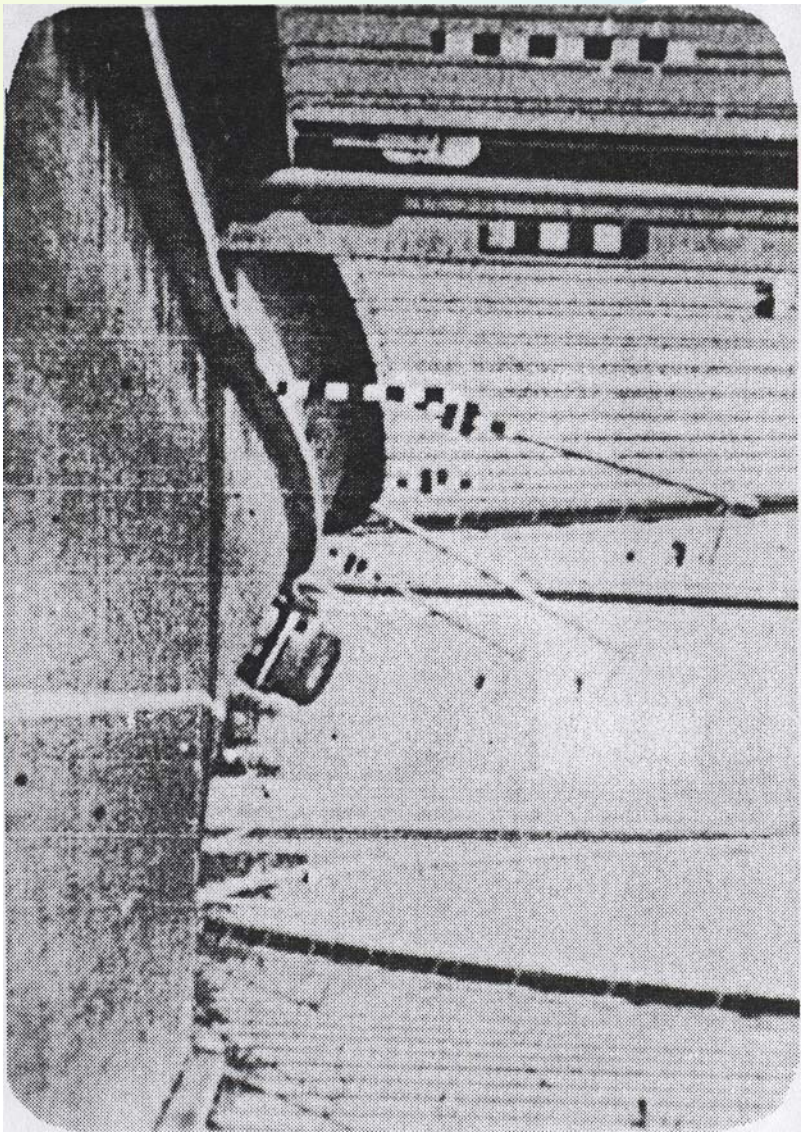
It now became necessary to return to the toll house for a fresh supply of film and there ensued a gap of some ten or twelve minutes in the observations.

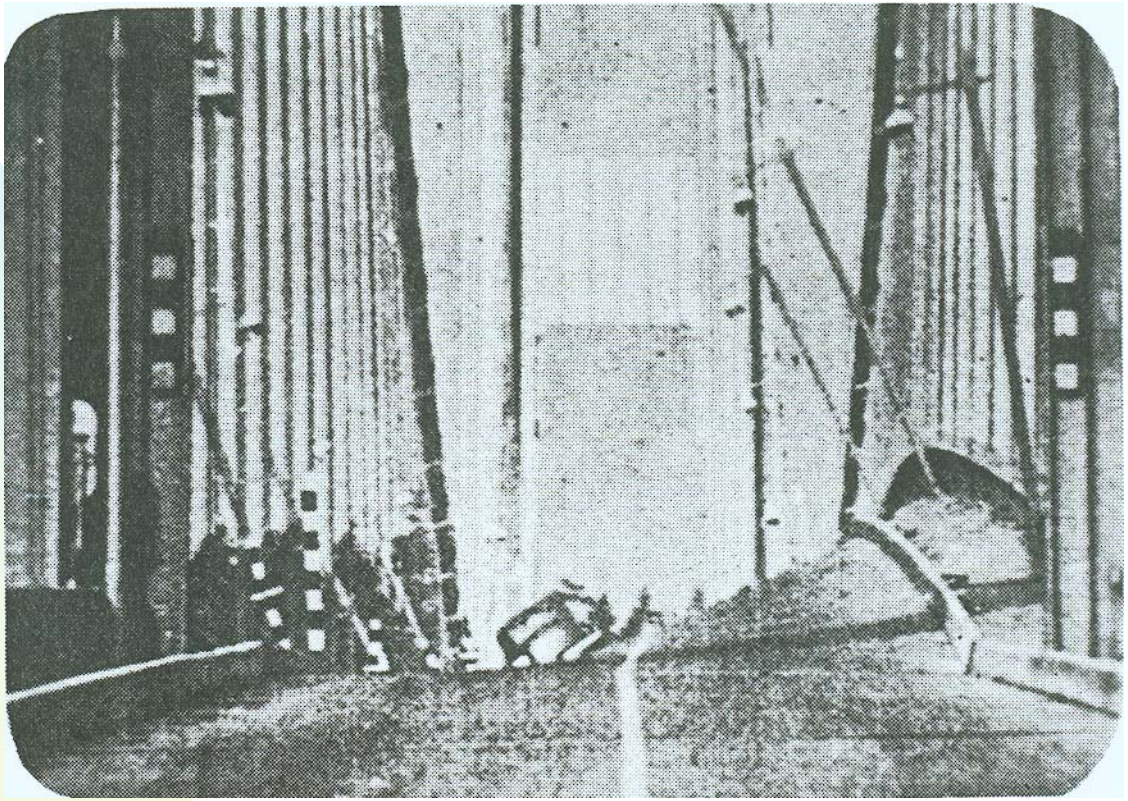
<u>the frequency had changed to 12 [cpm = 0.2 Hz]...</u>

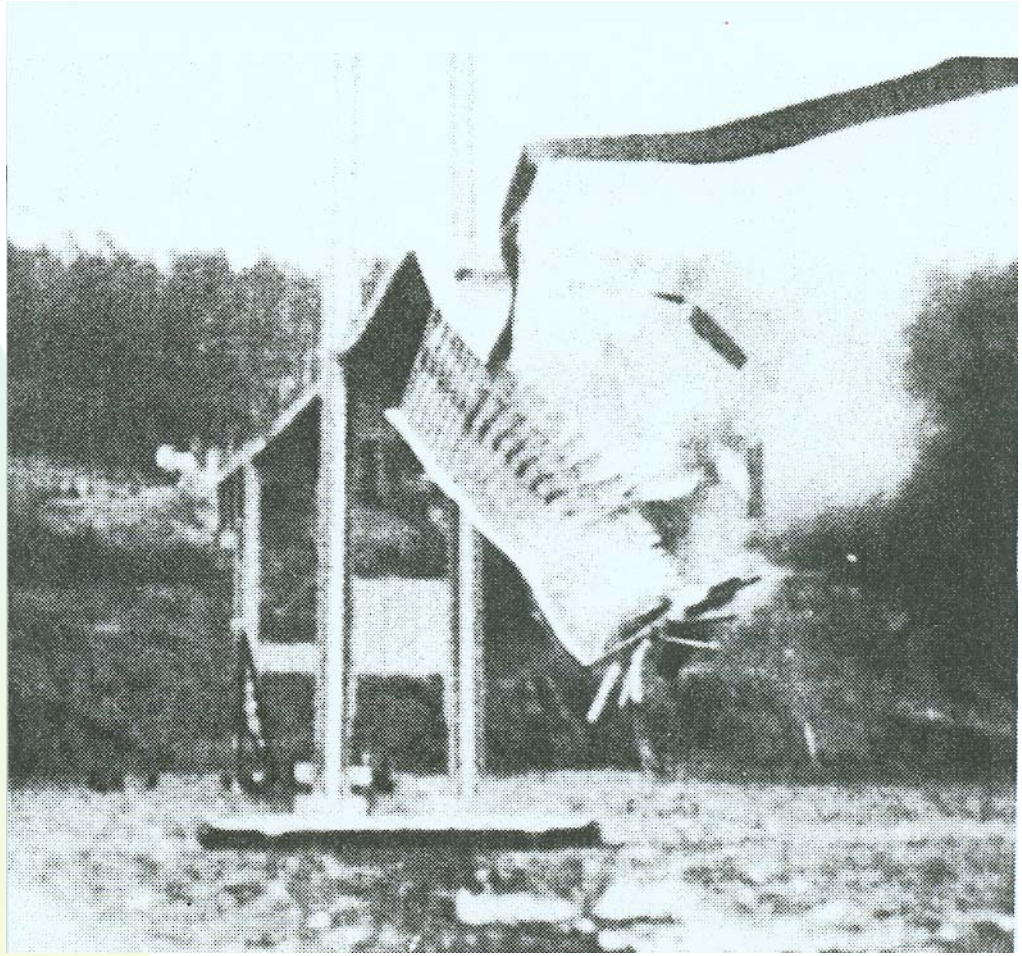
failure occurred so rapidly that observation become difficult and impression and fact are somewhat mixed."

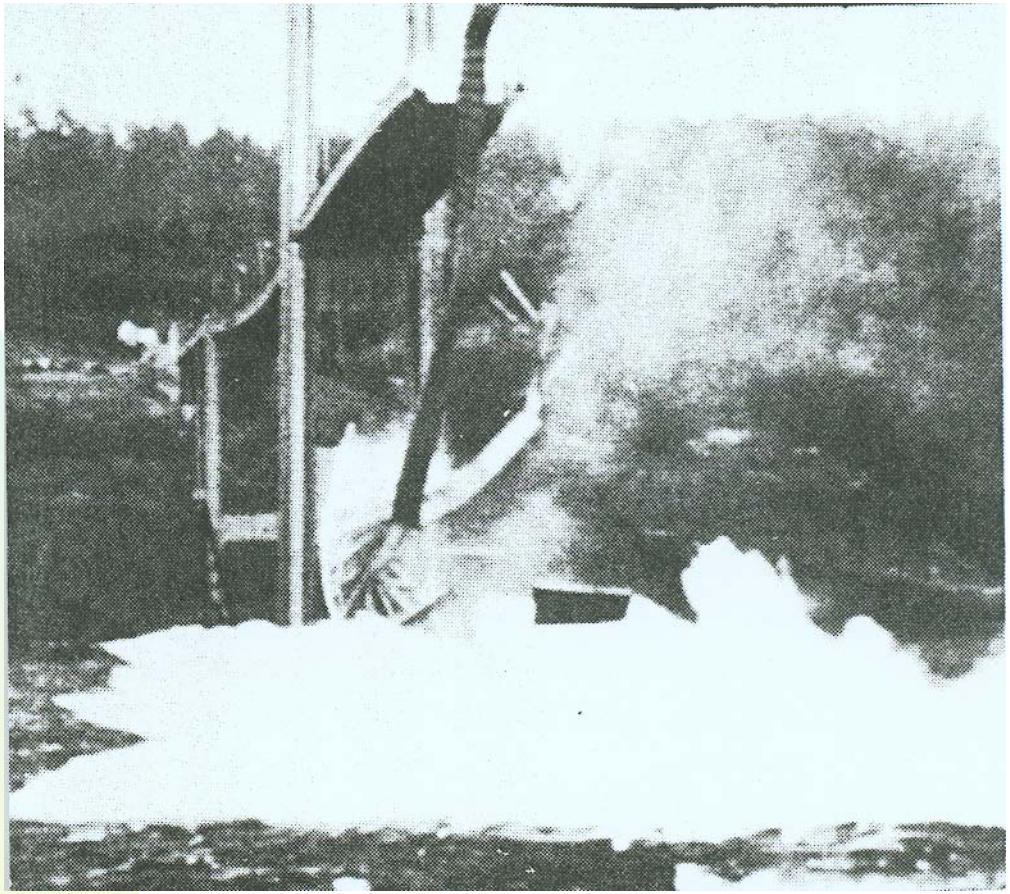


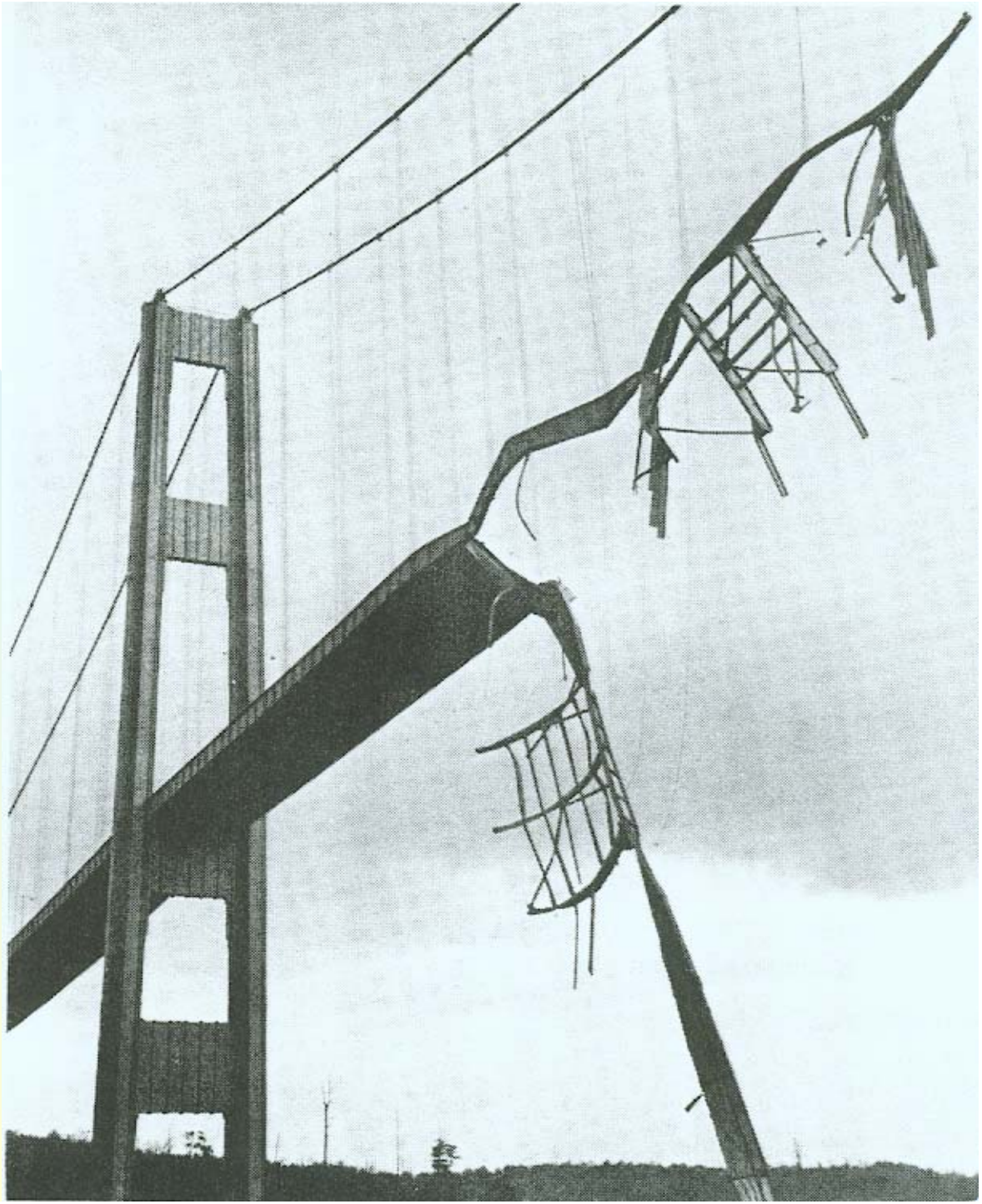
“Somewhat irregular torsion in main span after about 30 minutes of catastrophic motion.”



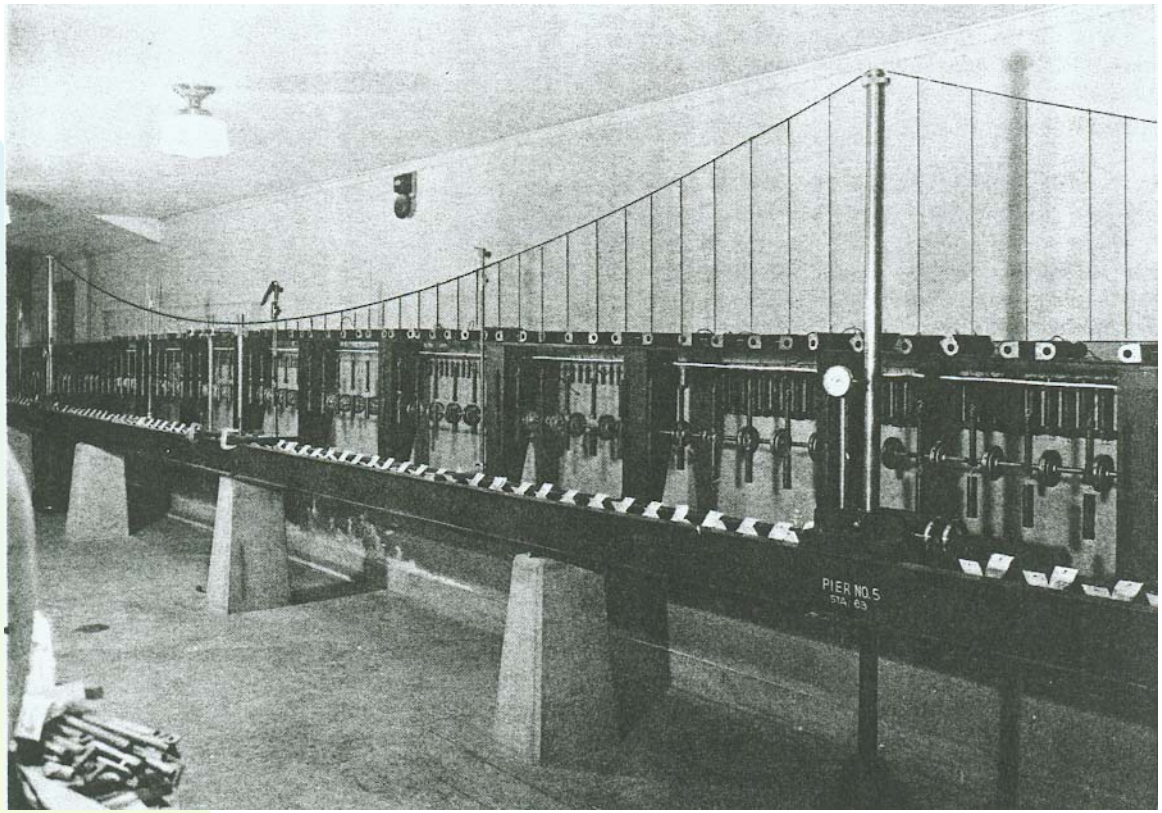








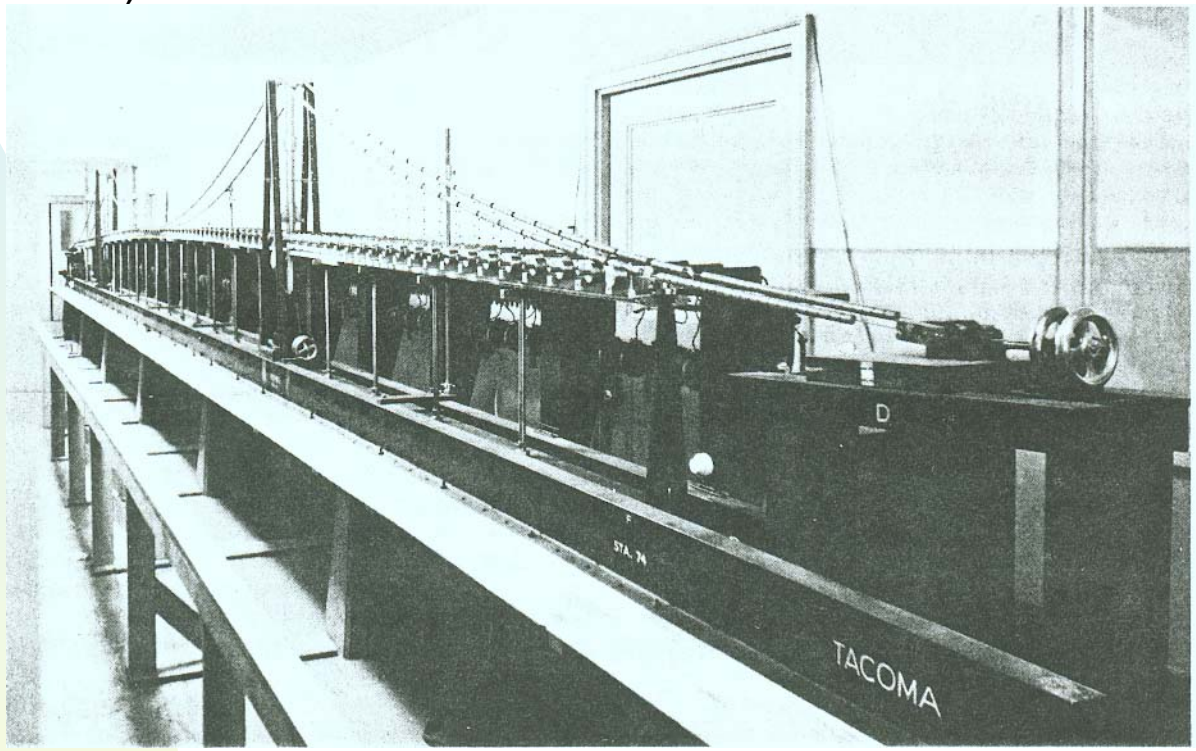
Static Model



Dynamic Model

$$\frac{\text{Length(bridge)}}{\text{Length(model)}} = 100$$

Model > 50 feet (15 m) long!



The motion was driven by electromagnets.

Used to measure:

- **the damping of different models**
- **effects of cables, shock absorbers**

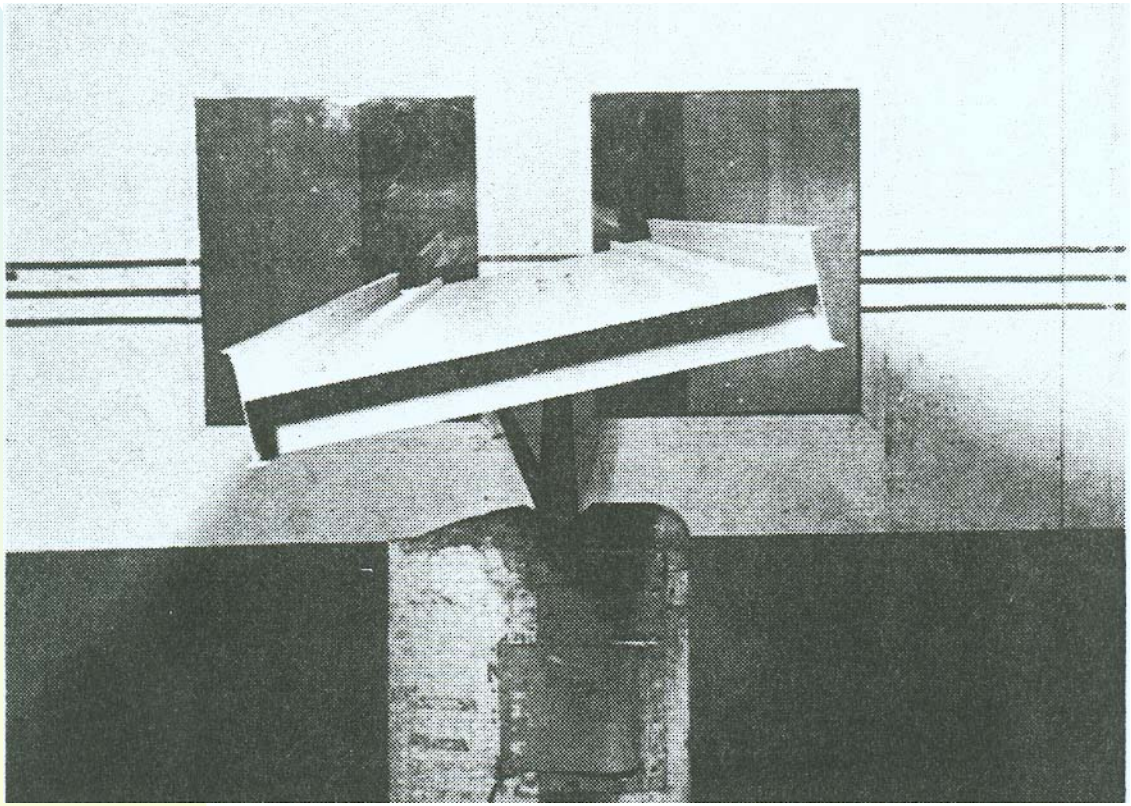
Scaling

Length	L (bridge) / L (model) = n
Area	A (bridge) / A (model) = n^2
Volume	V (bridge) / V (model) = n^3
Moment of Inertia	I (bridge) / I (model) = n^4
Acceleration	a (bridge) / a (model) = 1
Time	t (bridge) / t (model) = $n^{1/2}$
Velocity	v (bridge) / v (model) = $n^{1/2}$
Frequency	f (bridge) / f (model) = $n^{-1/2}$
Density	ρ (bridge) / ρ (model) = 1
Mass	m (bridge) / m (model) = n^3
Weight	W (bridge) / W (model) = n^3
Force	F (bridge) / F (model) = n^3

Wind Tunnel: Cross Sections

University of Washington, Seattle.

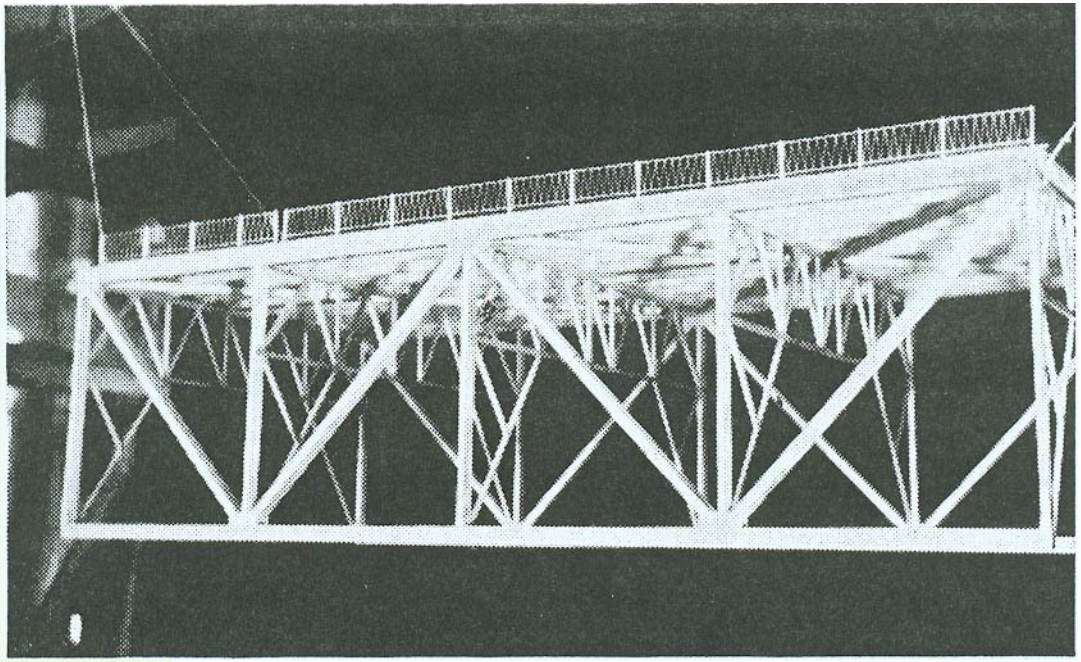
F. B. Farquharson et al.



Wind Tunnel: Cross Sections

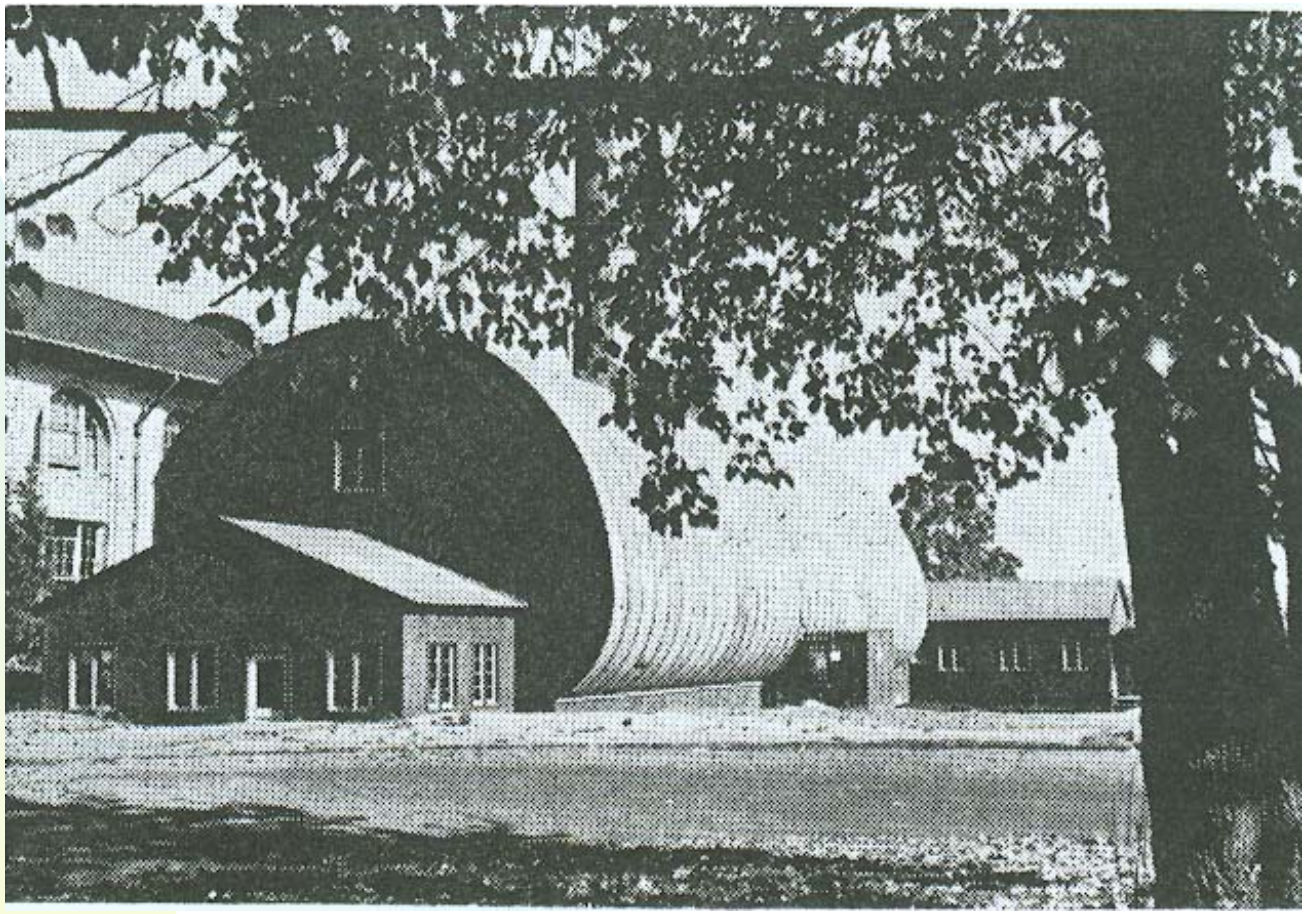
California Institute of Technology.

T. von Karman and L. G. Dunn.



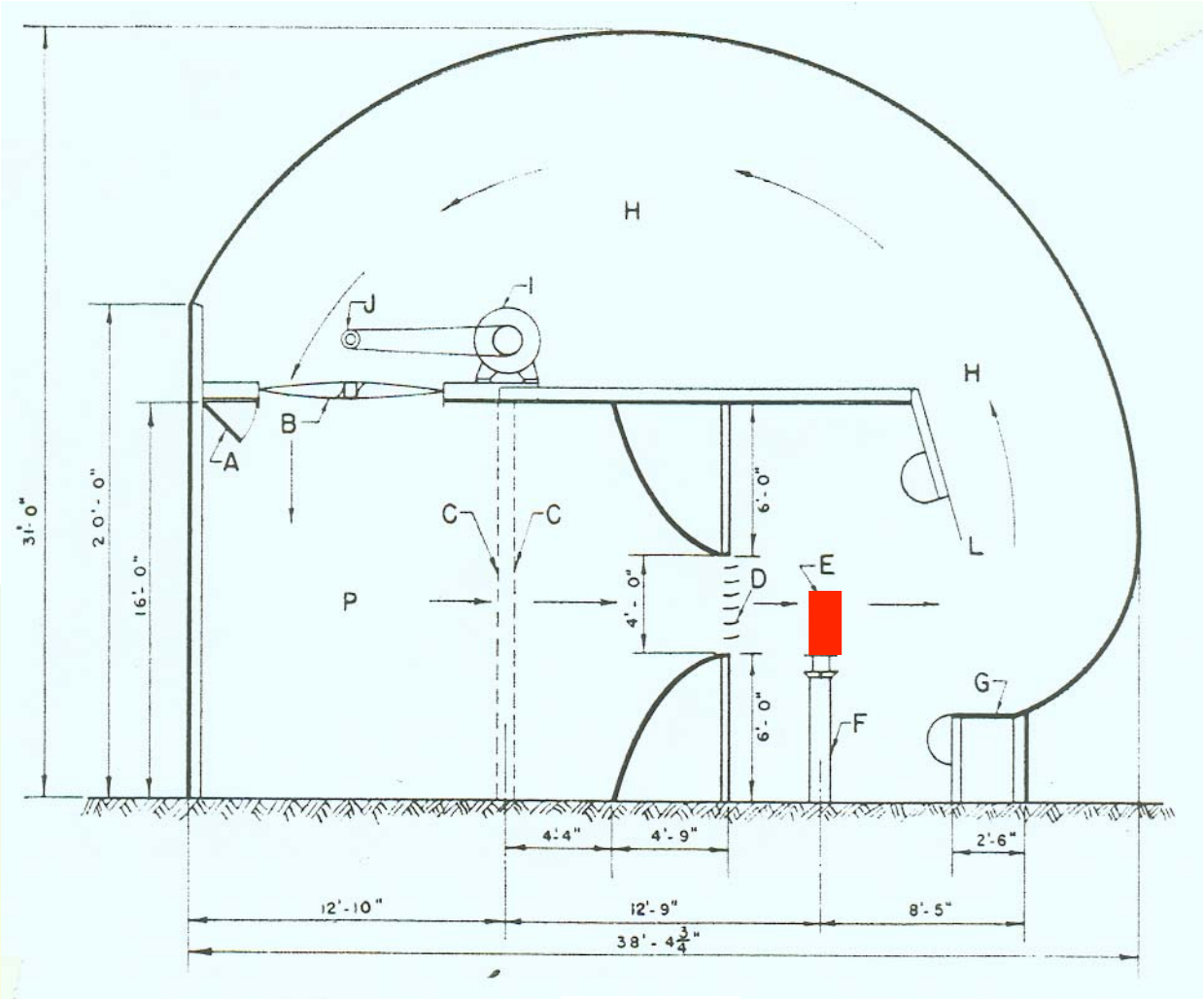
Wind Tunnel

University of Washington, Seattle.



Wind Tunnel

University of Washington, Seattle.

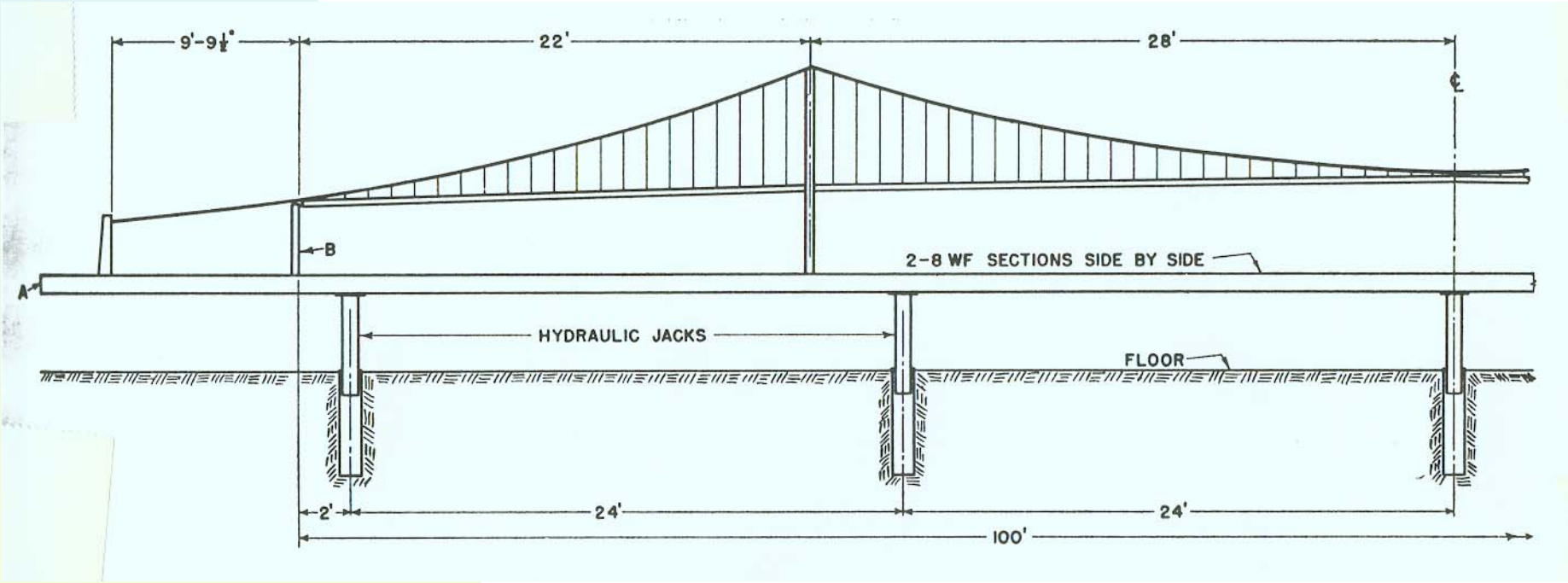


12 m

Full Model Wind Tunnel

Structural Research Laboratory, University of Washington, Seattle.

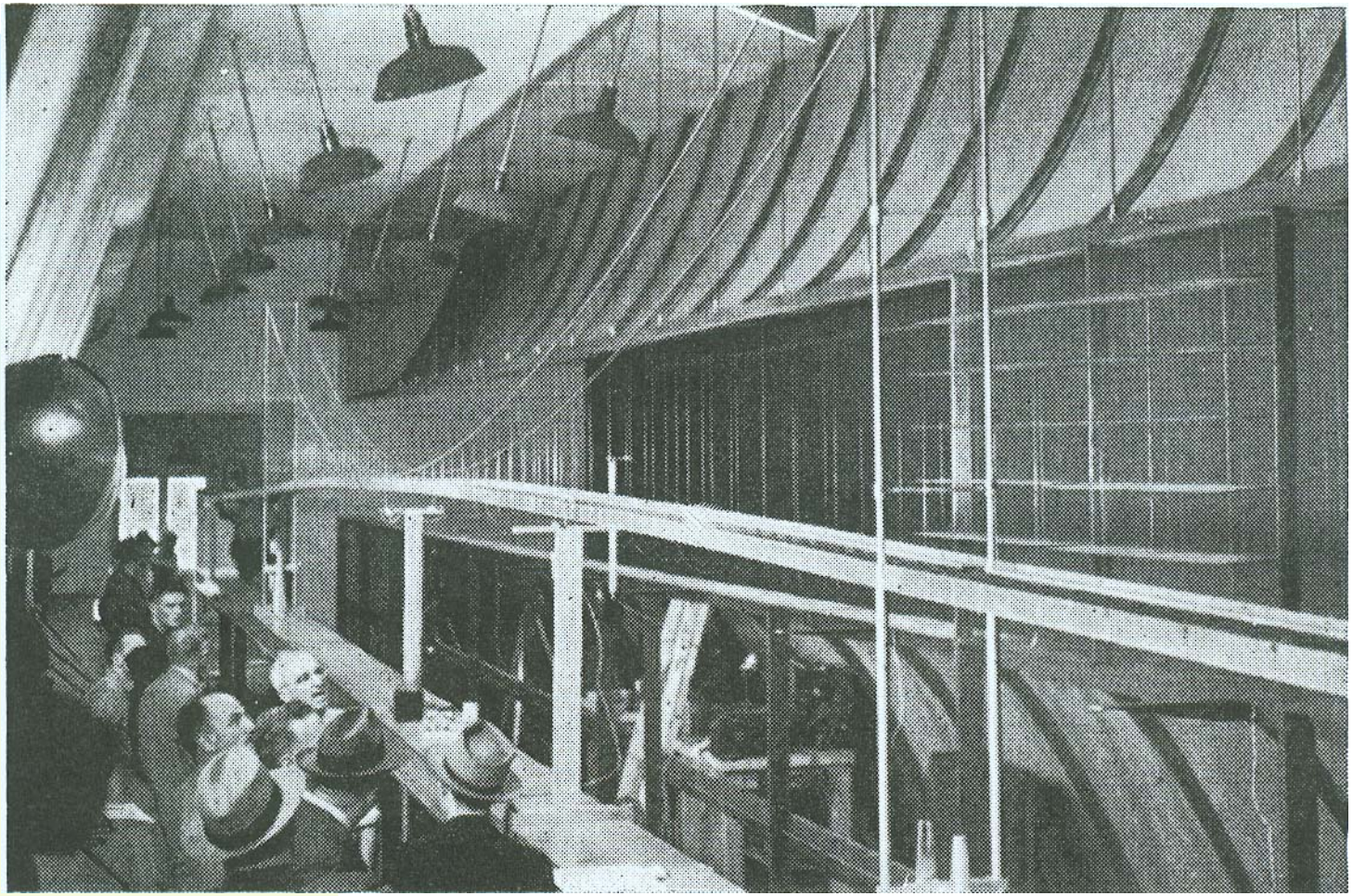
F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.



$$\frac{\text{Length(bridge)}}{\text{Length(model)}} = 50$$

Model > 100 feet (30 m) long!

Full Model Wind Tunnel



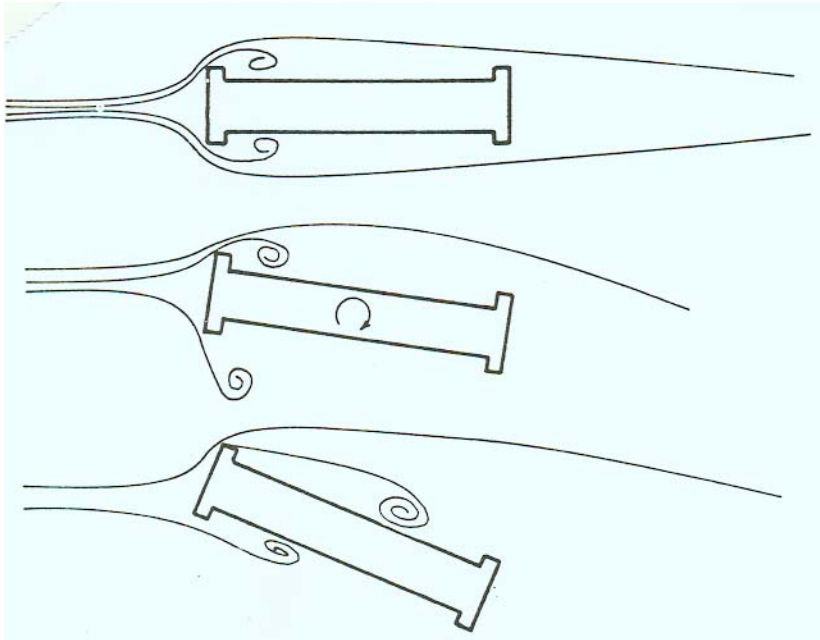
Full Model Wind Tunnel

Wind = 2.6 mph (4 km/hr): 2nd asymmetric vertical mode.

Cause of Failure

Positive Feedback

- The wind twisted the deck.
- The change in the angle of the deck caused the wind to change.
- The change in the wind made the deck twist more.



"when the section is rotated, the vortex pattern is distorted, as also indicated in Figure 7, and the vortex remaining nearest to the deck creates a high suction tending to further twist the deck"

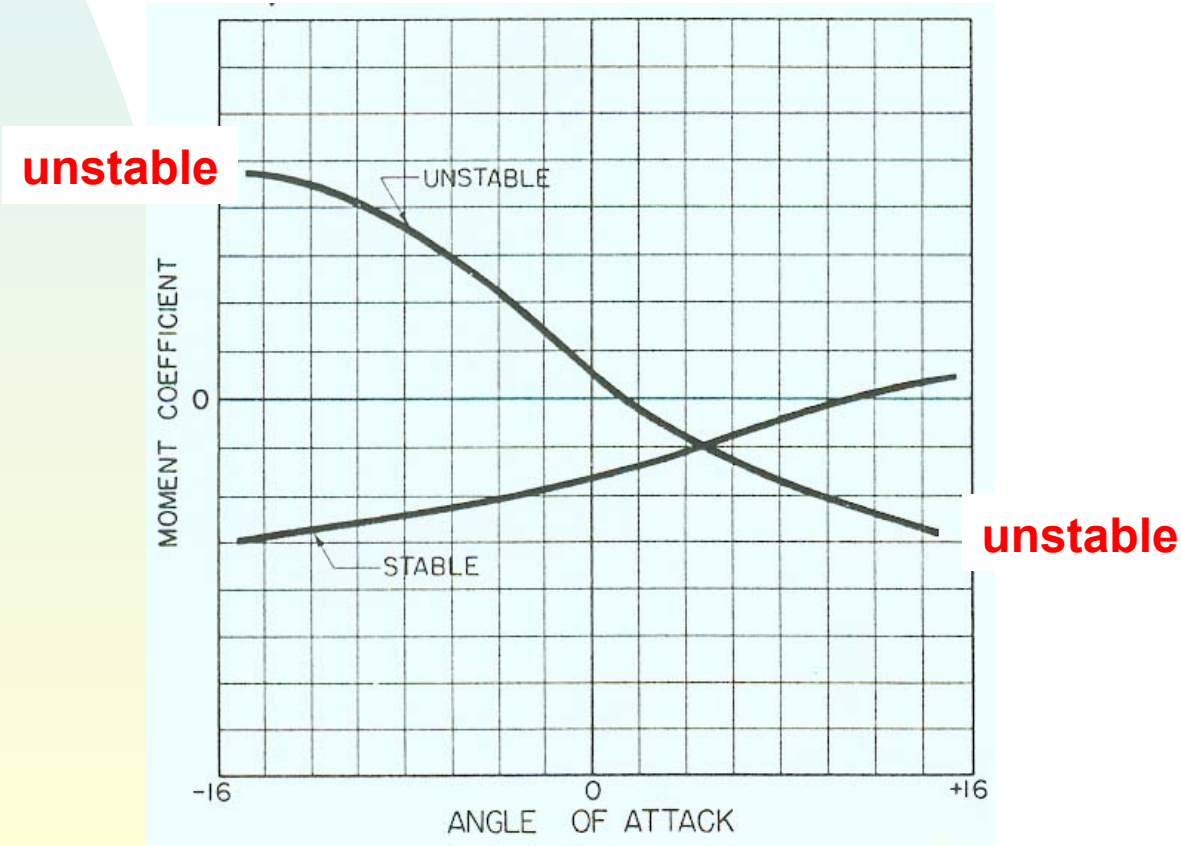
-R. H. Scanlan and J. W. Vellozzi Ann. NYAS 52:247-263, 1980

Positive Feedback

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

Static Wind Tunnel Tests



Positive Feedback

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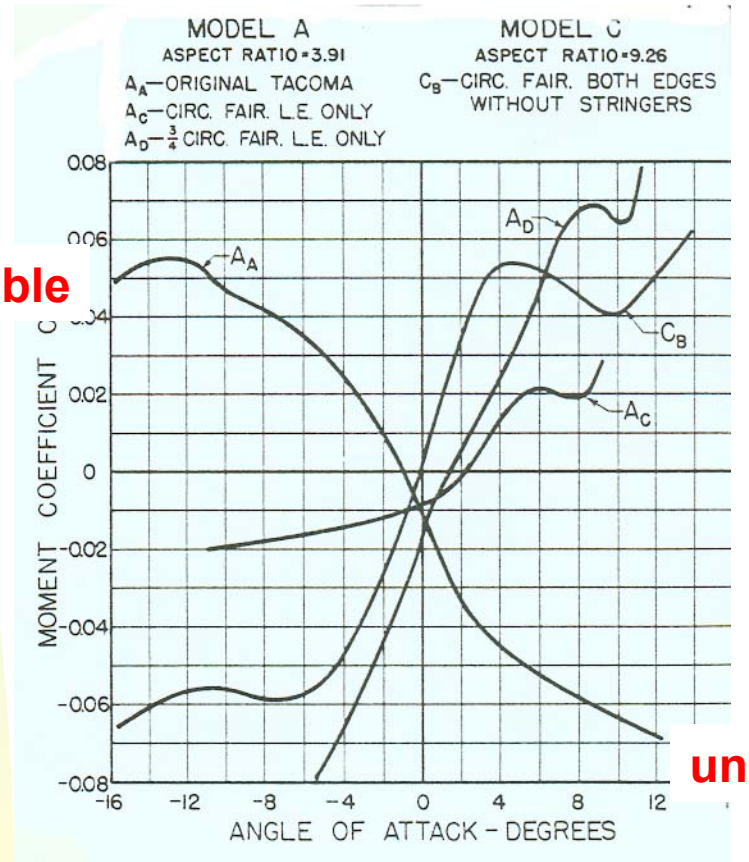
Static Wind Tunnel Tests

unstable



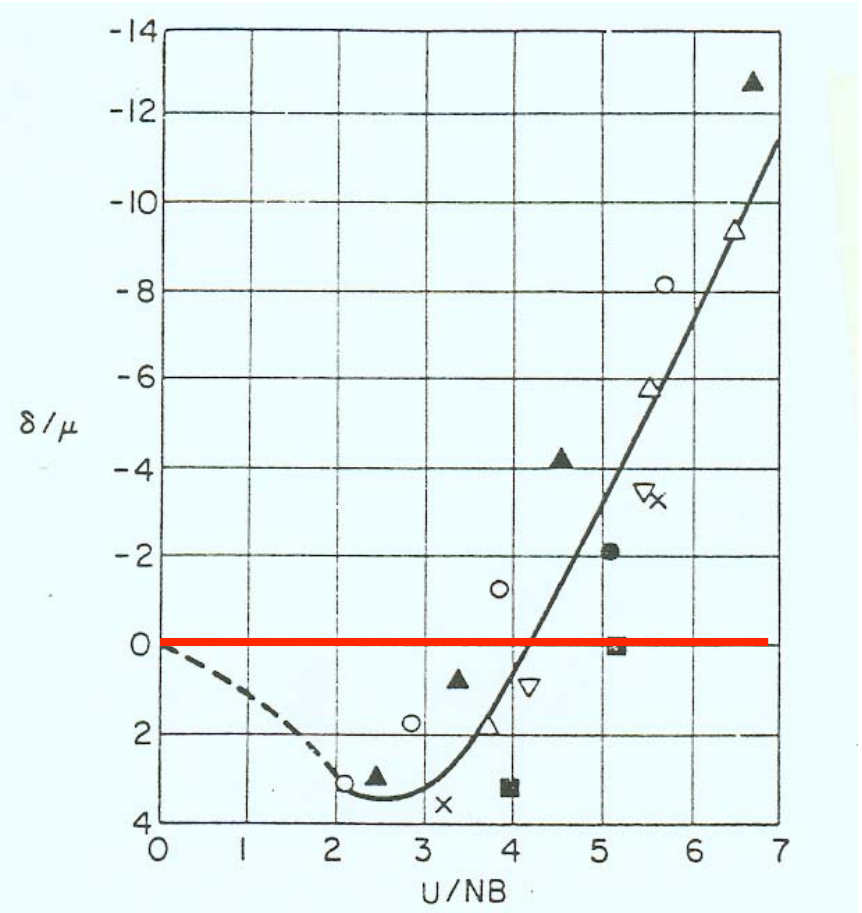
unstable

Positive Feedback

California Institute of Technology.

T. Von Karman and L. G. Dunn. 1950 Aerodynamic Stability of Suspension Bridges with with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part ?.

Dynamic Wind Tunnel Tests

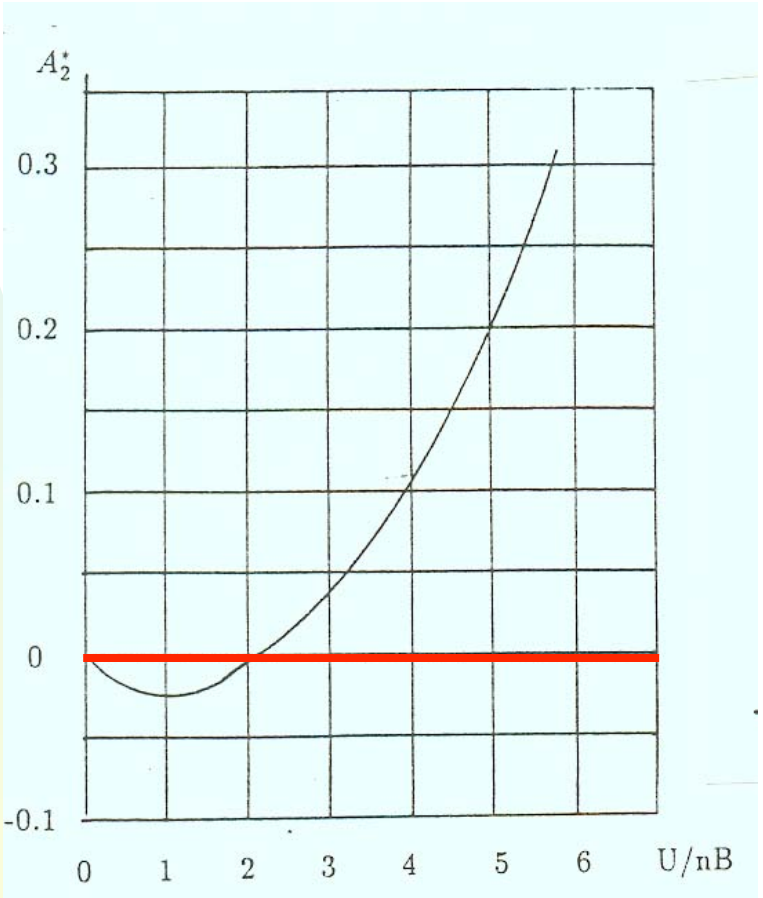


Positive Feedback

R. H. Scanlan and J. J. Tomko.

K. Y. Billah and R. H. Scanlan, 1991, Am. J. Phys. 59:118-1124.

Wind Tunnel Tests 1970's



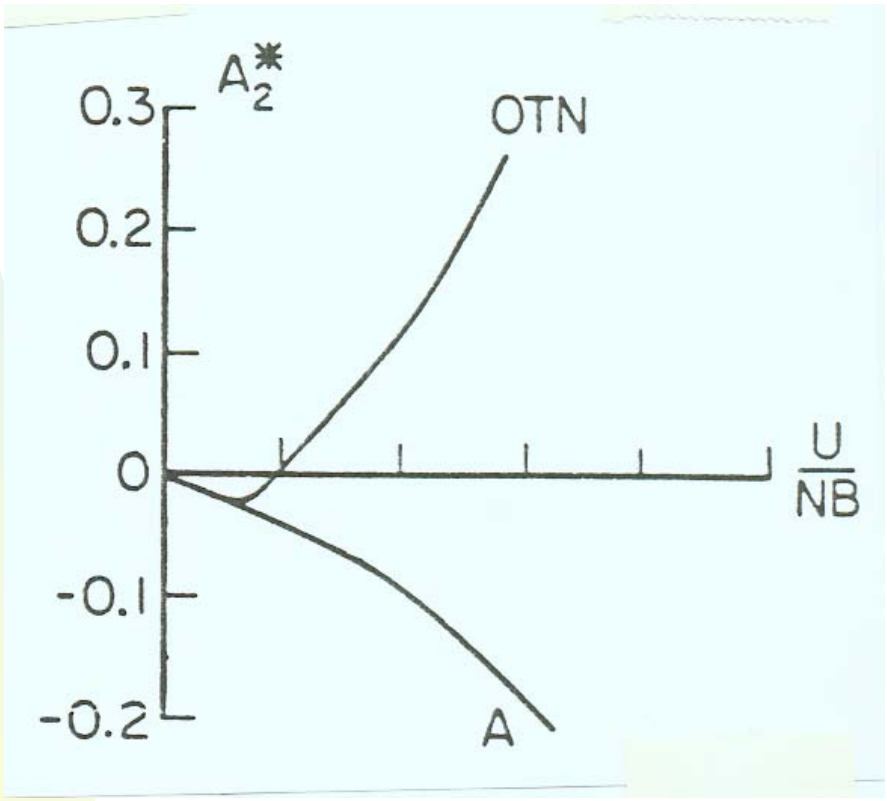
Old Tacoma Narrows Bridge

Positive Feedback

R. H. Scanlan and J. J. Tomko.

R. H. Scanlan and J. W. Vellozzi, 1980, Ann. NYAS 352:247-263.

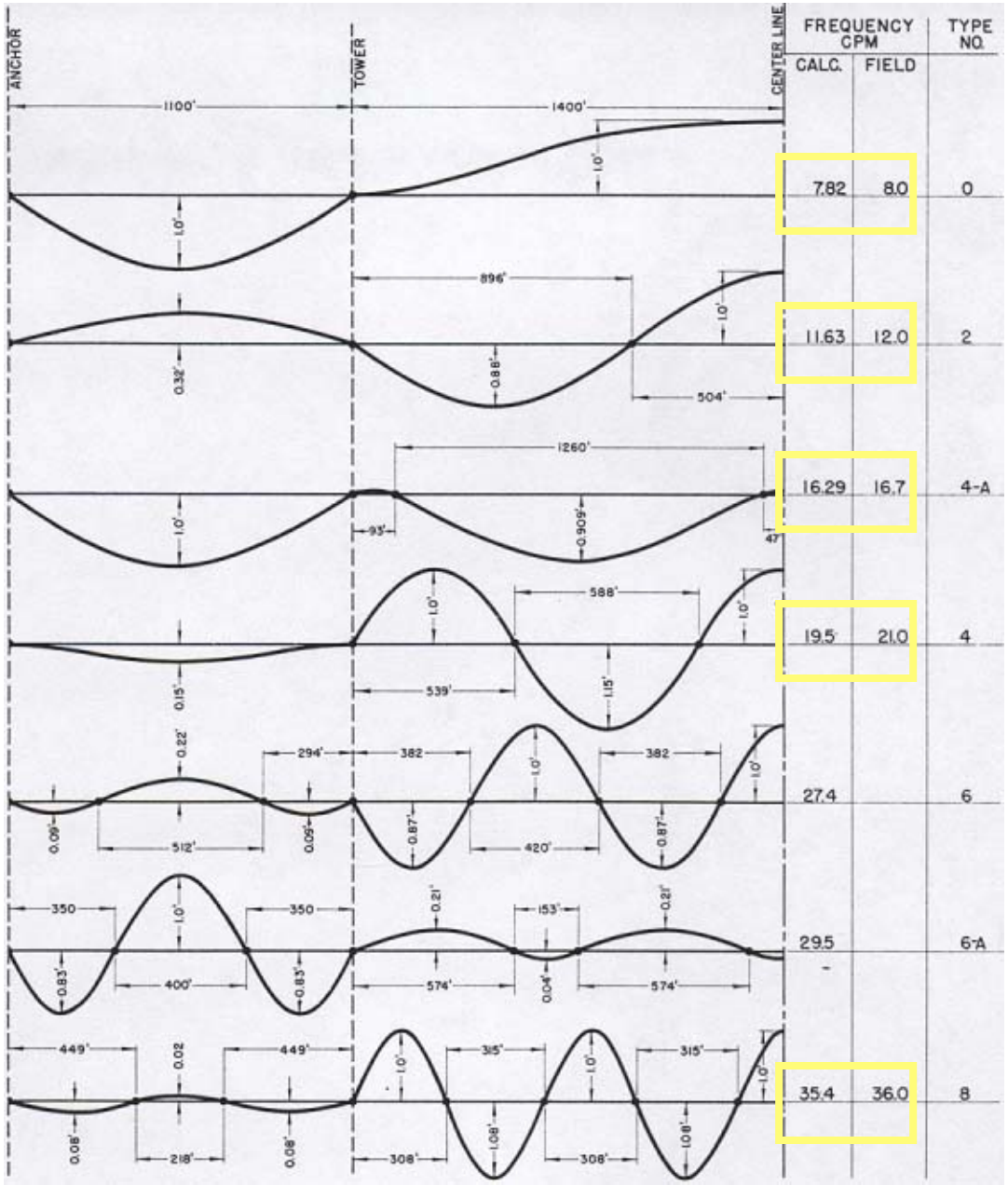
Wind Tunnel Tests 1970's



Airfoil, OTN = Old Tacoma Narrows Bridge

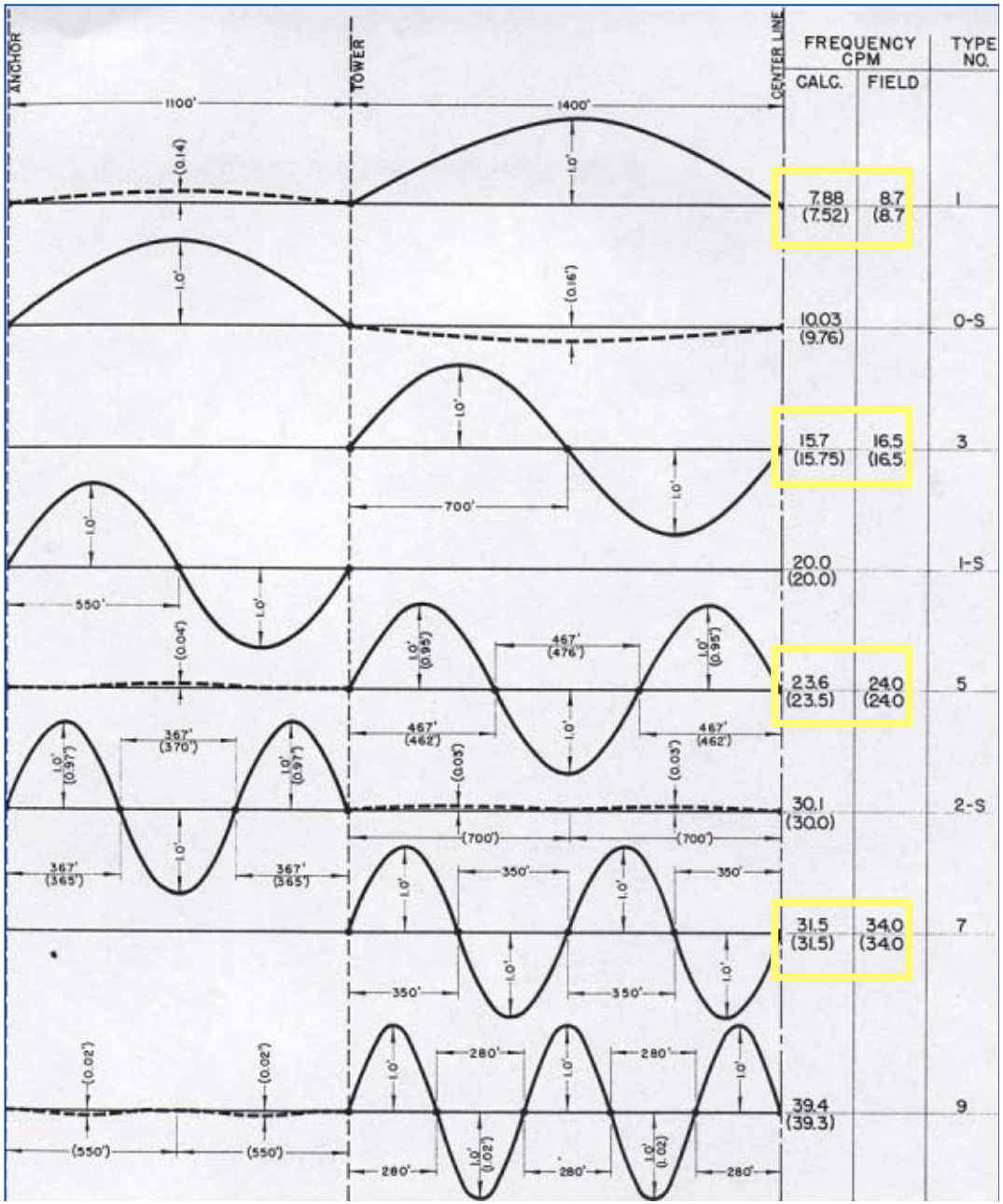
Calculated vs. Measured

Symmetric Modes



Calculated vs. Measured

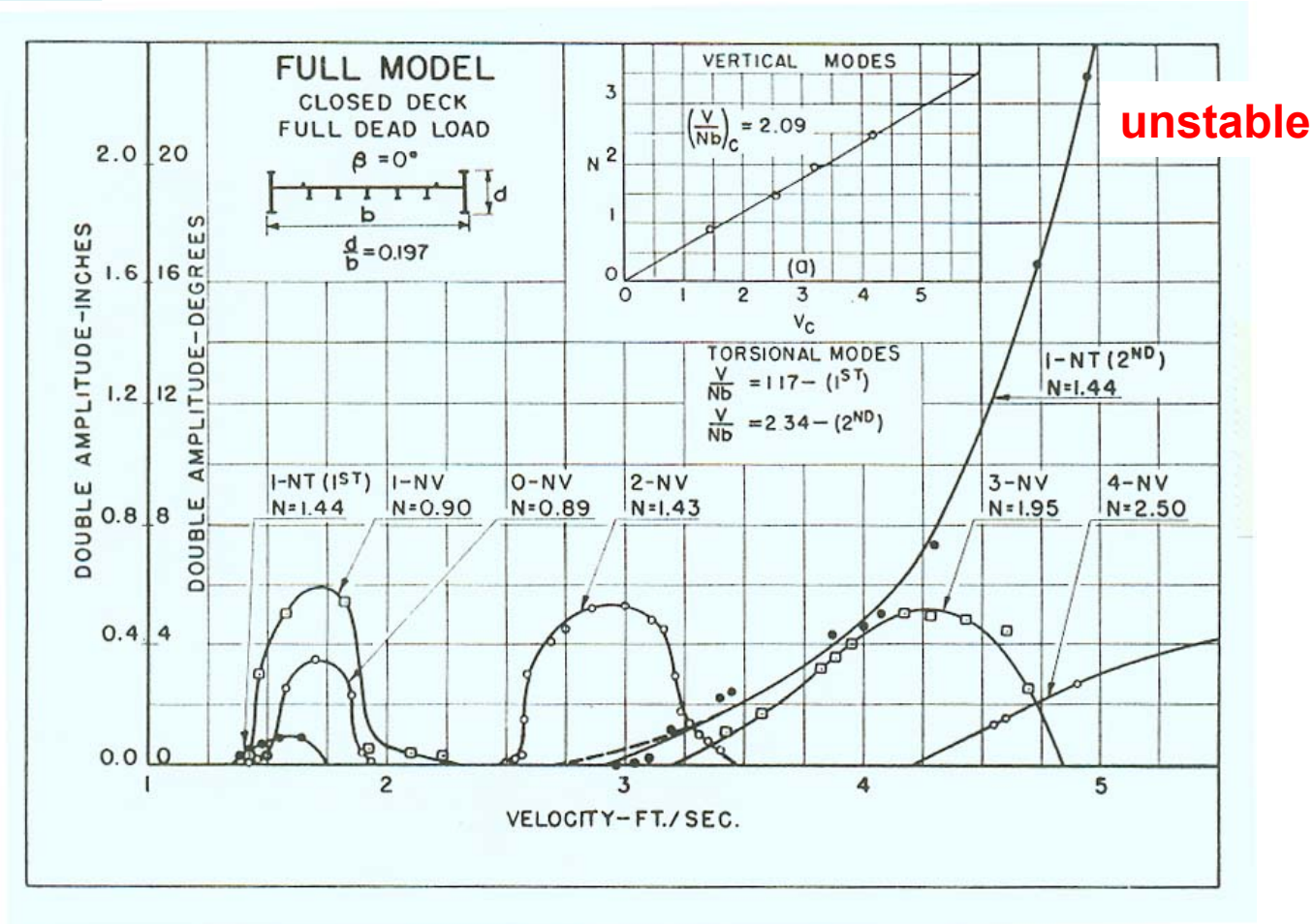
Asymmetric Modes



Full Model Wind Tunnel

Structural Research Laboratory, University of Washington, Seattle.

F. B. Farquharson 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.



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$$\frac{\text{Length (bridge)}}{\text{Length (model)}} = 50 \qquad \frac{\text{Velocity (bridge)}}{\text{Velocity (model)}} = 50^{1/2} \qquad \frac{\text{Frequency (bridge)}}{\text{Frequency (model)}} = 50^{-1/2}$$

The torsonal mode (1-NT) first appears at 7 mph and becomes catastrophic at 14 - 24 mph (<< 42 mph).

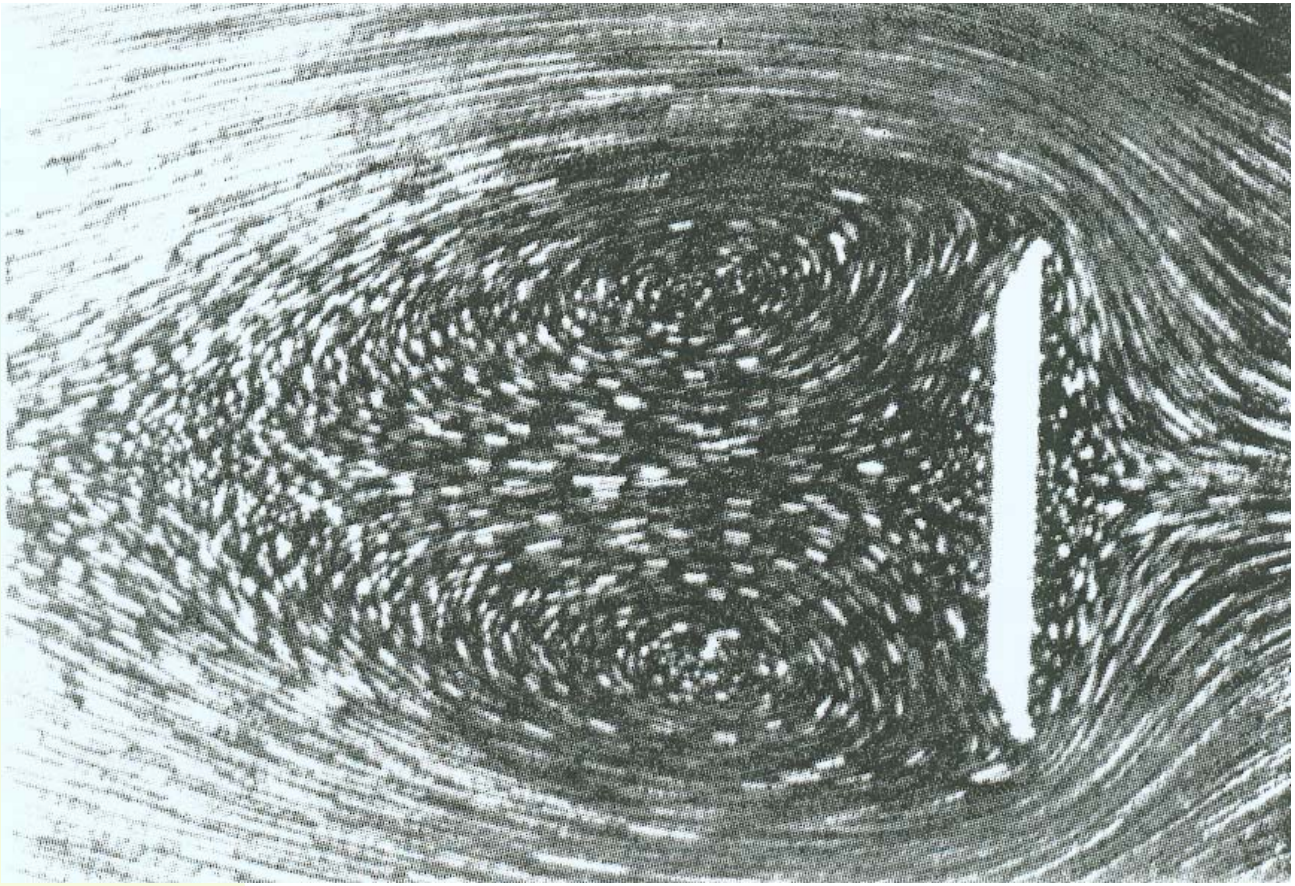
The frequency of this mode:

Model: 1.44 Hz

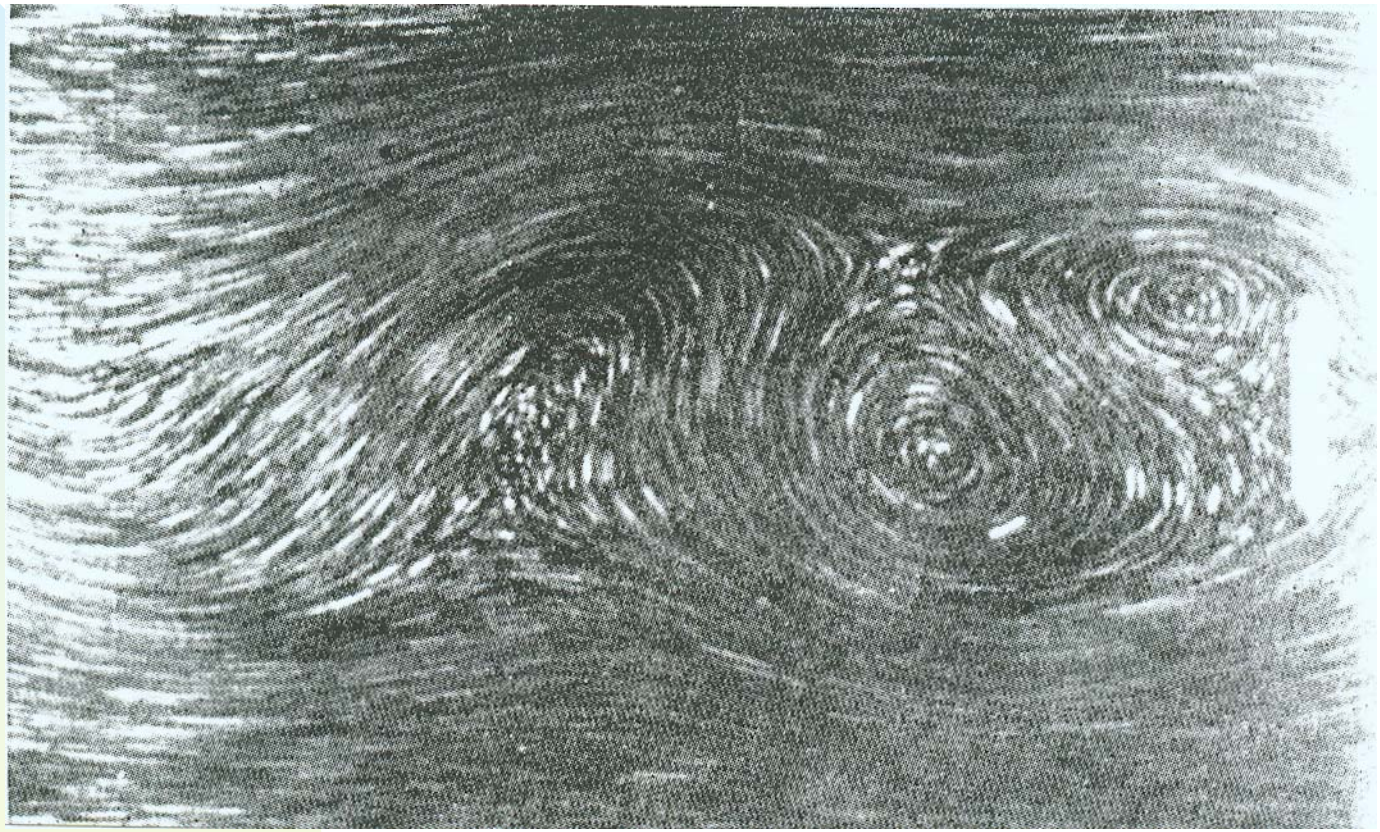
Corresponds to Computed Bridge: 12.2 cycles/minute.

Actual Bridge Measured: 12.0 cycles/minute

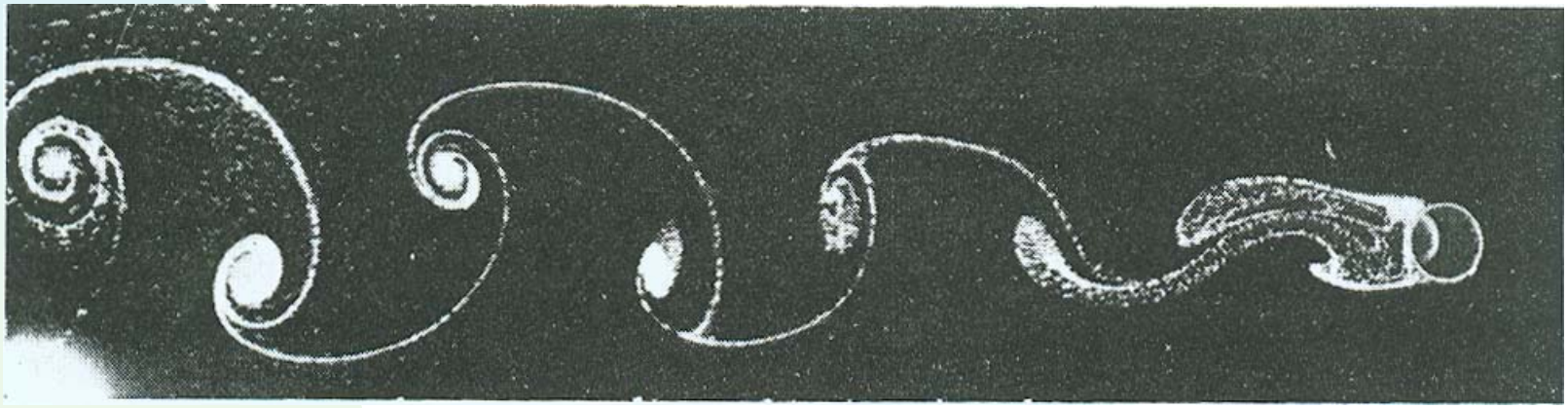
Vortices



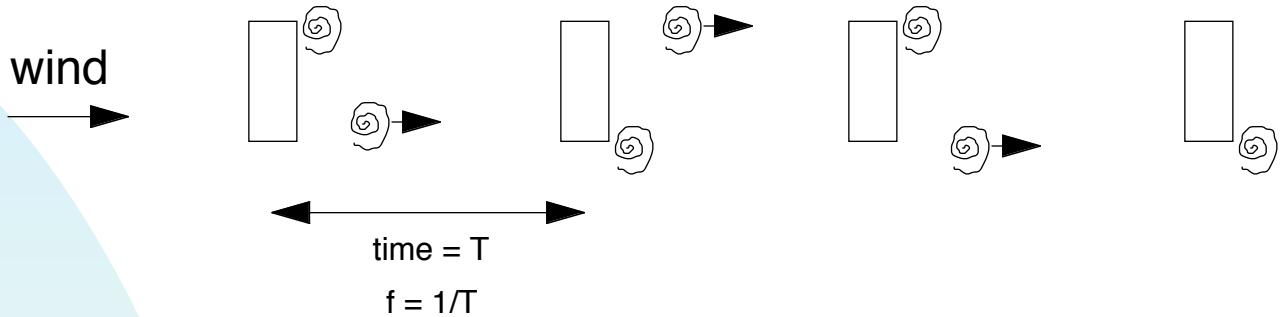
Shed Vortices



Vortex Street



NOT Driven by Vortices



Strouhal Frequency f = SV / D

Tacoma Narrow Brigde: S = 0.11, V = 42 mph, D = 8 ft.

Strouhal Frequency f = 1.0 Hz.

Bridge Motion Frequency = 0.2 Hz

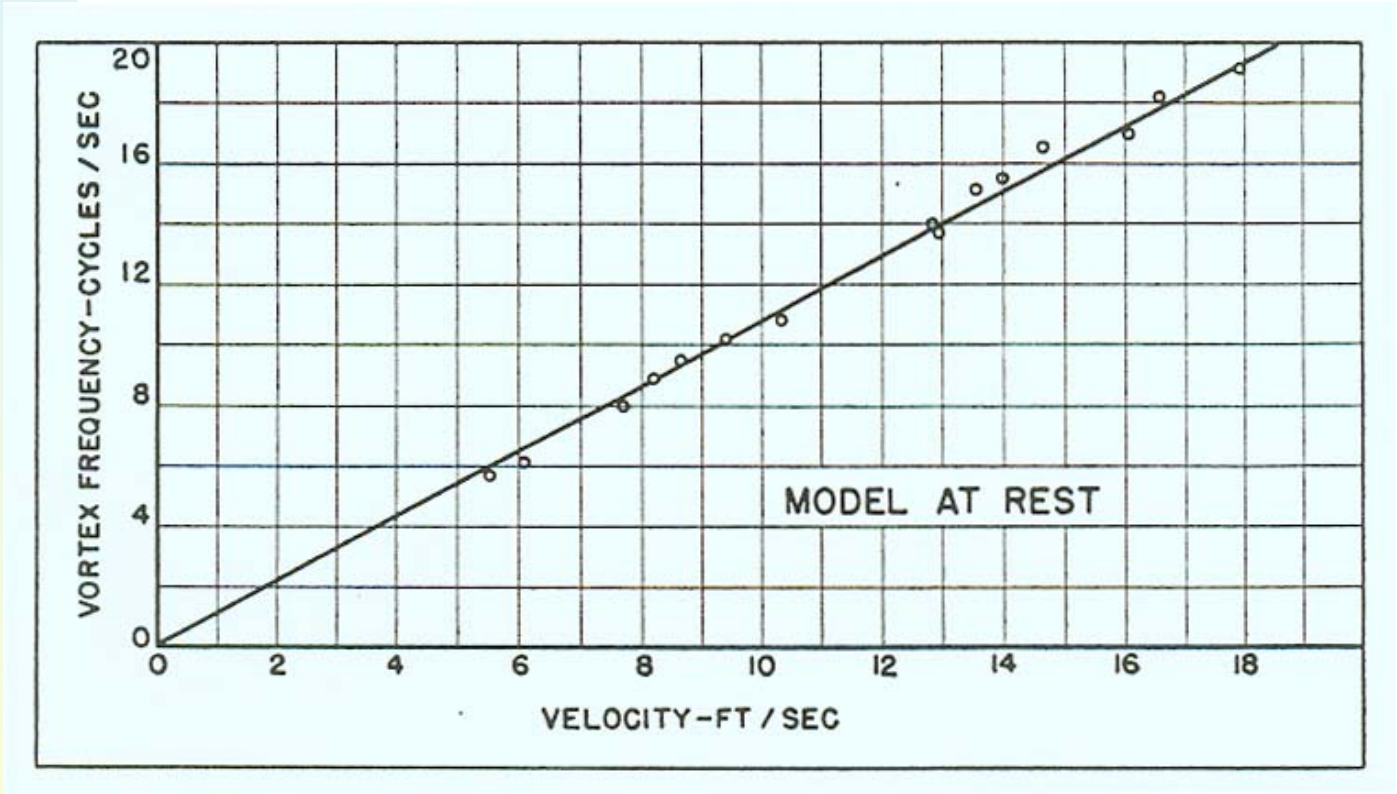
The alternative shed vortices did NOT drive the motion of the bridge.

The motion of the bridge controlled the release of the vortices.

Model at Rest

California Institute of Technology.

T. Von Karman and L. G. Dunn 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

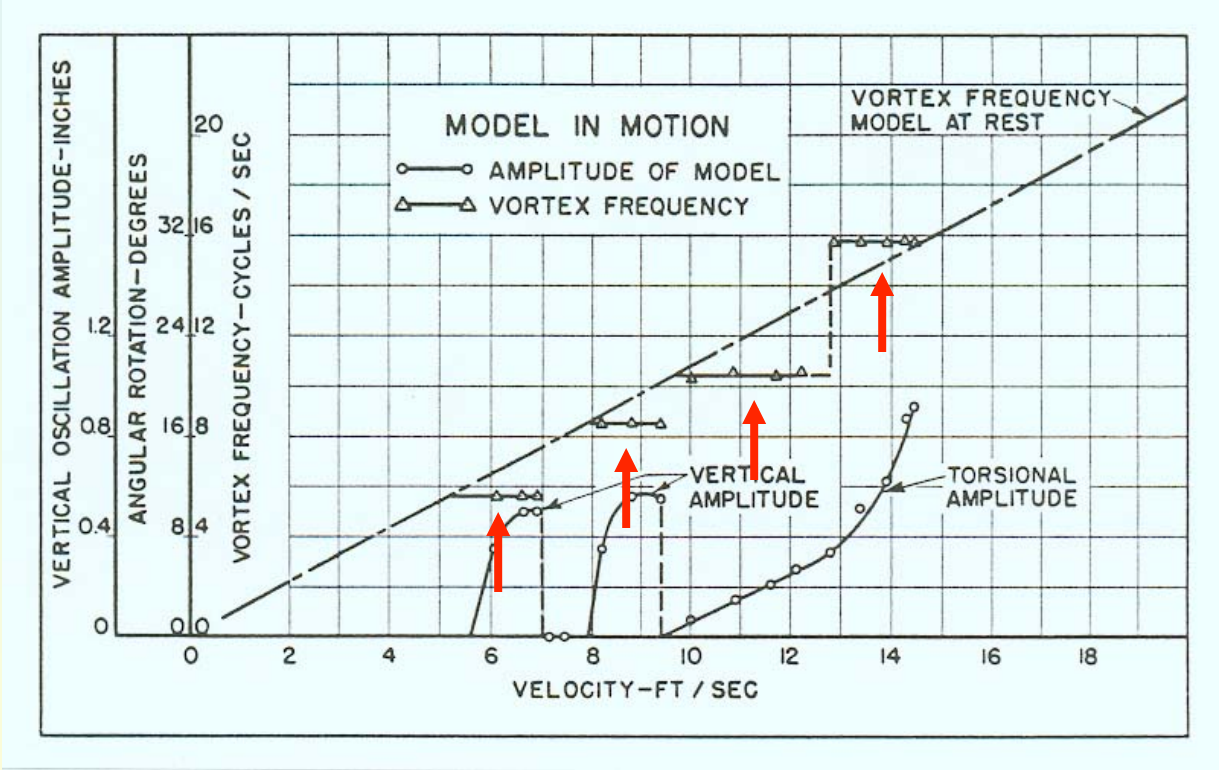


Model in Motion

California Institute of Technology.

T. Von Karman and L. G. Dunn 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

The Bridge controlled the vortices!



The Bridge Drove the Vortices

California Institute of Technology.

T. Von Karman and L. G. Dunn 1950 Aerodynamic Stability of Suspension Bridges with special reference to The Tacoma Narrows Bridge, University of Washington Engineering Experimental Station, Bulletin No. 116, Part III.

"The experimental results described in a previous report indicated rather definitely that the motions were the result of vortex shedding. Resonance between the frequency of vortex shedding and one of the natural frequencies of the bridge were often suggested as the reason for the vertical oscillations. However, this hypothesis does not explain the fact that the self-excited oscillations exist over rather wide ranges of velocities. It has been found that in general the vortex frequency produced by a blunt obstacle in the wind stream is proportional to the wind velocity...While the structure is at rest the vortex frequency is controlled by the wind...Beyond the critical wind velocities the oscillating structure and not the wind velocity controls the vortex frequency."

The Bridge Drove Itself

California Institute of Technology.

K. Y. Billah and R. H. Scanlan 1991 Am. J. Phys. 59:118-112.

"Did the vortices cause the motion or the motion cause the vortices? In this case (flutter) it was the latter...The final destructive oscillation of the old Tacoma Narrows bridge produced a *flutter* wake, not a Karman vortex sheet...The action which brought the bridge down, occurred in a fundamentally antisymmetric torsion mode...basically a single-degree-driven unstable oscillation with effective negative damping representing an inflow of wind energy cause by the synchrony of motion-induced pressures with the motion itself."

The Bridge Drove Itself

California Institute of Technology.

K. Y. Billah and R. H. Scanlan 1991 Am. J. Phys. 59:118-112.

"Could this be called a resonance phenomena? [It could] if we now identify the source of the periodic impulses as *self-induced,* the wind supplying the power, and the motion supplying the power-trapping mechanism. If one wishes to argue, however, that it was a case of *externally forced linear resonance,* the mathematical distinction between Eqs. (1) and (3) is quite clear, self-excited systems differing strongly enough from ordinary linear resonant ones. The [elementary physics] texts we have consulted have not gone this far in explanation."

Externally forced resonance:

$$\ddot{x} + A\dot{x} + Bx = f(t)$$ *non-autonomous* *Eq. (1)*

Self-excitation (Tacoma Narrow bridge):

$$\ddot{x} + A\dot{x} + Bx = f(x, \dot{x})$$ *autonomous* *Eq. (3)*

The New Tacoma Narrows Bridge

Look at that Truss!

Fixing the Problem

Restrict the motion of the bridge.

Stiffen the span with a truss.

Bronx-Whitestone bridge in New York City

Damp the oscillations with shock absorbers.

Commodore Barry bridge, Chester, Pennsylvania.

Not good: Basically, letting the energy from the wind into the bridge, then trying to contain it.

Prevent the wind from giving its energy to the bridge.

Streamlining to reduce vortex formation.

Long's Creek bridge, Severn bridge, U.K.

Open span, wind flows through,to reduce vortex.

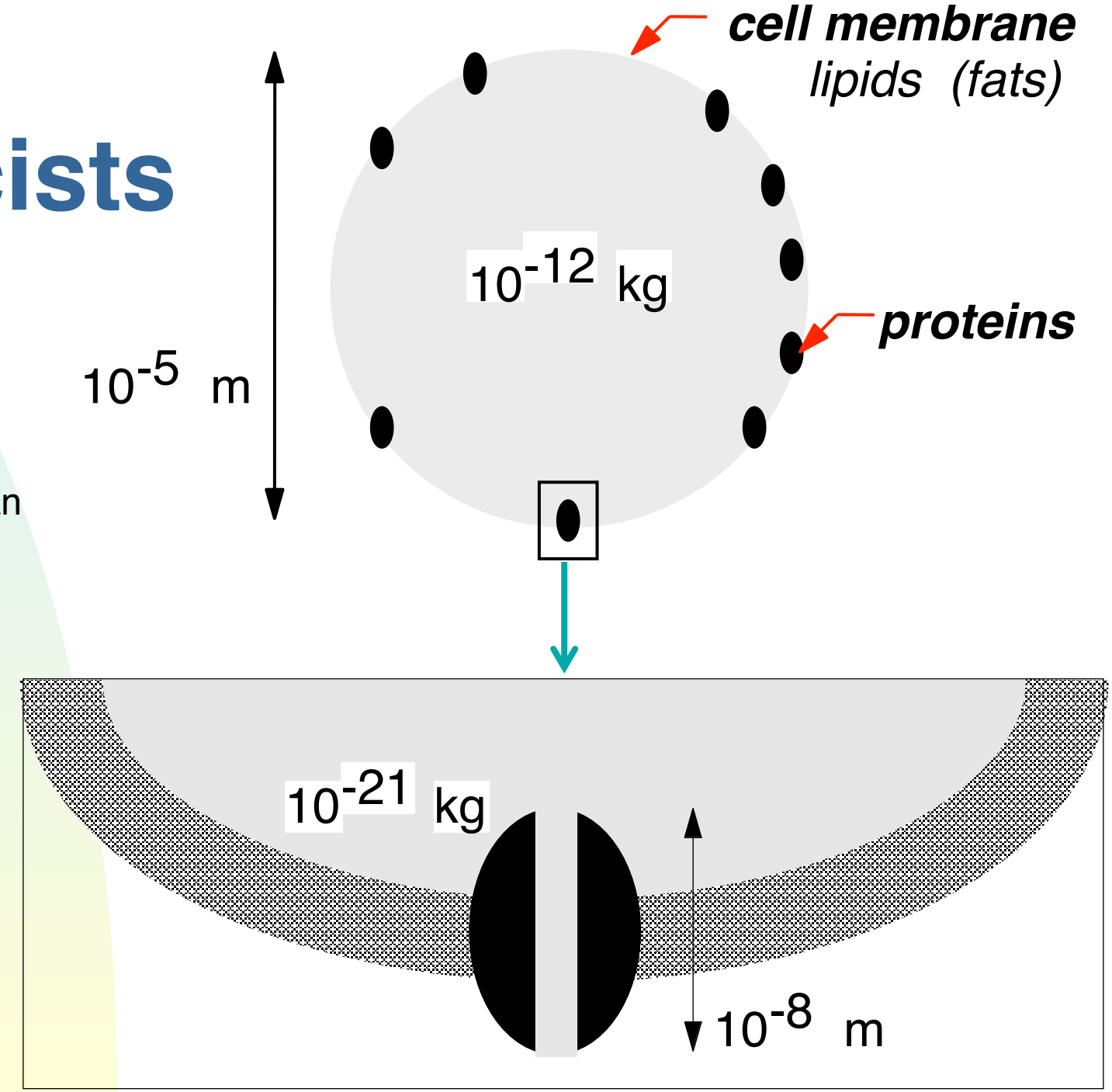
Forth Road bridge, U.K.

Long Span Bridges, 1980, Ann. NYAS 352.

For Physicists

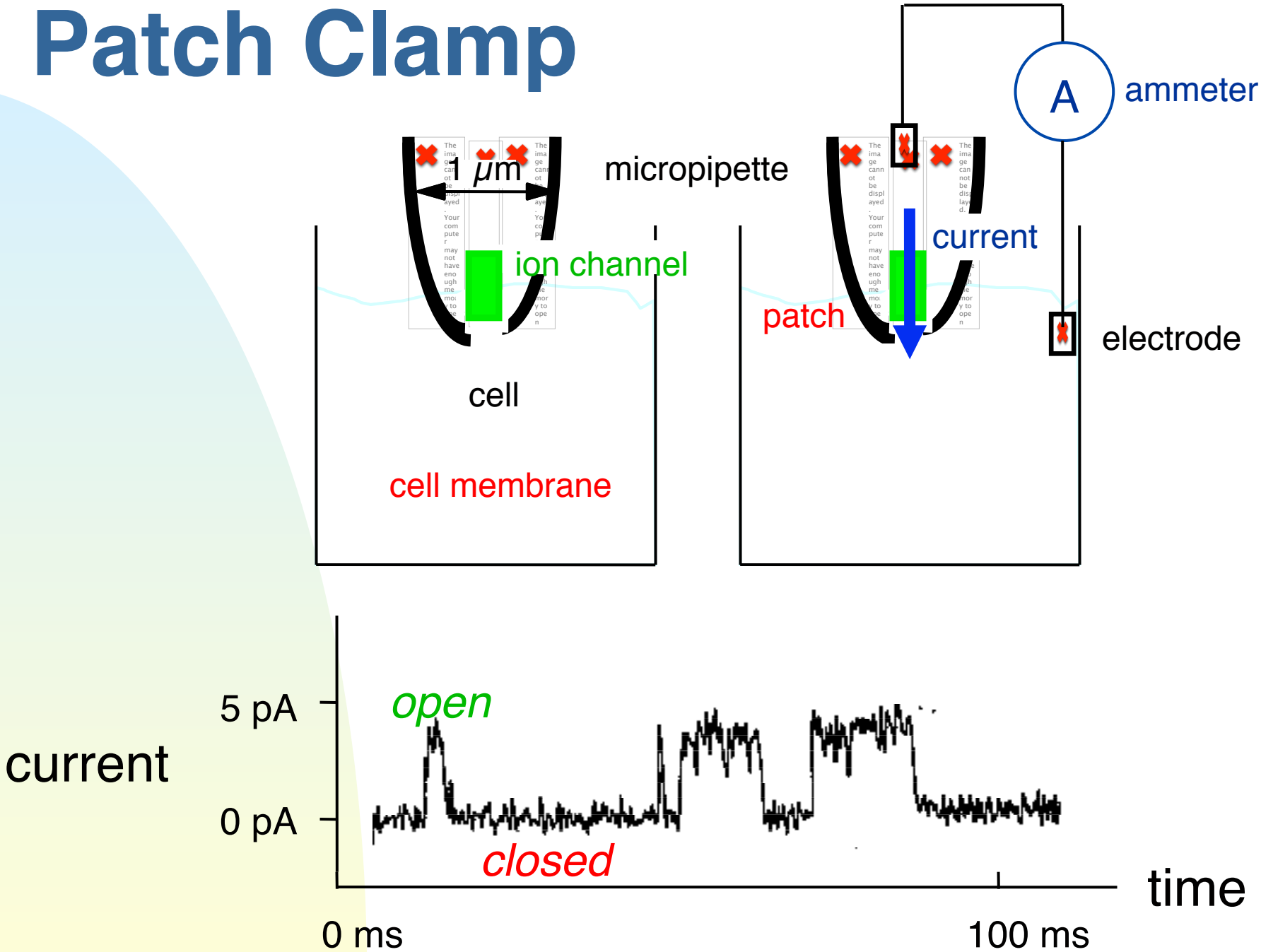
Cell

10^{14} ≈ human



Ion Channel

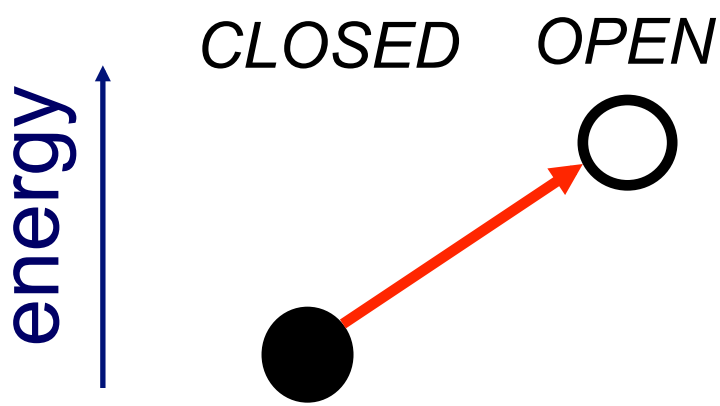
Patch Clamp


1 μm
micropipette
ion channel
cell
cell membrane
A
ammeter
current
patch
electrode
current
5 pA
0 pA
open
closed
time
0 ms
100 ms

Usual Picture

Ion channels are like small molecules, relentlessly kicked by the surrounding heat from one state to another.

The change of states is driven by chance kT thermal fluctuations.



random, kT

Alternative Picture

Ion channels are little mechanical machines with sticks and springs.

The change of states is driven by coherent motions that result from the structure and the atomic, electrostatic, and hydrophobic forces in the channel protein.

deterministic, mechanical

Ion Channels

If a simple mechanical structure, such as a bridge, can have such surprising dynamical behavior and such a strong interaction with its environment, what can we expect of the dynamics of a much more complex ion channel protein, with intertwined structural and functional elements developed through a billion years of evolution?

Failure or Success?

"...the Tacoma Narrows bridge failure has given us invaluable information...It has shown [that] every new structure which projects into new fields of magnitude involves new problems for the solution of which neither theory nor practical experience furnish an adequate guide. It is then that we must rely largely on judgment and if, as a result, errors or failures occur, we must accept them as a price of human progress"

- Othmar Ammann

"No one *wants* to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art. Contrary to their popular characterization as intellectual conservatives, engineers are really among the avant-garde. They are constantly seeking to employ new concepts to reduce the weight and thus the cost of their structures...The engineer always believes that he is trying something without error, but the truth of the matter is that each new structure can be a new trial...Such is the nature not only of science and engineering, but of all human endeavors."

- Henry Petroski

H. Petroski, To Engineer Is Human, Vintage Books, 1992

References

Aerodynamic Stability of Suspension Bridges
with special reference to
The Tacoma Narrows Bridge
A Report of an Investigation conducted by The Structural Research Laboratory, University of Washington under the direction of The Washington Toll Bridge Authority in cooperation with The Public Roads Administration, Federal Works Agency, University of Washington Engineering Experiment Station Bulletin No. 116, Parts I, II, and III.

R. H. Scanlan and J. W. Vellozzi. 1980. Catastrophic and annoying responses of long-span bridges to wind action. In, Long-Span Bridges, ed. E. Cohen and B. Birdsall, Annals o fthe New York Academy of Sciences, 352:247-263.

K. Y. Billah and R. H. Scanlan. 1991. Resonance, Tacoma Narrows bridge failure, and undergraduate physics textbooks. American Journal of Physics 59(2):118-124, Feb. 1991.