Dr. Tanaka Seminar
No.1

Wind Resistant Design
Of
Long Span Bridges
（Introduction）

1

The Beginning of Modern Suspension Bridges

- In 19C, suspensions' disasters were so many.

Just before collapse in 29th Nov. 1836

Just after collapse

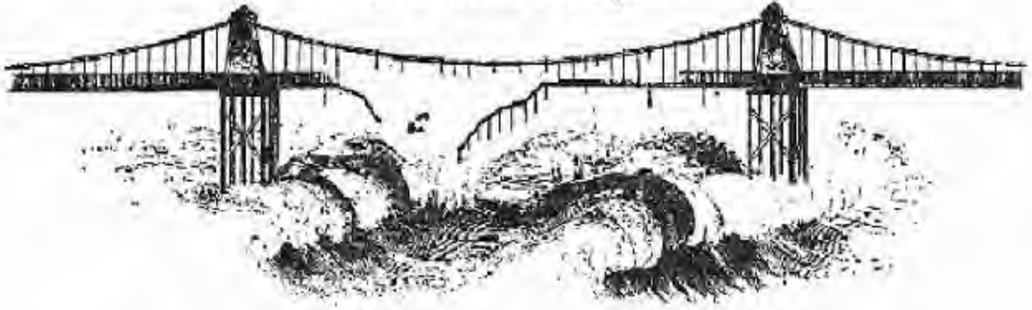


Fig. Failure of the Brighton Chair Pier

The suspension bridge designed by Finney

Finney was the first designer who design the original suspension bridge, which is composed with piers, towers, cable, hangers etc.

TABLE *Progress in Record-Span Suspension Bridges*

Year Completed	*Bridge Name*	*Span Length (m)*
1883	Brooklyn	486.0
1903	Williamsburg	487.5
1909	Manhattan[a]	450.0
1924	Bear Mountain	497.0
1926	Delaware River	533.0
1929	Ambassador	564.0
1931	George Washington	1,067.0
1936	San Francisco-Oakland Bay[a]	704.0
1937	Golden Gate	1,280.0
1939	Bronx-Whitestone[a]	701.0
1940	Old Tacoma Narrows[a]	853.0
1957	Mackinac[a]	1,158.0
1964	Verrazano-Narrows	1,298.0

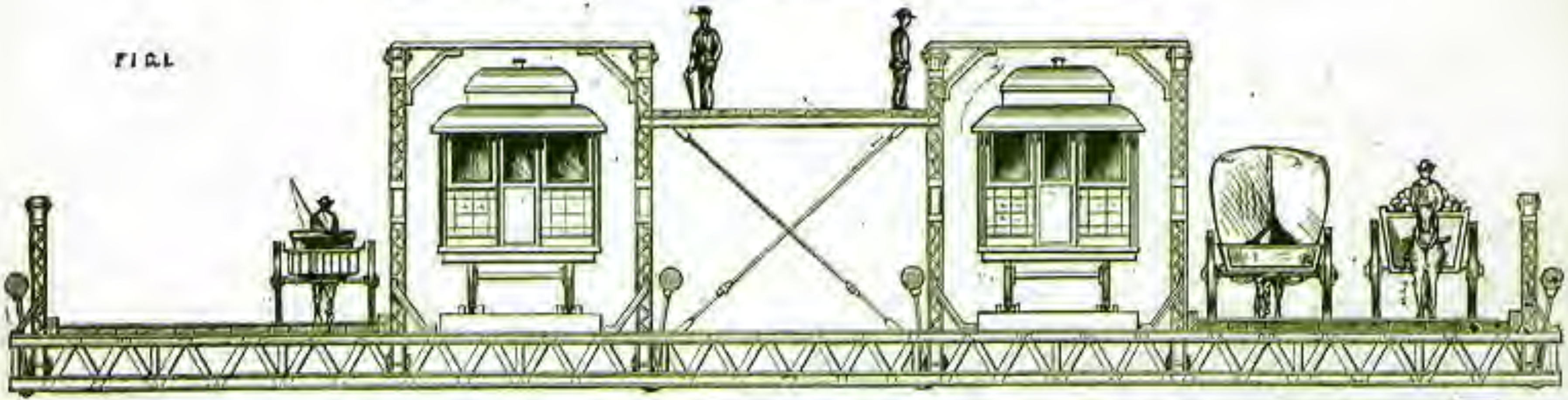
Menai Bridge 1826 (British)   176 m

Brooklyn Bridge (USA) 1883

THE BROOKLYN SUSPENSION BRIDGE.

MESSRS. JOHN A. ROEBLING AND WASHINGTON A. ROEBLING, ENGINEERS.

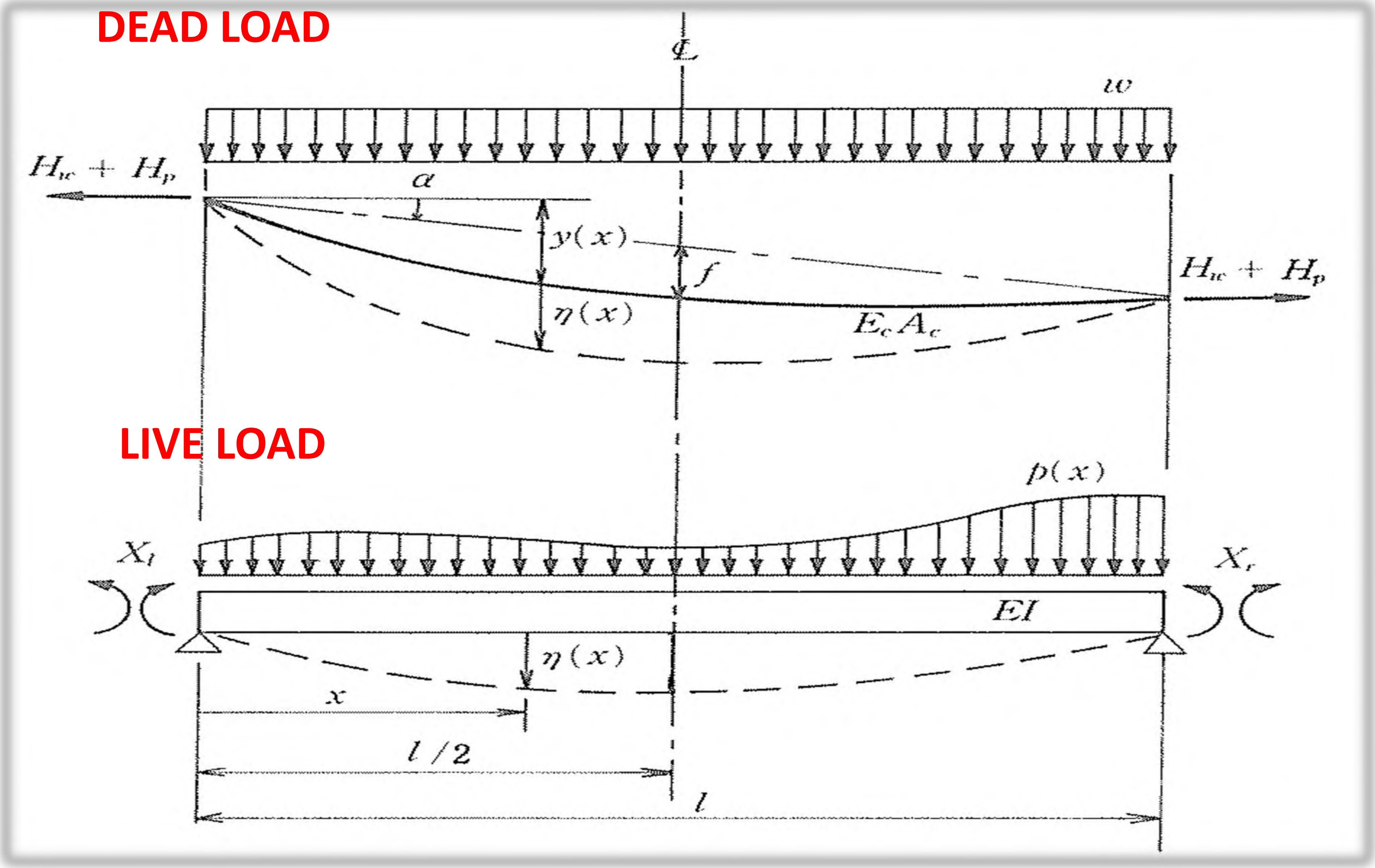
FIG. 1.



Leon Moisseiff (1872-1943)

Othmar Ammann (1879-1965)

Deflection Theory



Moment becomes small !!

Elastic Theory

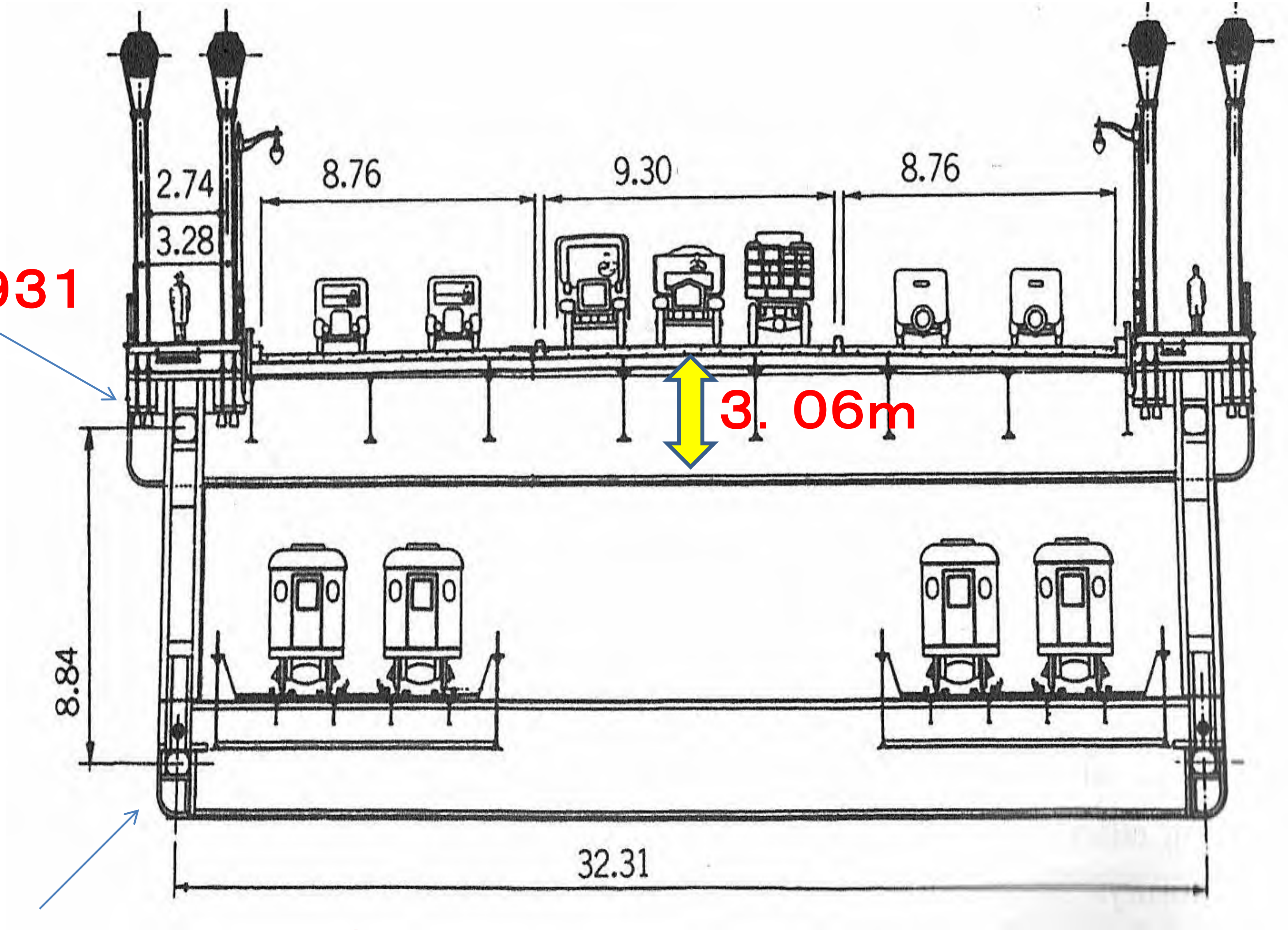
$$M(x)=M_0(x)-H_p\cdot y(x)+X_t(x) \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

Deflection Theory

$$M(x)=M_0(x)-H_p\cdot y(x)-\underline{(H_w+H_p)}\cdot\eta(x)+X_t(x) \quad \cdots\cdots\cdots\cdots \quad (2)$$

George Washington Bridge
(1931) 1067 m

Traffic was very busy



1931

3. 06m

Installed in 1962

George Washington Bridge (1962)After Attaching Lower Truss Members

San Francisco-Oakland Bay Bridge (1936)

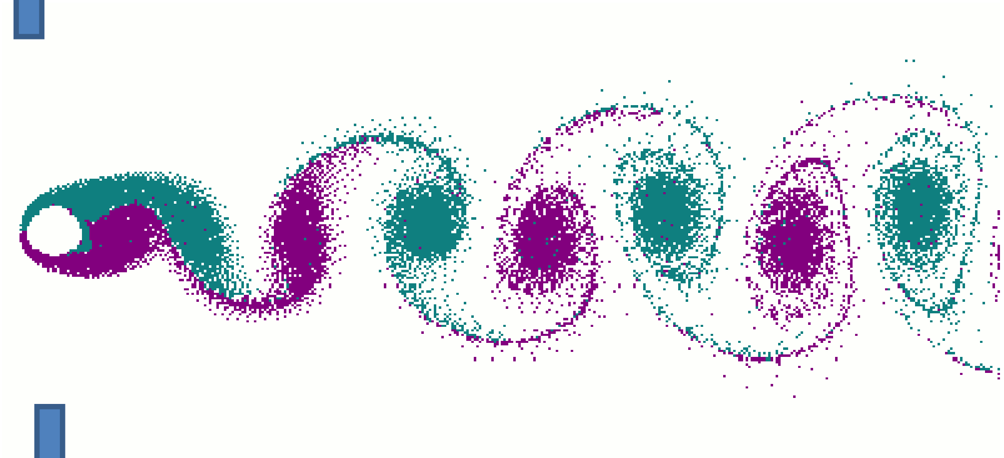
Golden Gate Bridge (1937) 1280 m

Tacoma Narrows Bridge (1940)   855m

Collapse of Original Tacoma Narrows Bridge

Karman Vortex Streets

Coincide
with
Eigen value
of Cylinder



Mechanics of Vortex

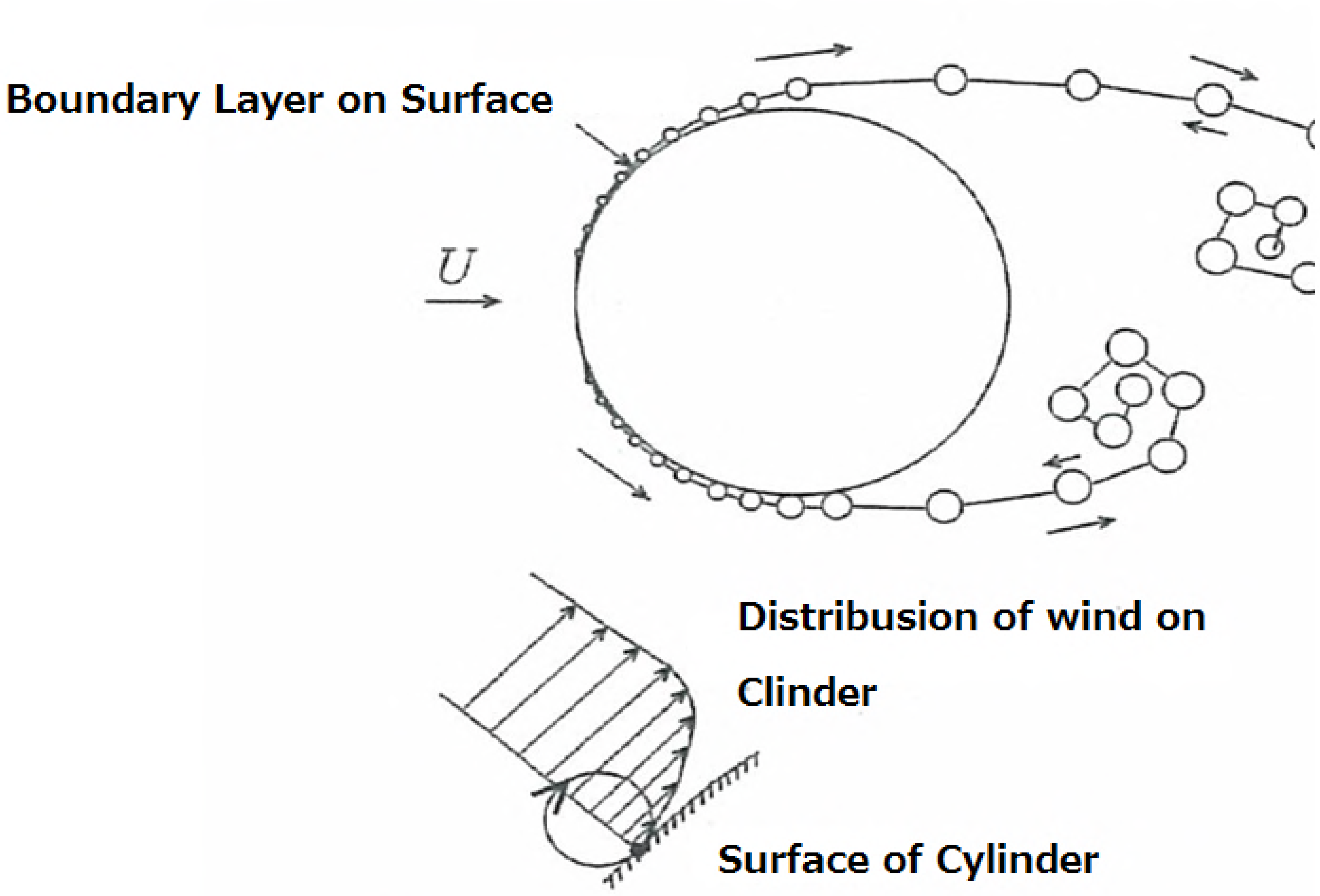
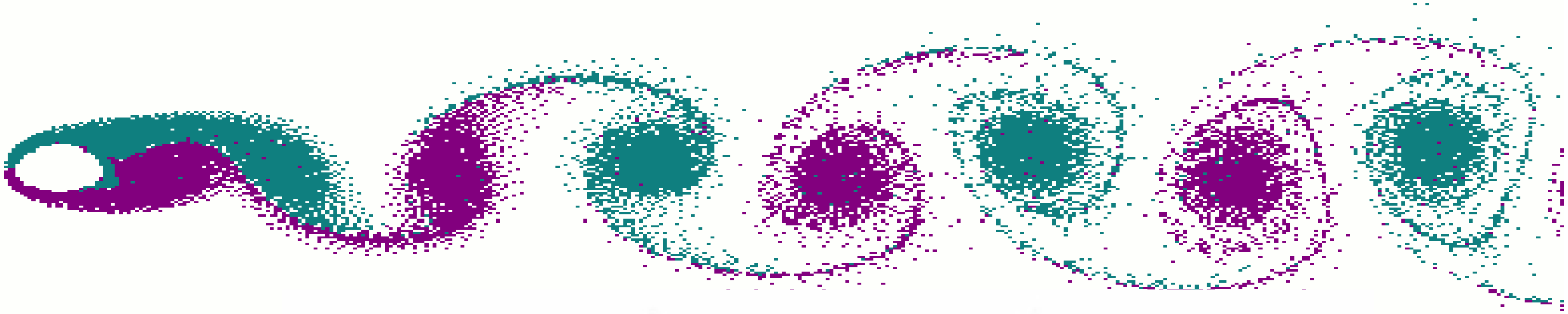
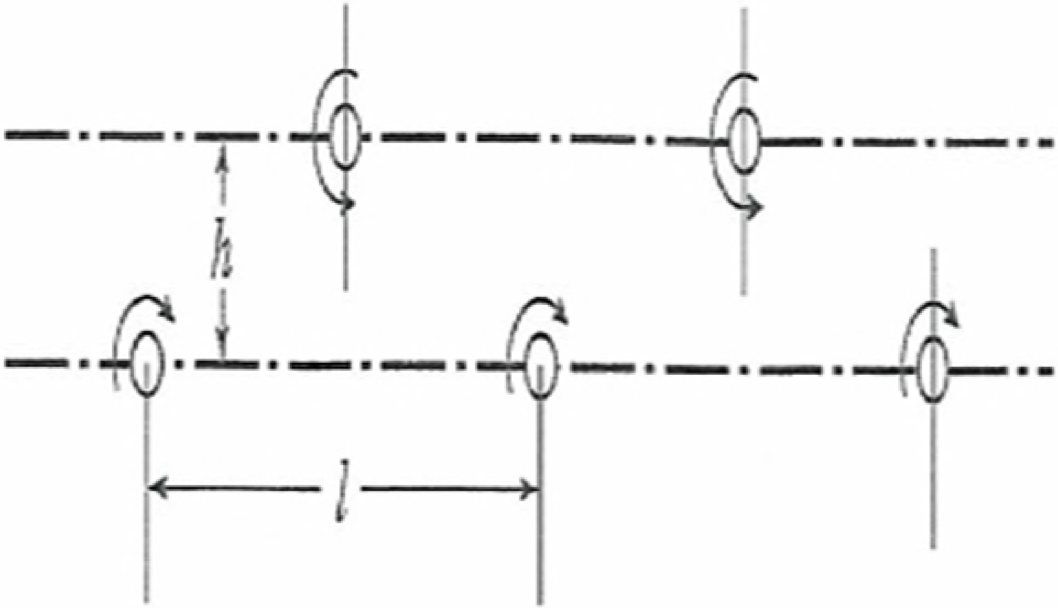


Fig Mechanism of Inducing Karman Vortex



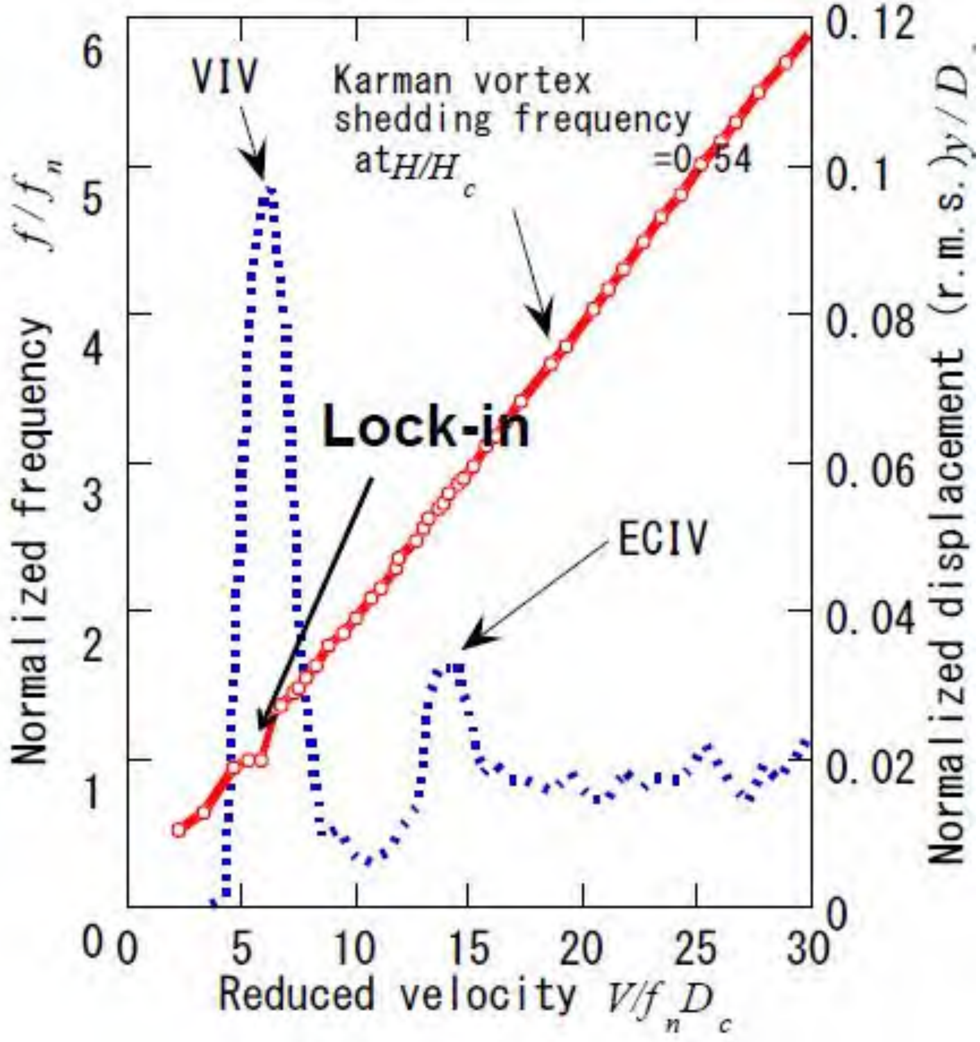


Karman Vortex Streets are ;

Stable if $h/l = 0.283$

Vortex-induced vibration of a tower with circular section

By Prof. FUJINO



Strouhal Number (St.)

- Vertical First Mode
- St. = f x D / U = 0.11 (Original Tacoma Bridge)

Where f: frequency [1/s]
D: Frontal dimension [m]
U: Wind Velocity [m/s]

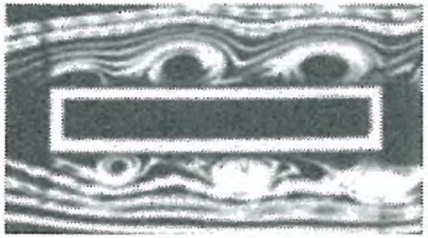
- At the collapse of bridge:

U cr = 0.2 Hz x 2.44 m / 0.11 = 4.44 m/s

U cr is much different from 18.6 m/s which Prof.Farquharson measured.

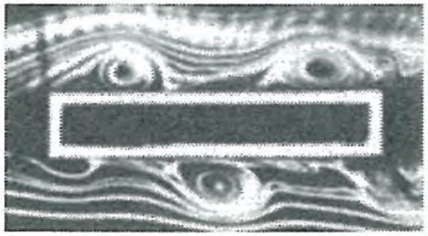
Therefore Karman vortex street is not the cause.

Historical "*Miss understanding*"

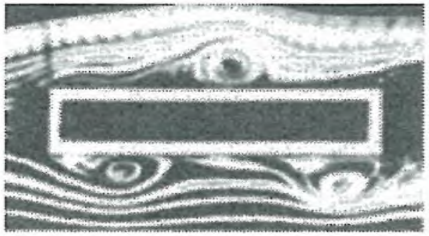


$V_r = 0.80$

$V_r = 0.88$

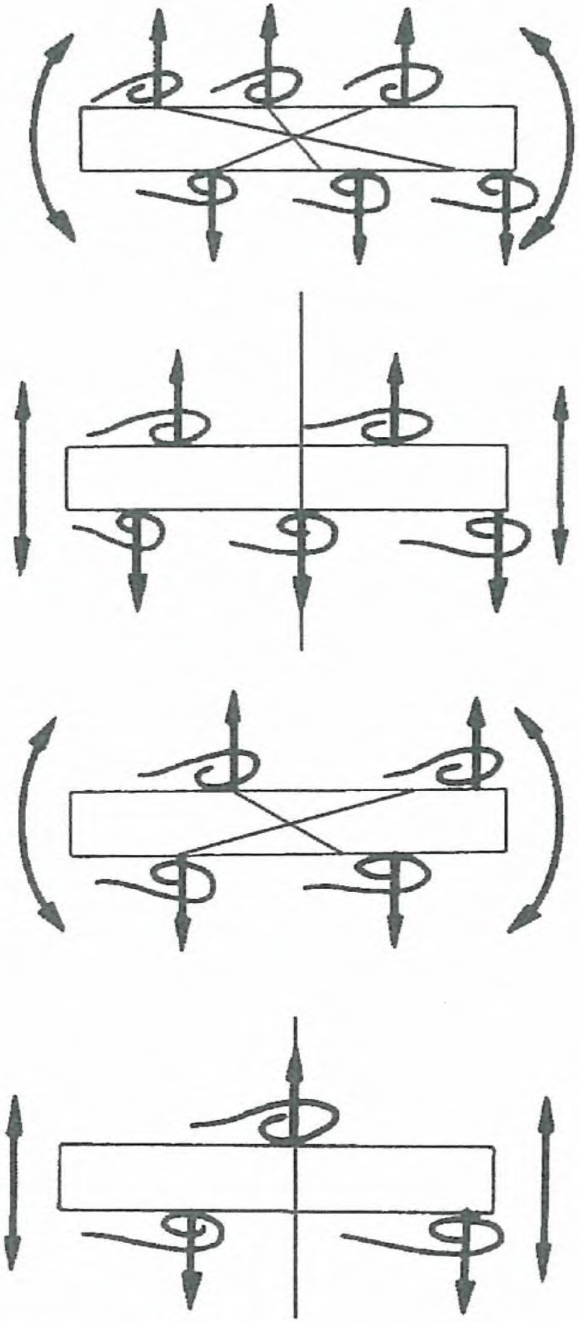


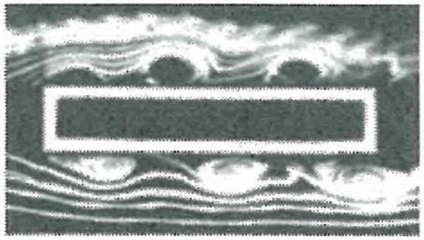
$V_r = 1.08$



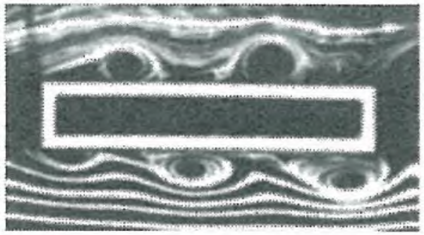
$V_r = 1.40$

Bending

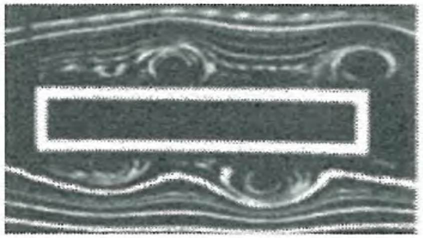




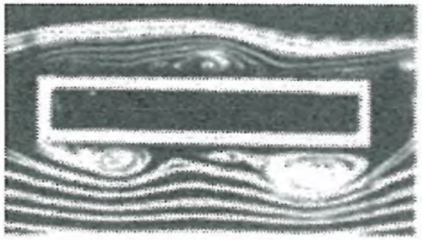
$V_r = 0.76$



$V_r = 0.90$

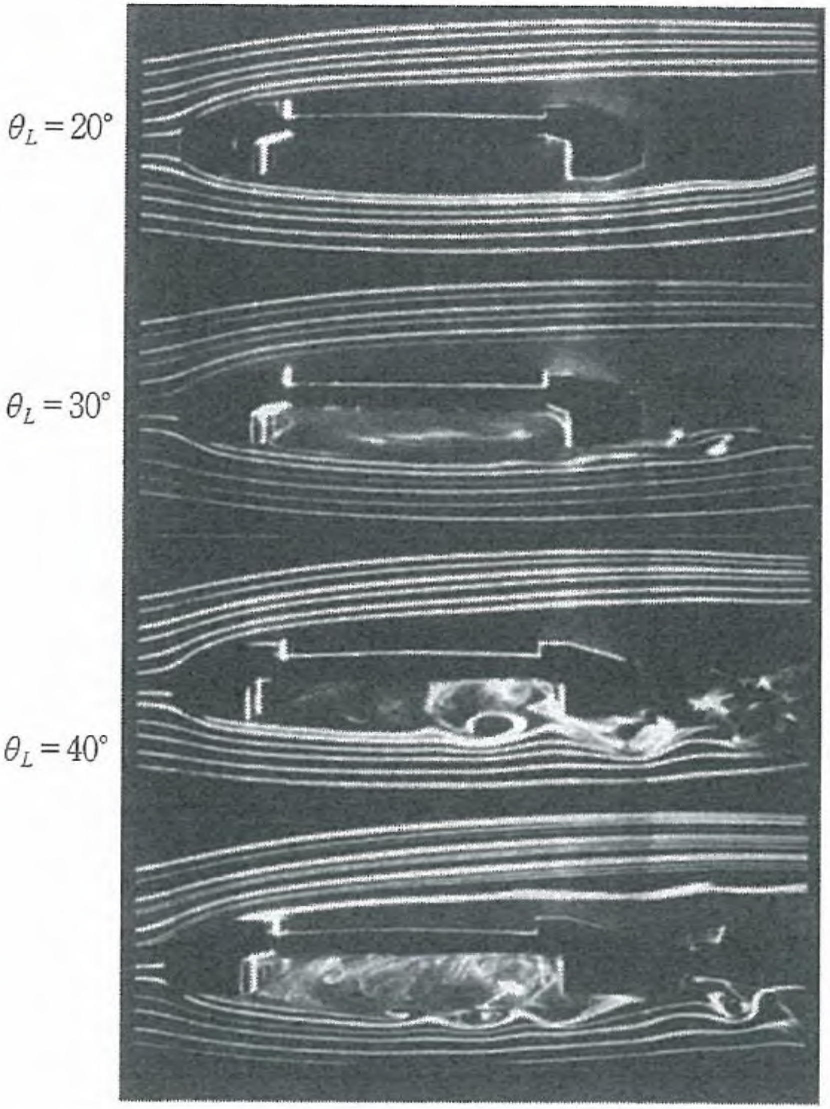


$V_r = 1.10$

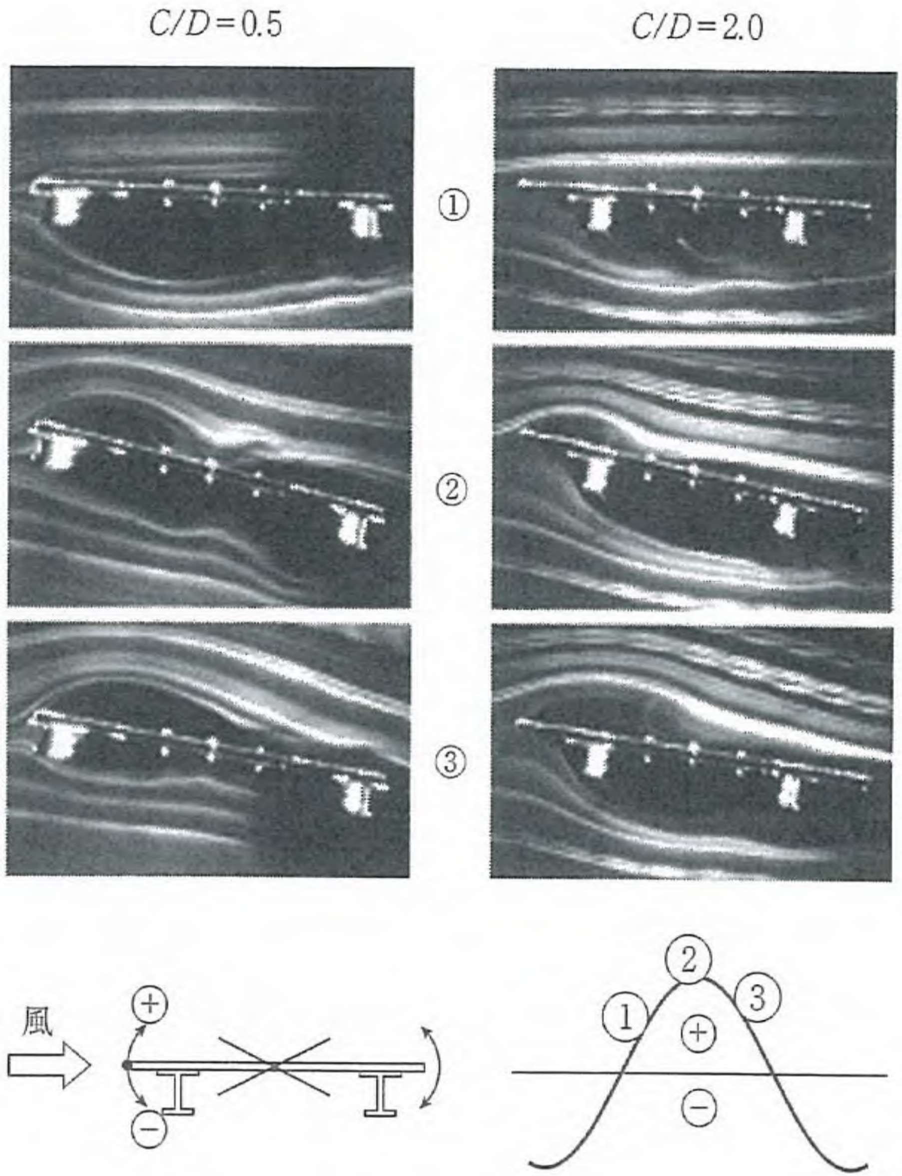


$V_r = 1.40$

Torsion



PC cable Stayed Bridge Deck Section

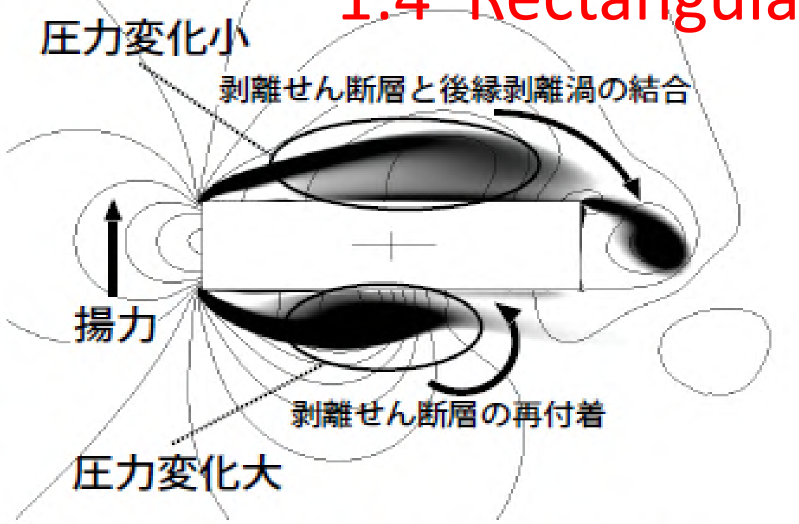


Twin Girder Deck

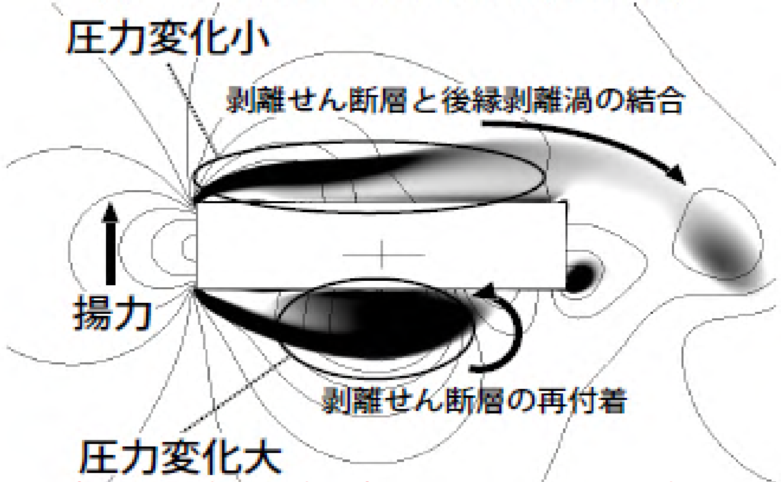
F. I. V. on Bending & Torsion

1:4 Rectangular

From: Dr. Maruoka

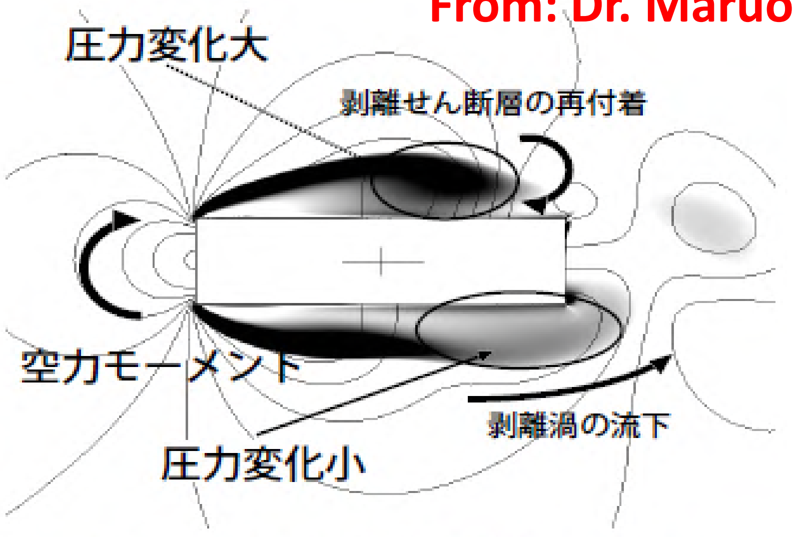


(a)　渦度強度・圧力の関係 (3/4 周期)

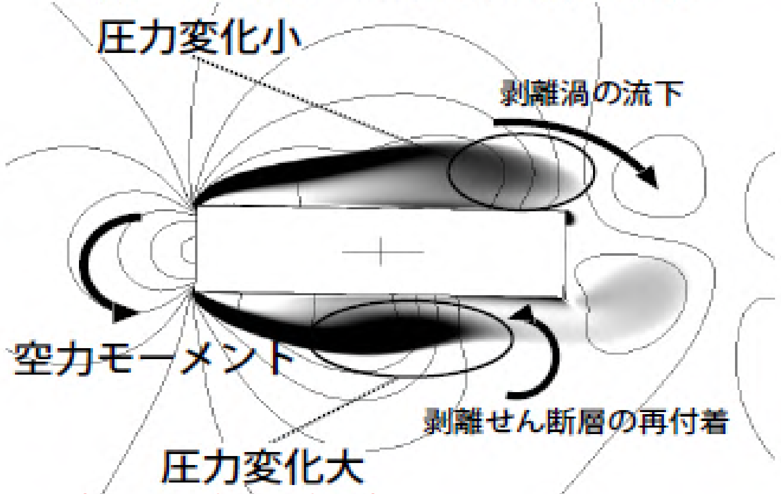


Flow Induced Vibration on Bending

(b)　渦度強度・圧力の関係 (4/4 周期)



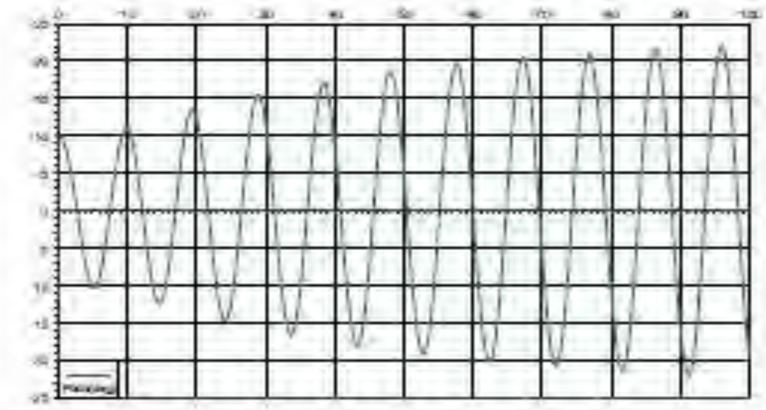
(a)　渦度強度・圧力の関係 (3/4 周期)



Flow Induced Vibration on torsion

(b)　渦度強度・圧力の関係 (4/4 周期)

Computer Simulation by COWI

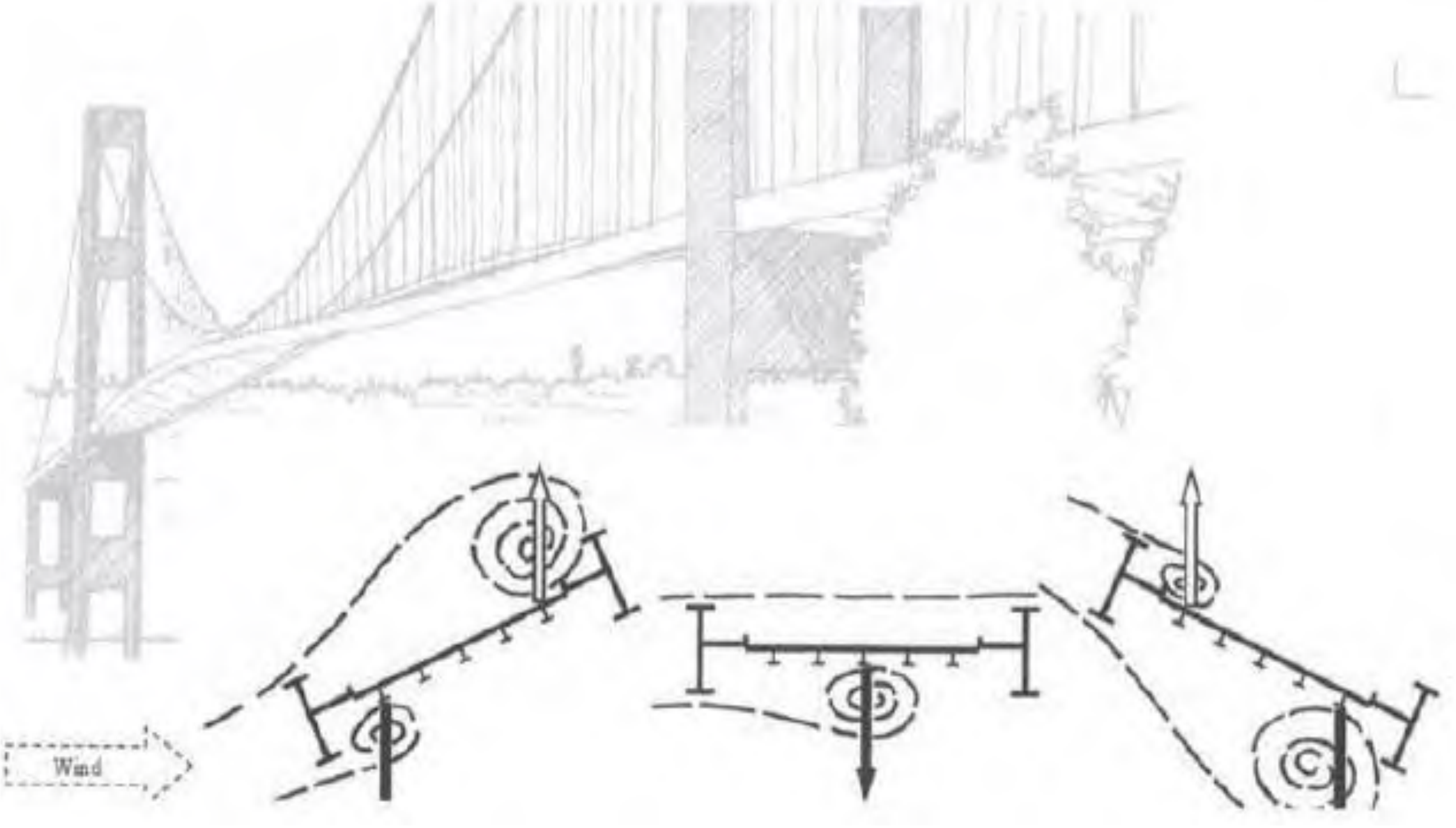


Flutter instability

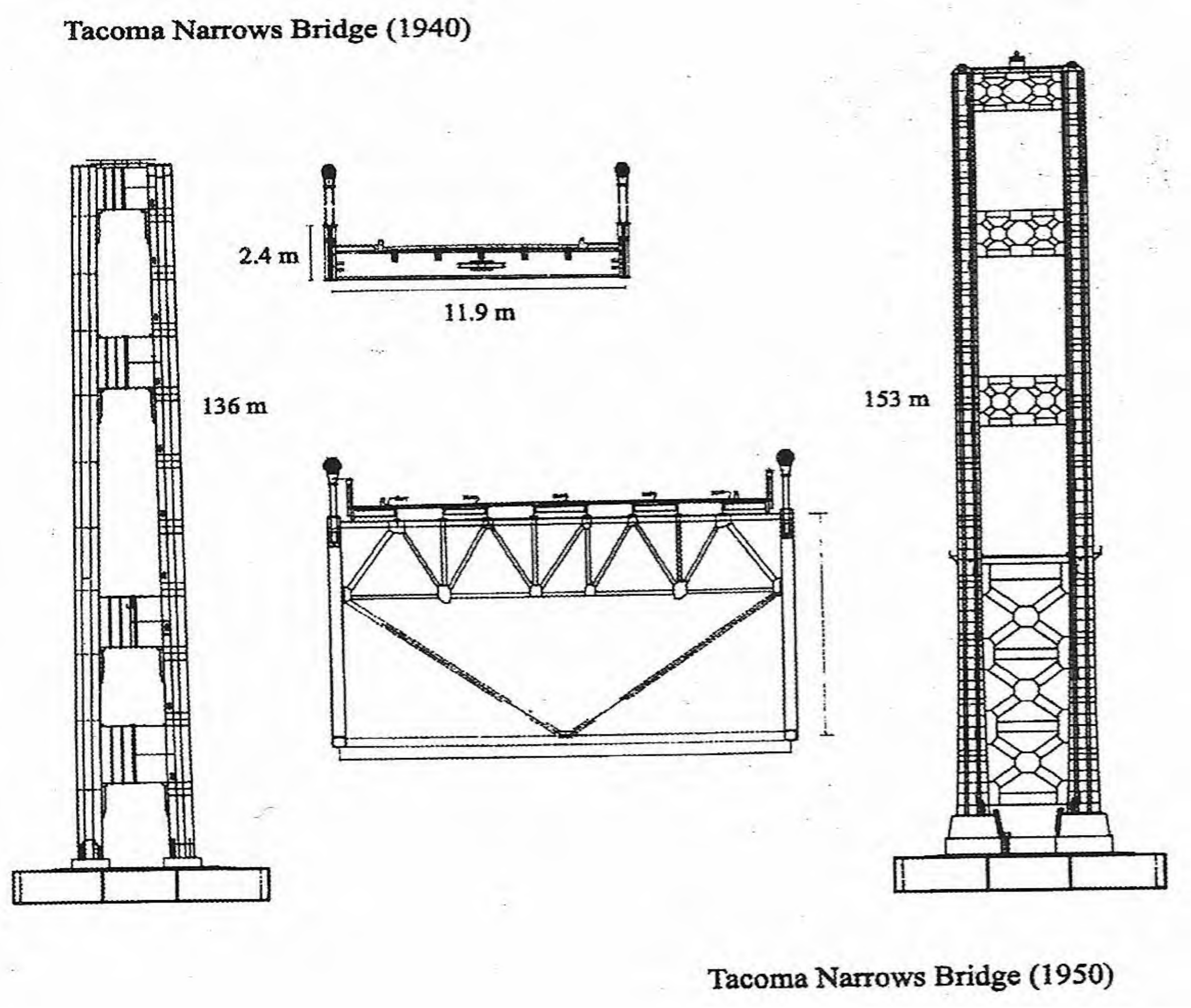
Aeroelastic instability (divergent motion of the deck) must be confirmed not to occur at wind speeds foreseen within the design life of the bridge.

Divergent motion (twist) of bridge girder

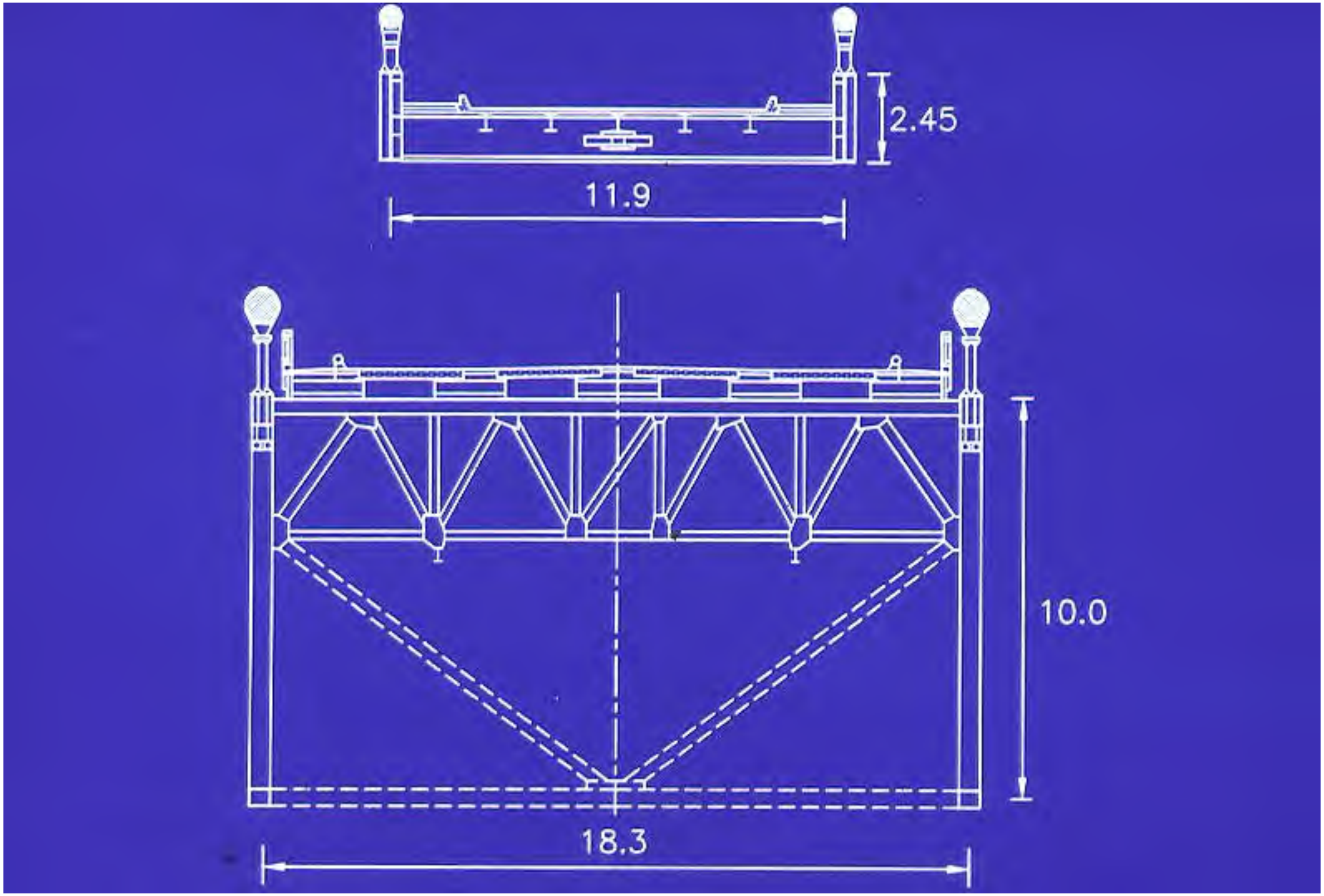
Torsional Oscillation Mechanism
By Dr. Alan Larsen

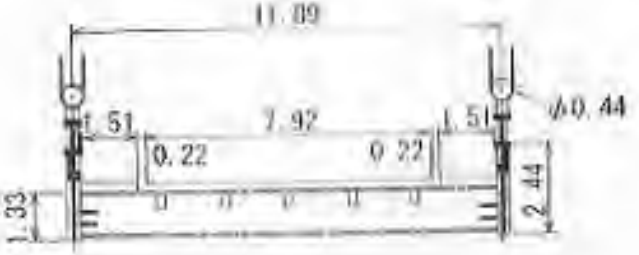


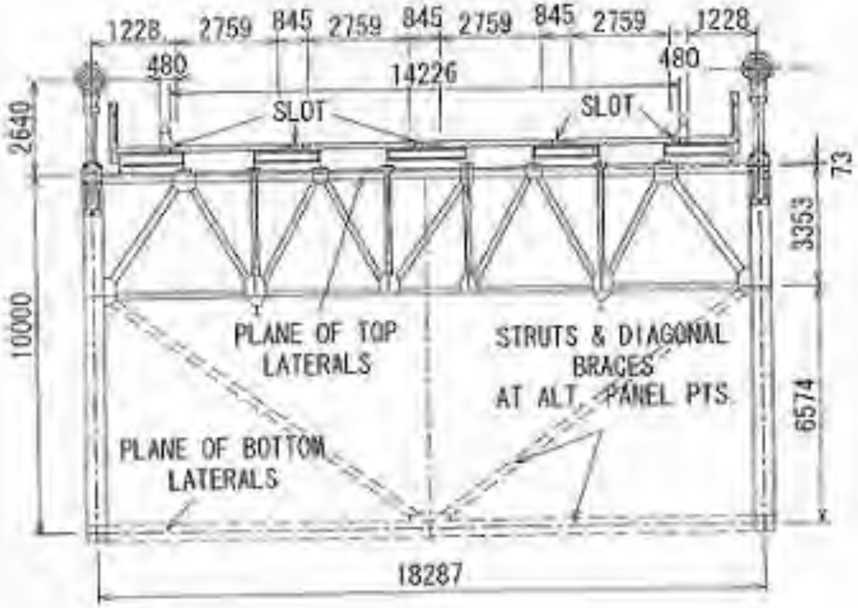
Comparison between new and old Tacoma Narrows Bridge

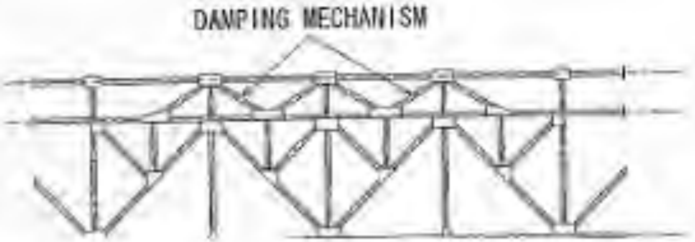


Change of Deck Section

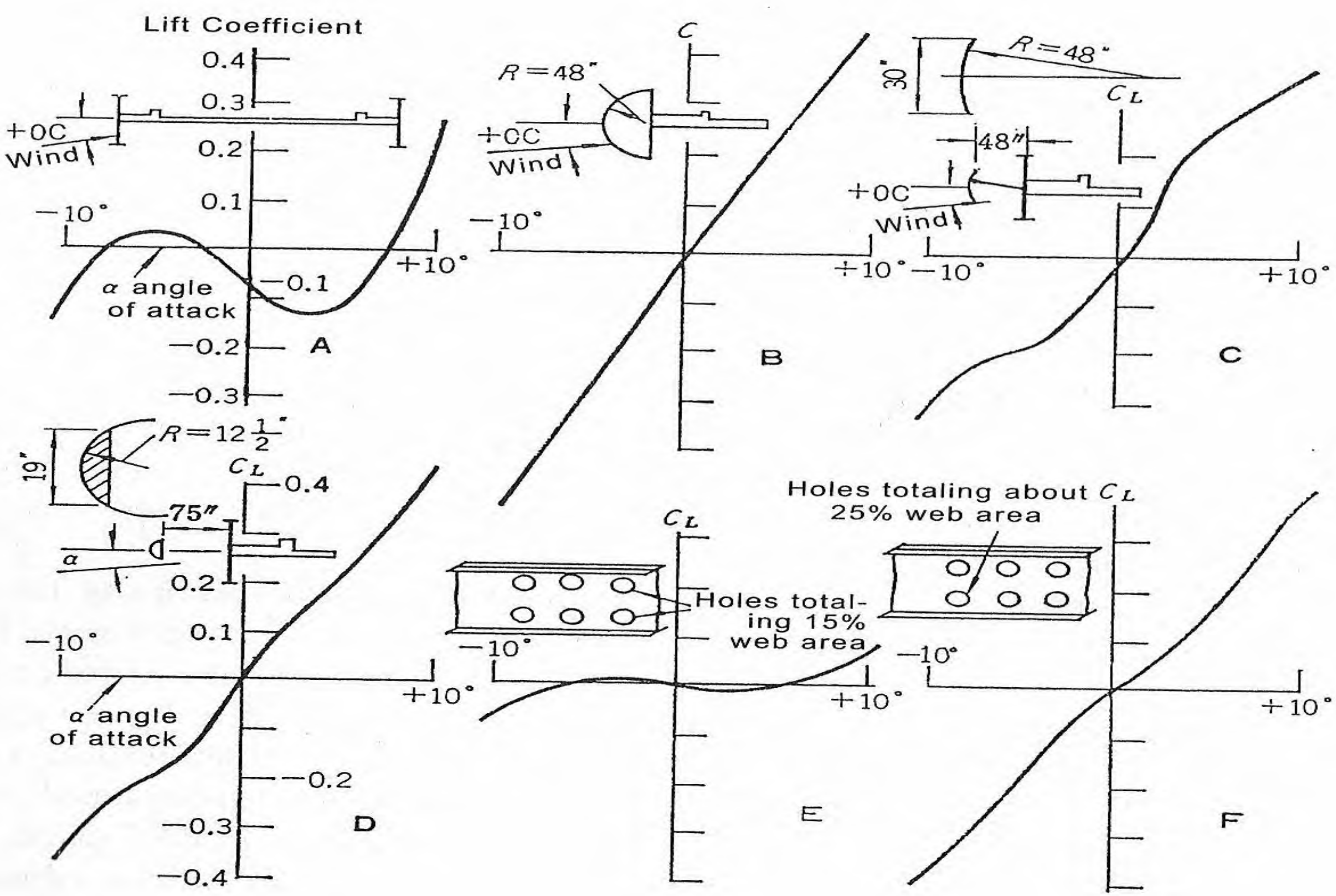



11.09
φ0.44
1.51
7.92
1.51
0.22
0.22
1.33
2.44

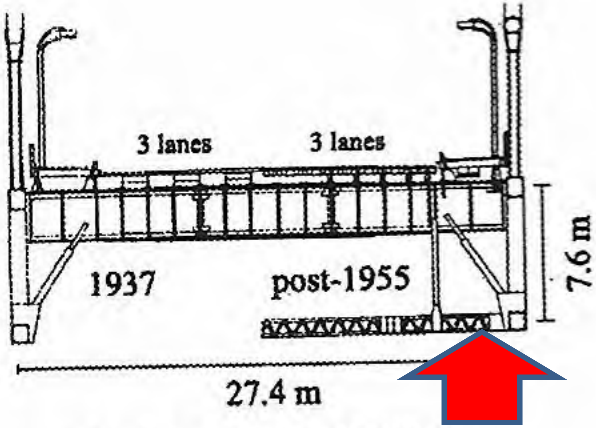

1228
2759
845
2759
845
2759
845
2759
1228
480
14226
480
SLOT
SLOT
2640
73
3353
10000
PLANE OF TOP LATERALS
STRUTS & DIAGONAL BRACES AT ALT. PANEL PTS.
6574
PLANE OF BOTTOM LATERALS
18287


DAMPING MECHANISM

Ideas to prevent vibration by Prof.Farquharson

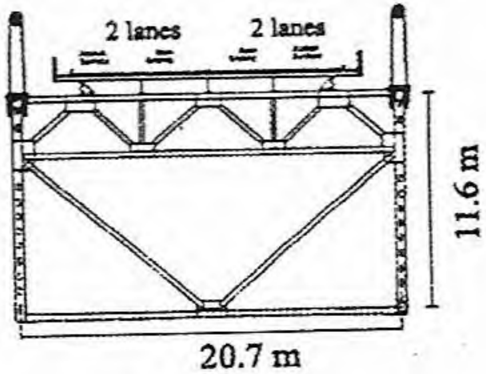


After Collapse of Tacoma Narrows Br. (1)

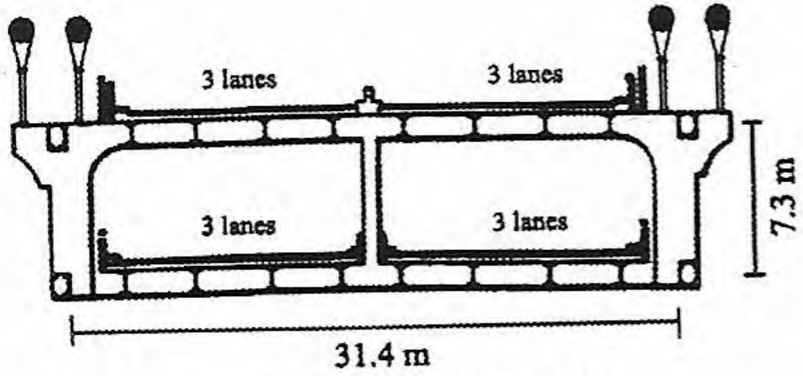


Golden Gate (1937)

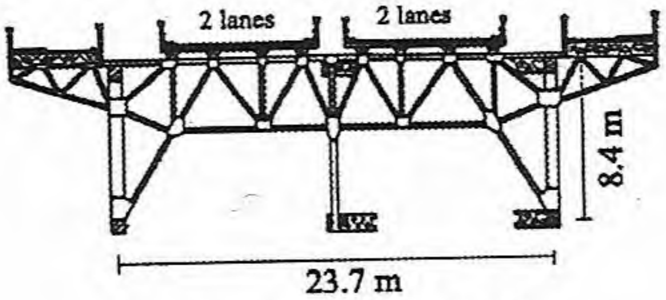
For Stability



Mackinac (1957)



Verrazano-Narrows (1964)

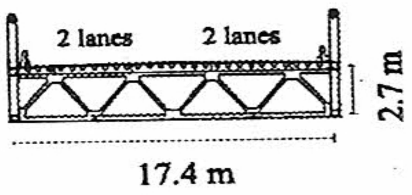


Forth Road (1964)

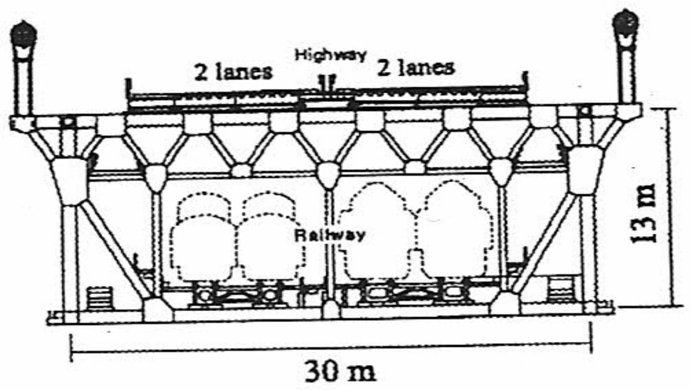
Oscillation of Golden Gate Bridge

- 4th December 1951, vertical oscillations reached 3.3m by strong NW direction winds.

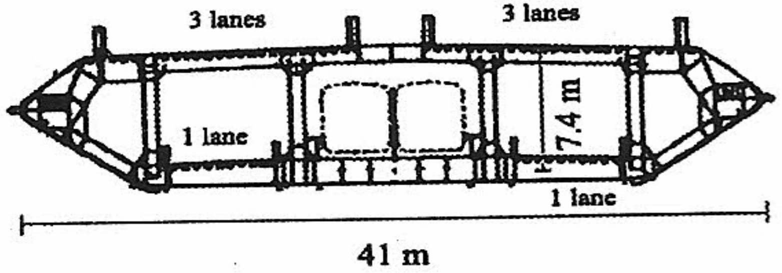
After Collapse of Tacoma Narrows Br. (2)



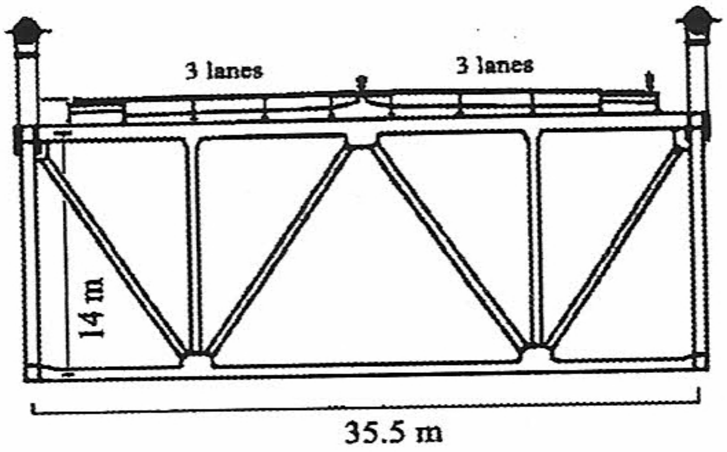
A. Murray MacKay (1970)



Seto Ohashi (1988)

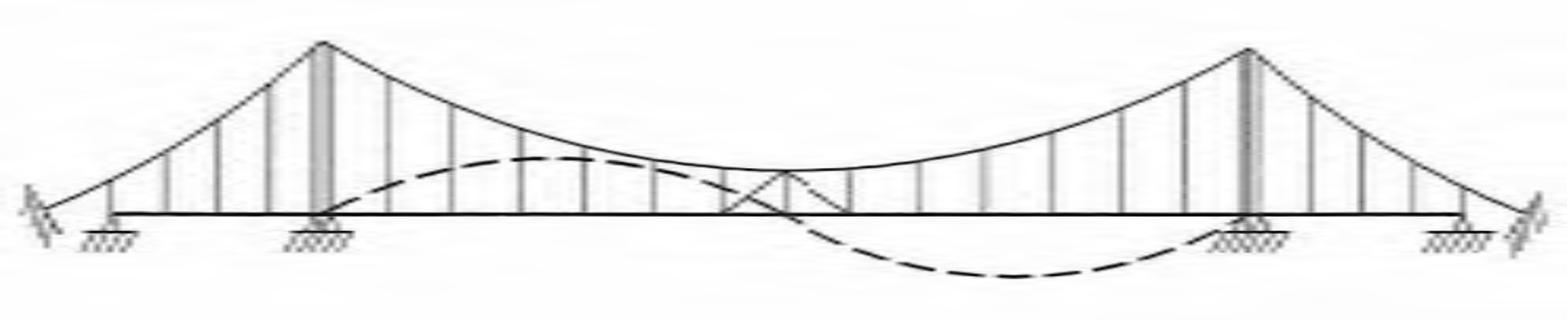


Tsing Ma (1997)

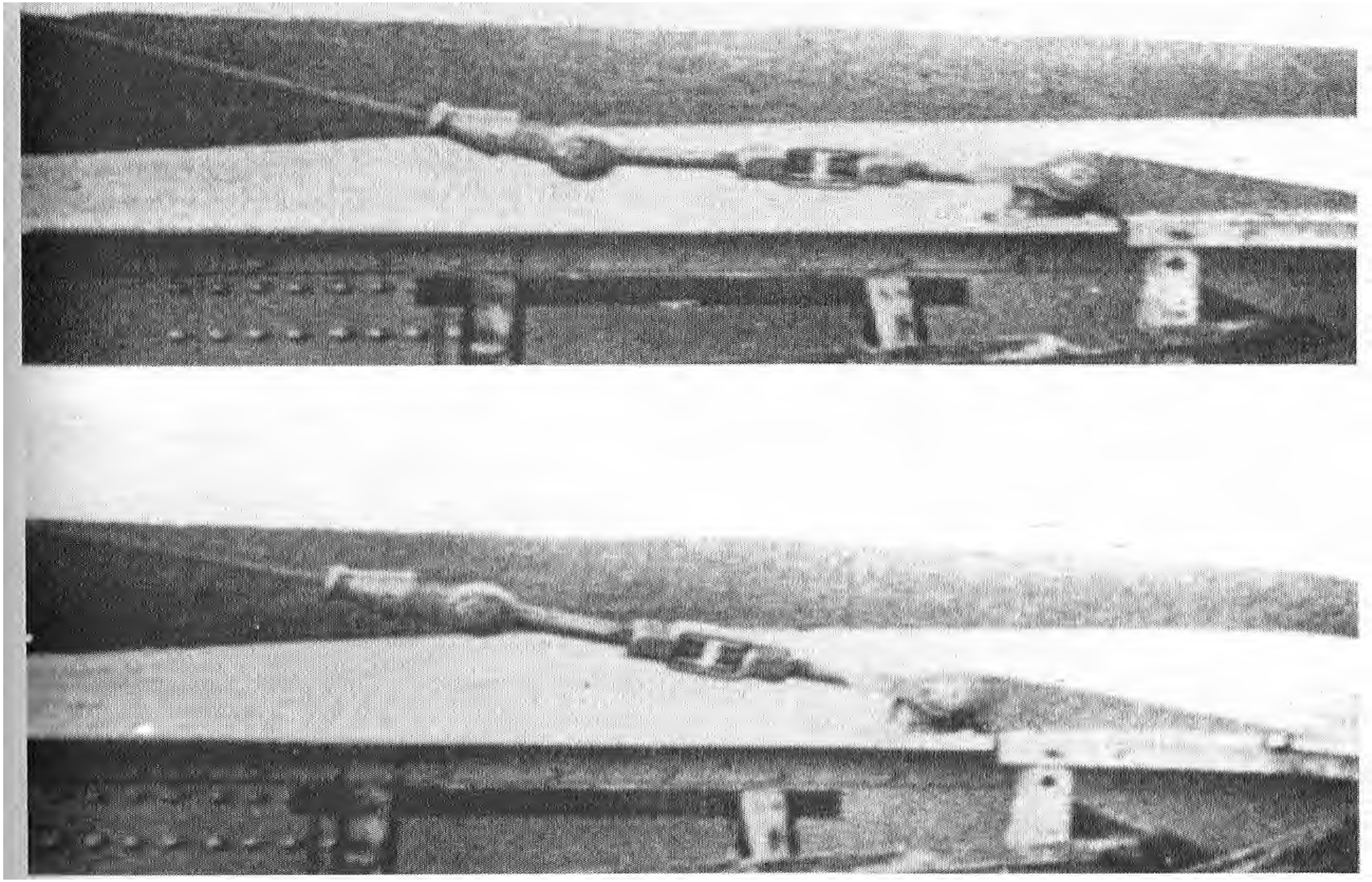


Akashi Kaikyo (1998)

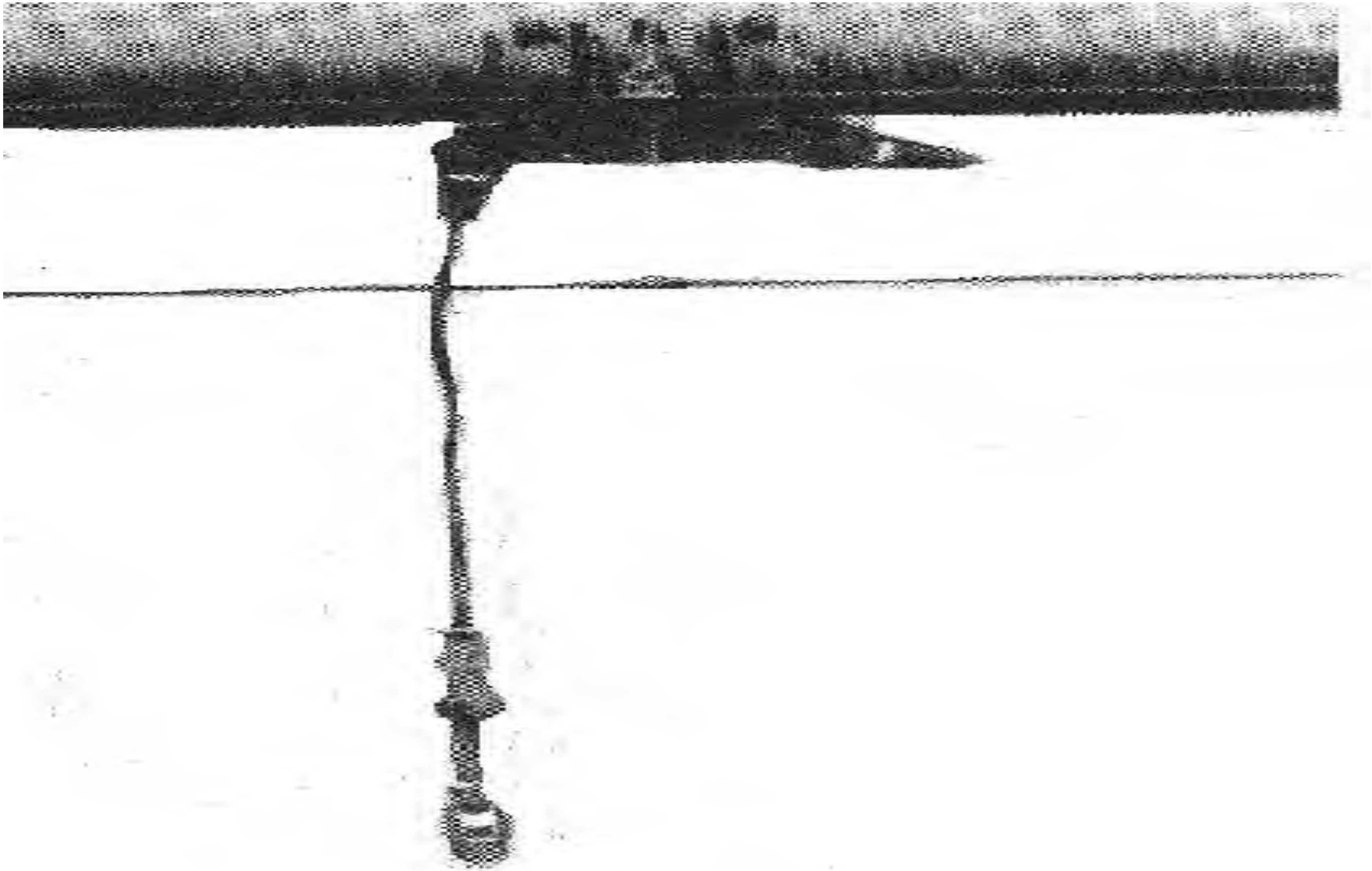
Role of the Center Diagonal Stays



Center diagonal stay just before collapse

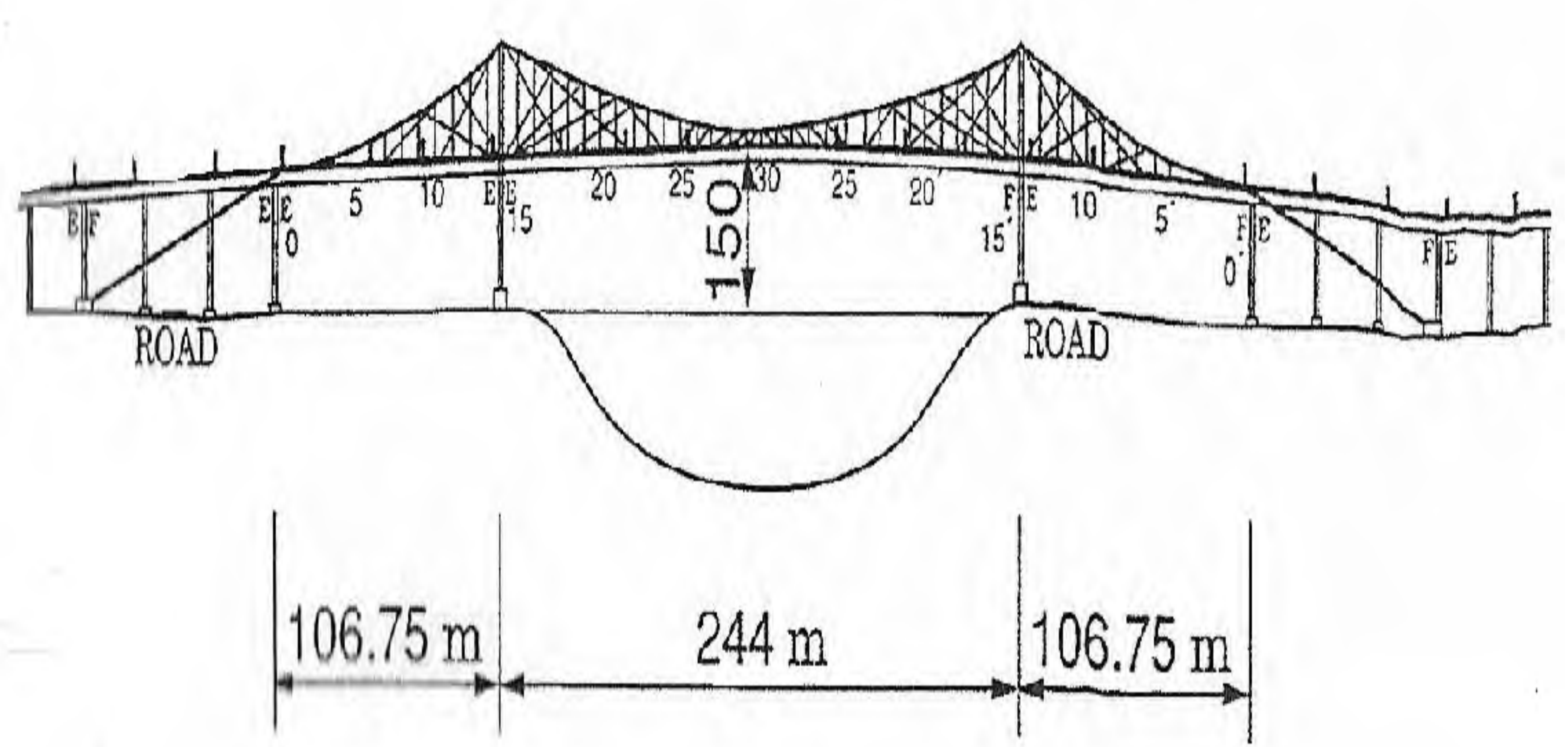


Collapse of center diagonal stay

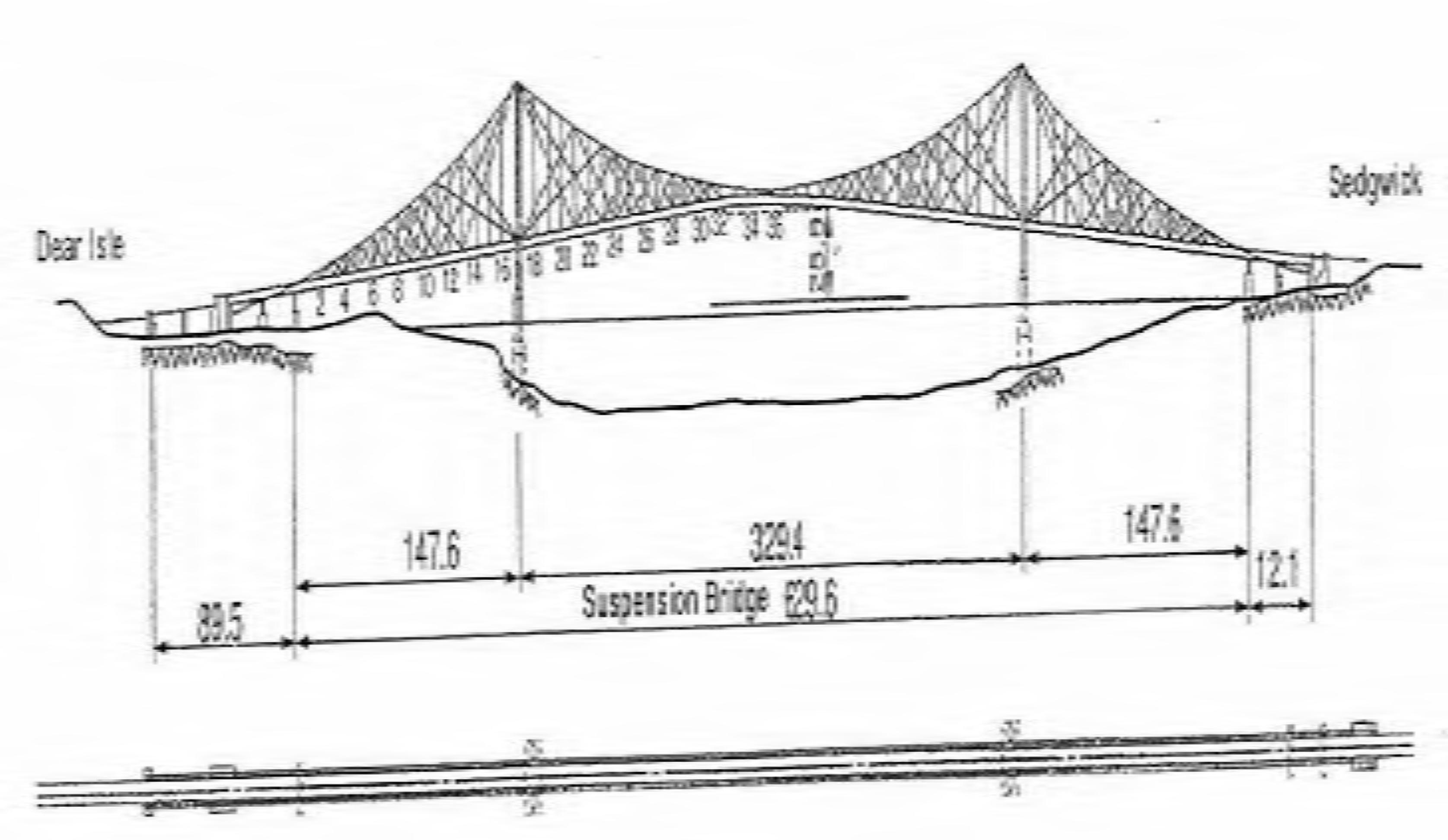


David P Steinman (1886-1960)

Thousand Island Bridge



Deer Isle Bridge

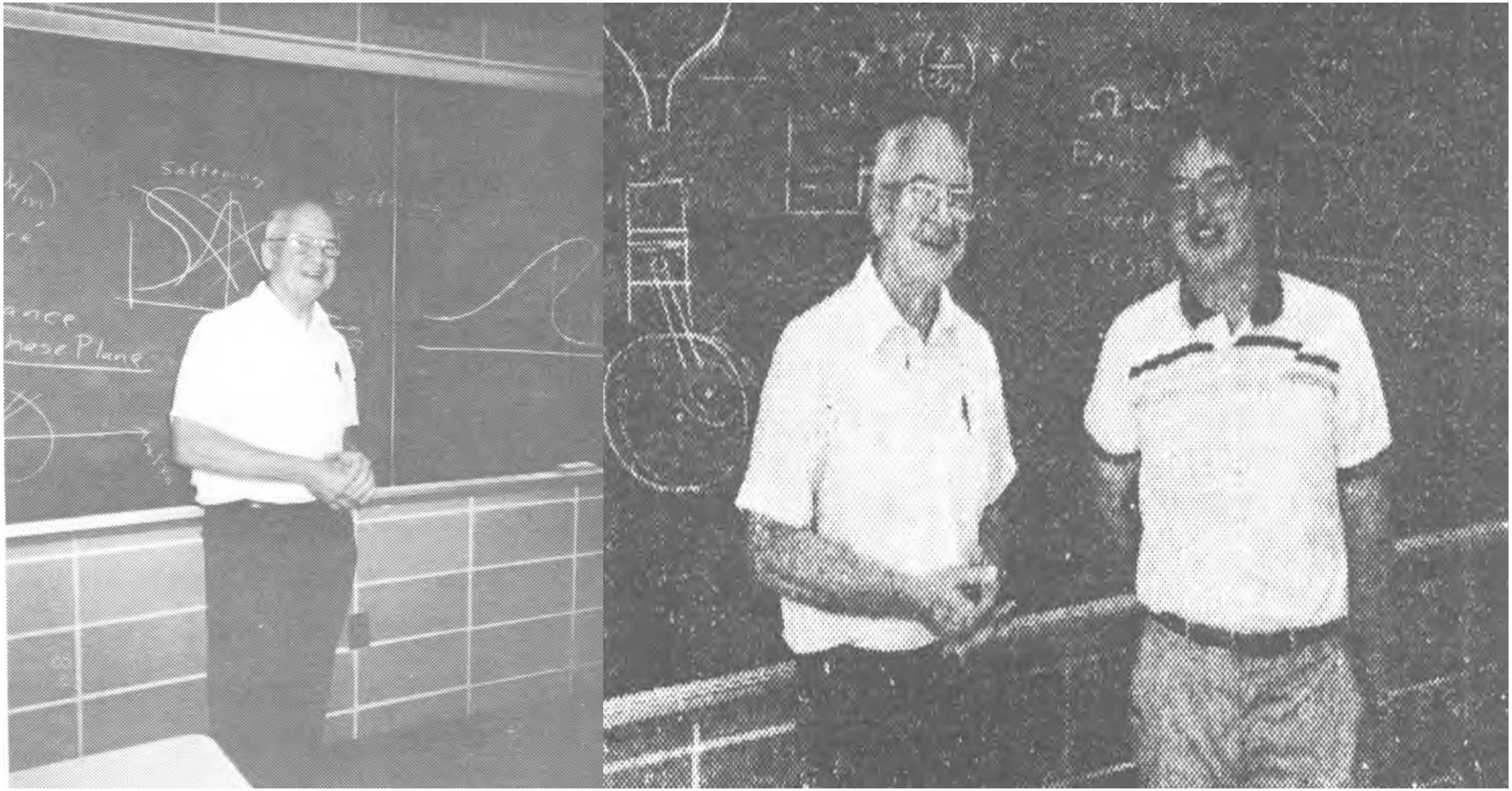


New Tacoma   Narrows Bridge (1950)

Application of Truss Deck

The Second Tacoma Narrows Bridge

Prof.R.H. Scanlan & H.Tanaka (1984)



Lecture of Structural Dynamics at Princeton University (USA)

Wing Theory

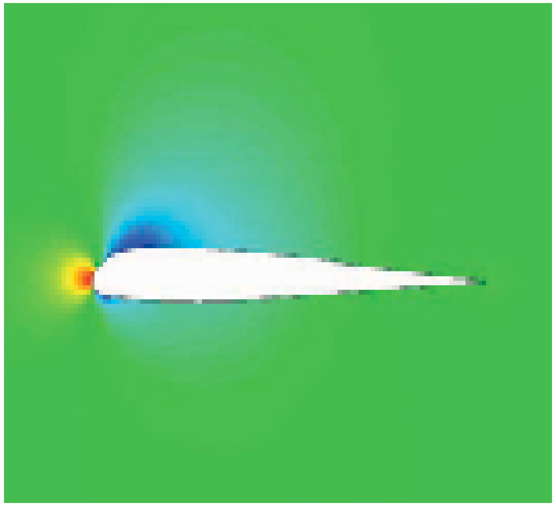


FIG Static Pressure Field on a NACA Airfoil

(Trailing edge **fulfills Kutta condition**)

Bluff Body (e.g., Bridges)

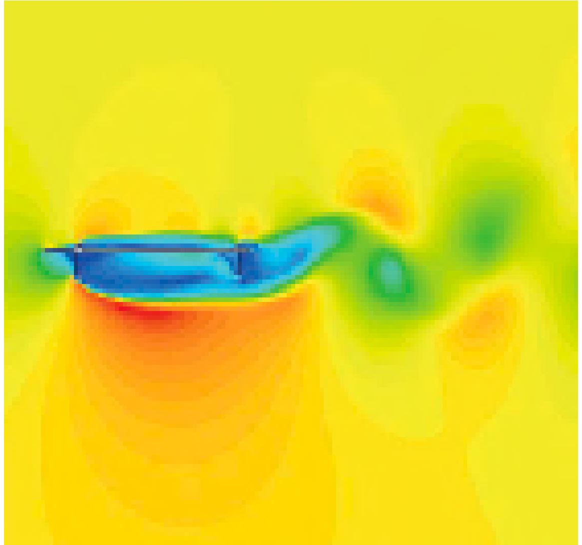
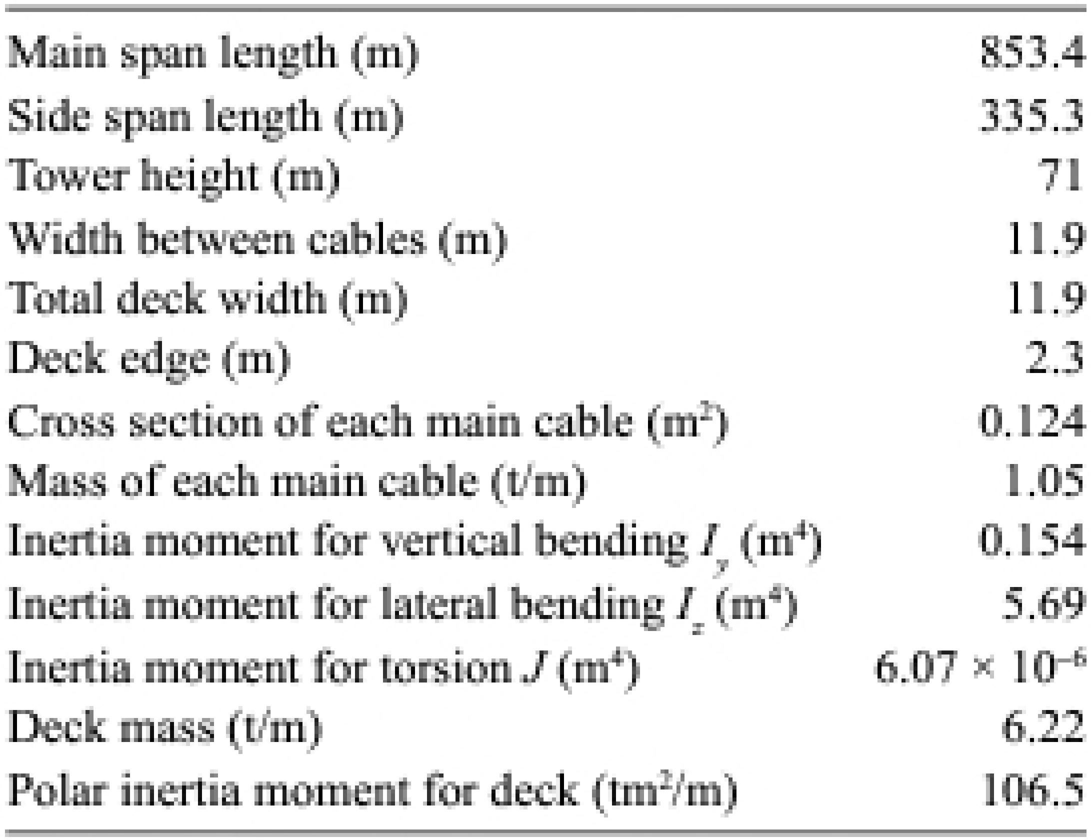


FIG Flow around Bluff Bodies

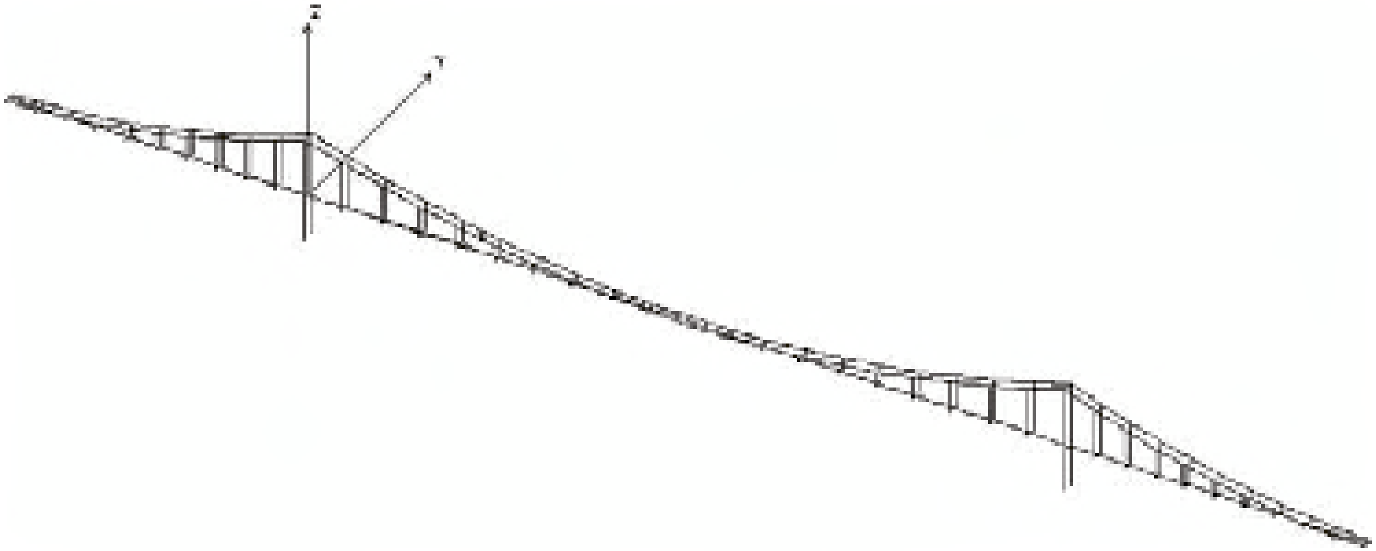
(trailing edge does **not fulfill Kutta condition**)

Dimension of Original Tacoma Bridge

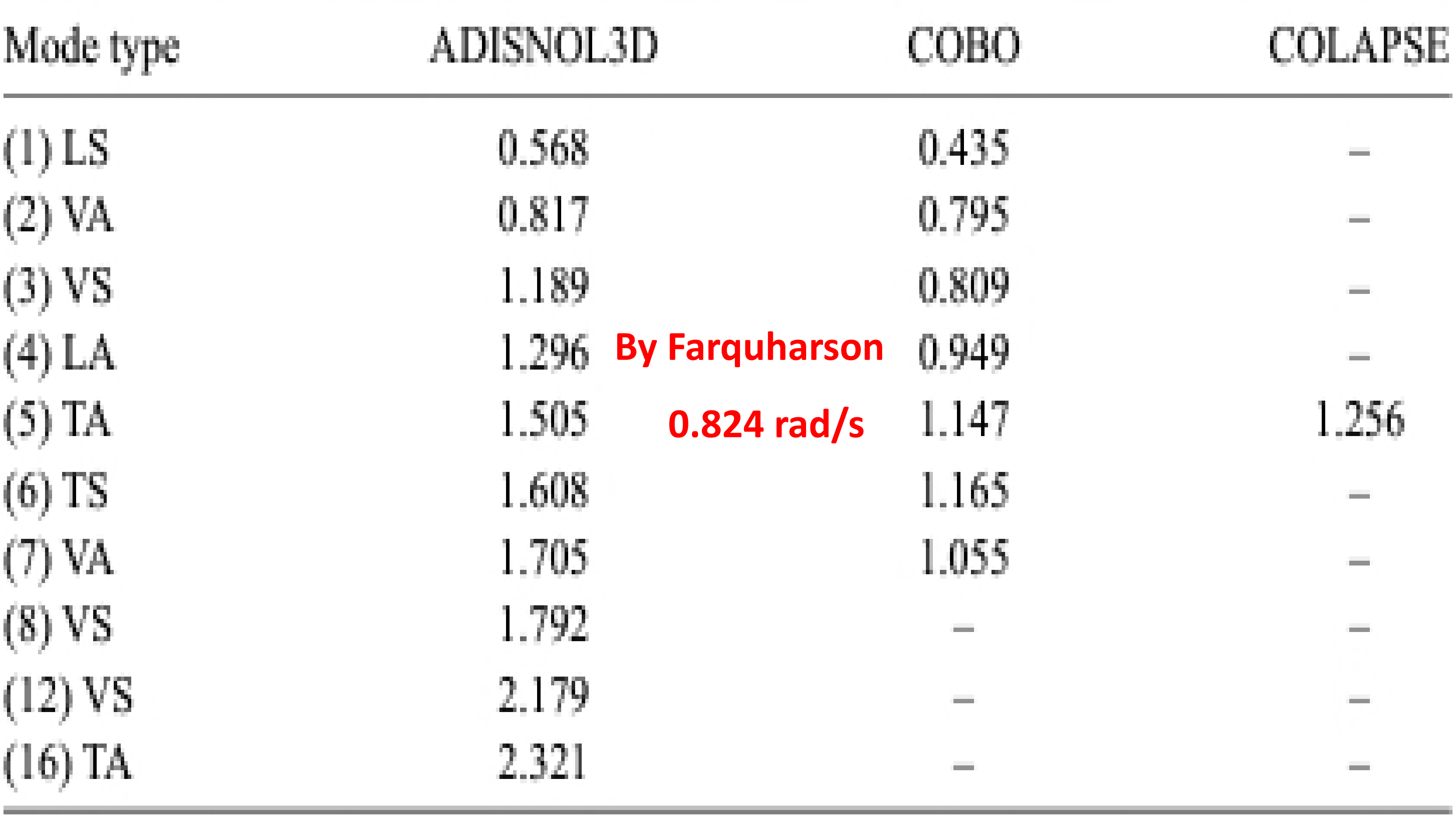


Main span length (m)	853.4
Side span length (m)	335.3
Tower height (m)	71
Width between cables (m)	11.9
Total deck width (m)	11.9
Deck edge (m)	2.3
Cross section of each main cable (m^2)	0.124
Mass of each main cable (t/m)	1.05
Inertia moment for vertical bending I_y (m^4)	0.154
Inertia moment for lateral bending I_z (m^4)	5.69
Inertia moment for torsion J (m^4)	6.07×10^{-6}
Deck mass (t/m)	6.22
Polar inertia moment for deck (tm^2/m)	106.5

Finite Model of Original Tacoma Bridge



Comparison of national frequencies (Unit: 2πf)



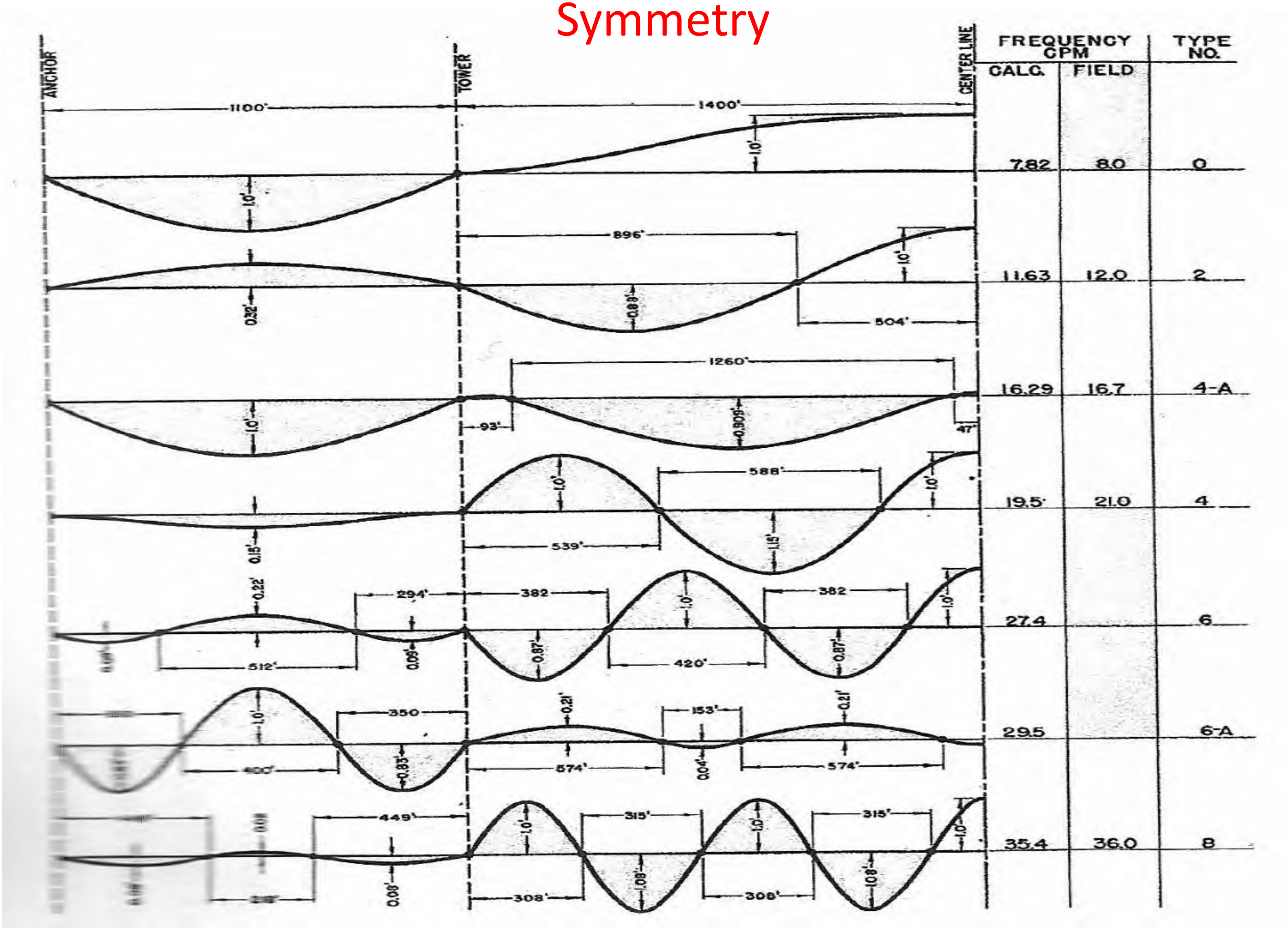
Mode type	ADISNOL3D	COBO	COLAPSE
(1) LS	0.568	0.435	–
(2) VA	0.817	0.795	–
(3) VS	1.189	0.809	–
(4) LA	1.296	0.949	–
(5) TA	1.505	1.147	1.256
(6) TS	1.608	1.165	–
(7) VA	1.705	1.055	–
(8) VS	1.792	–	–
(12) VS	2.179	–	–
(16) TA	2.321	–	–

By Farquharson

0.824 rad/s

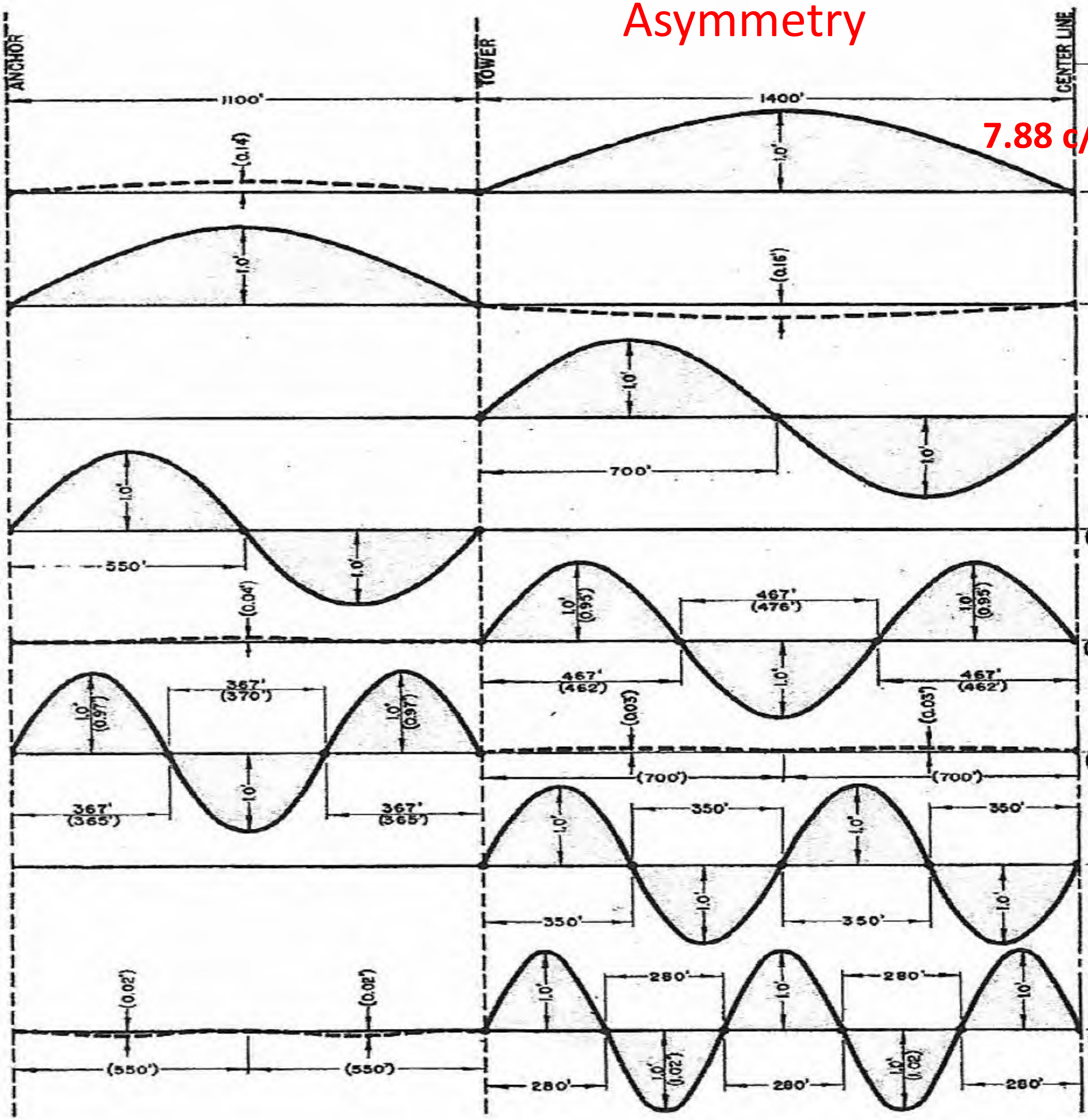
Vibration Modes

Symmetry



FREQUENCY CPM CALC.	FREQUENCY CPM FIELD	TYPE NO.
7.82	8.0	0
11.63	12.0	2
16.29	16.7	4-A
19.5	21.0	4
27.4		6
29.5		6-A
35.4	36.0	8

Asymmetry



7.88 c/min = 0.824 rad/s

FREQUENCY CPM		TYPE NO.
CALC.	FIELD	
7.88 (7.52)	8.7 (8.7)	1
10.03 (9.76)		O-S
15.7 (15.75)	16.5 (16.5)	3
20.0 (20.0)		1-S
23.6 (23.5)	24.0 (24.0)	5
30.1 (30.0)		2-S
31.5 (31.5)	34.0 (34.0)	7
39.4 (39.3)		9

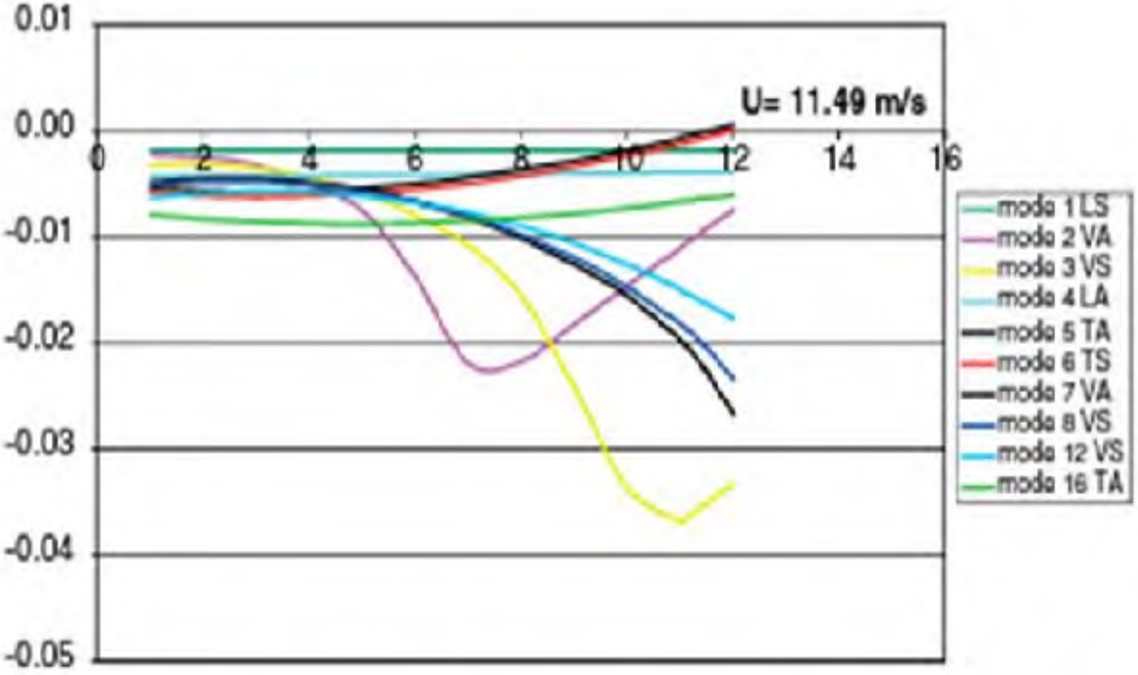


Figure Evolution of α in comparison with U using 10 modes.

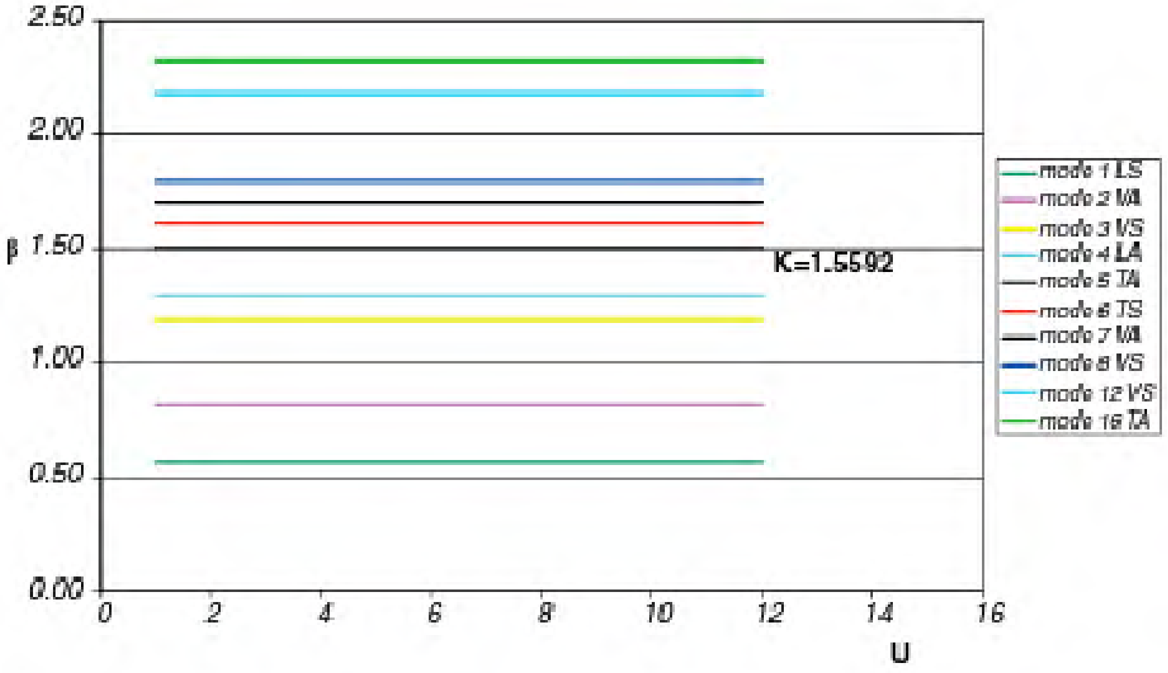


Figure Evolution of β in comparison with U using 10 modes.

Comparison between analysis and measurement on Original Tacoma Bridge

Analyses	**U(m/s)**
Jurado, 2modes$\xi = 0.00318$	11.49
Jurado, 10modes $\xi = 0.00318$	11.49
Scanlan torsional flutter $\xi = 0.003$	7.60
Scanlan torsional flutter $\xi = 0.010$	10.23
Farquharson real collapse	18.77

Flutter Solution by Prof. Scanlan

- *Single-degree-of-freedom torsional flutter*

$$I\left[\ddot{\alpha} + 2\zeta_{\alpha}\omega_{\alpha}\dot{\alpha} + \omega_{\alpha}^{2}\alpha\right] = F(\alpha,\dot{\alpha}),$$

$$F(\alpha,\dot{\alpha}) = A_{2}\dot{\alpha} + A_{3}\alpha,$$

Non-dimensional Form:

$$F(\alpha,\dot{\alpha}) = \tfrac{1}{2}\rho U^{2}(2B^{2})\left[KA_{2}^{*}(B\dot{\alpha}/U) + K^{2}A_{3}^{*}\alpha\right],$$

Flutter Derivatives by Scanlan

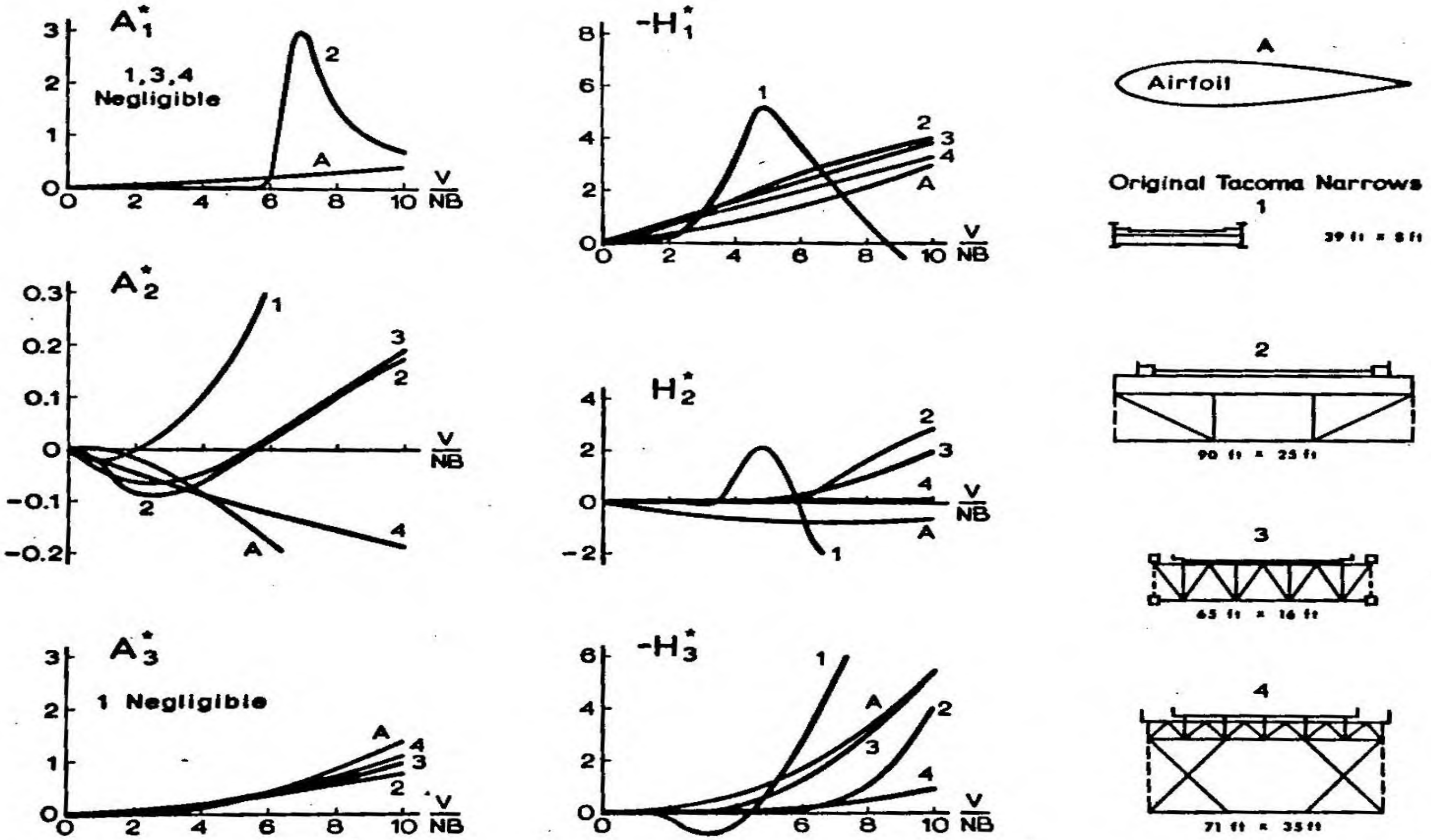
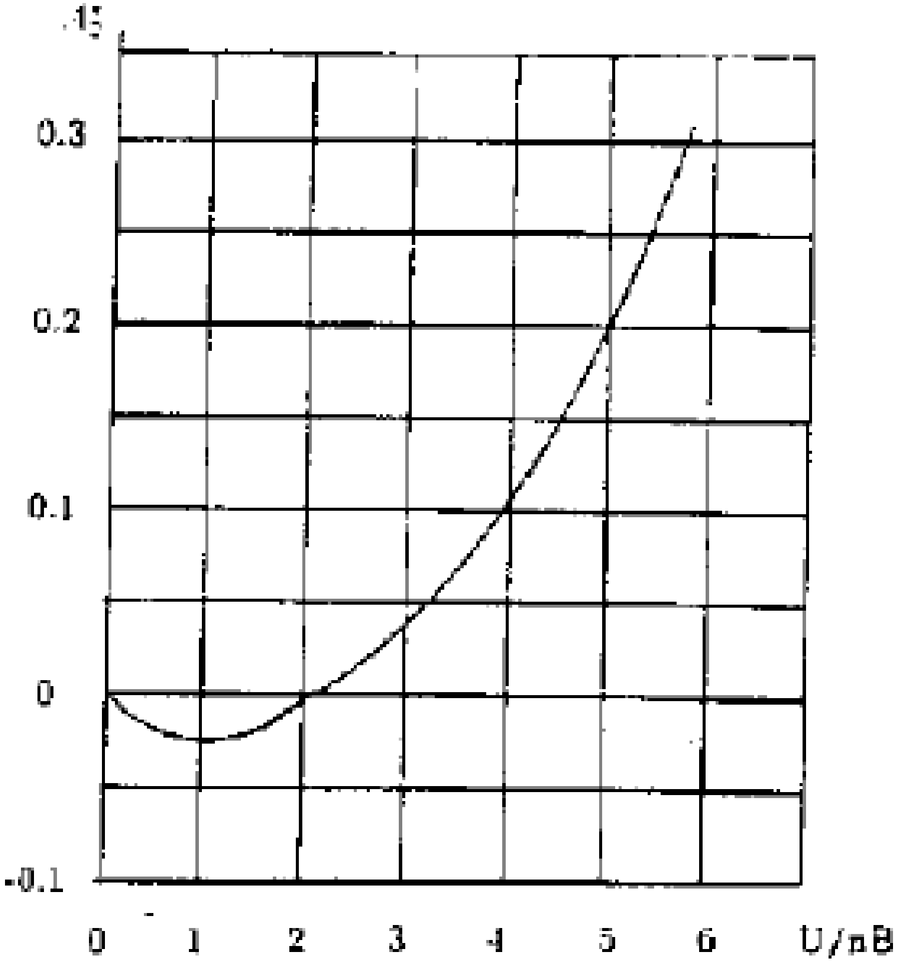


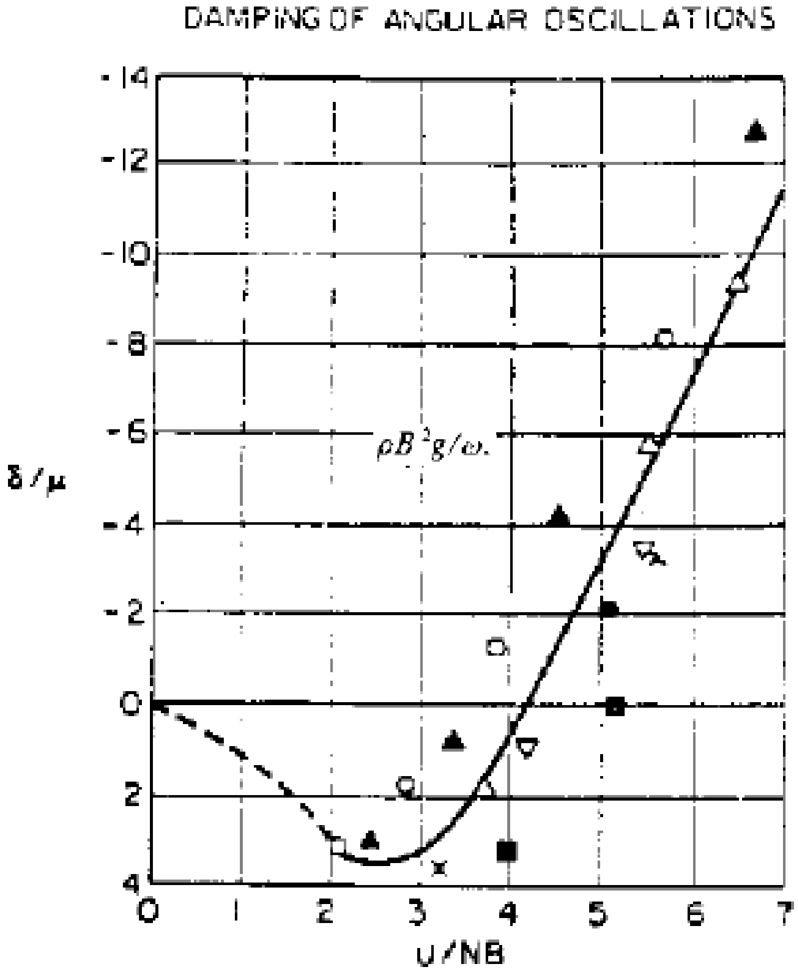
FIGURE 3.2

AERODYNAMIC COEFFICIENTS

Flutter derivatives A_2^*

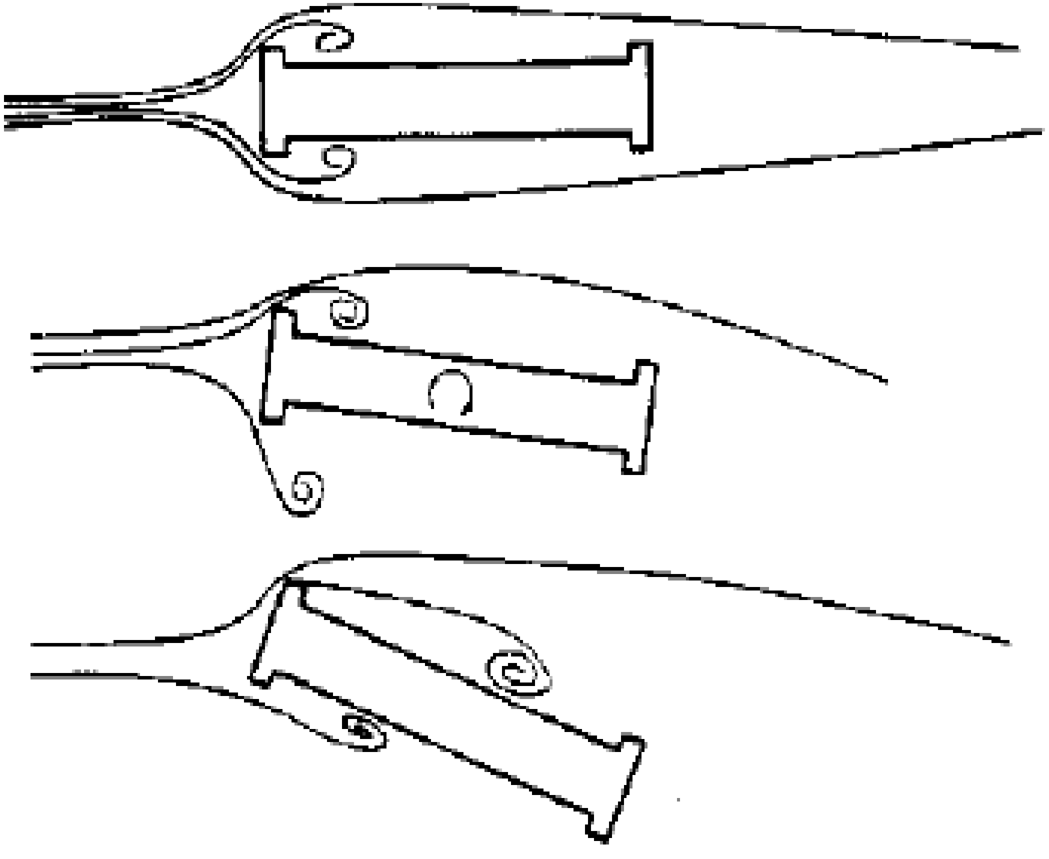


Karman & Dunn



μ : Mass Ratio $\rho B^2 g/\omega.$ Ω : weight/foot

Vortex Pattern over Rotating Deck Section drawn by Scanlan



Dimension of Tacoma Narrows Bridge

m = 4.249 t/m

r (Rotation Radius): 4.573 m

g (Gravity) 9.8 m/s2

I (Polar moment) 178 tm2/m

ρ （Air density）0.00123 t/m3

B = 11.89 m

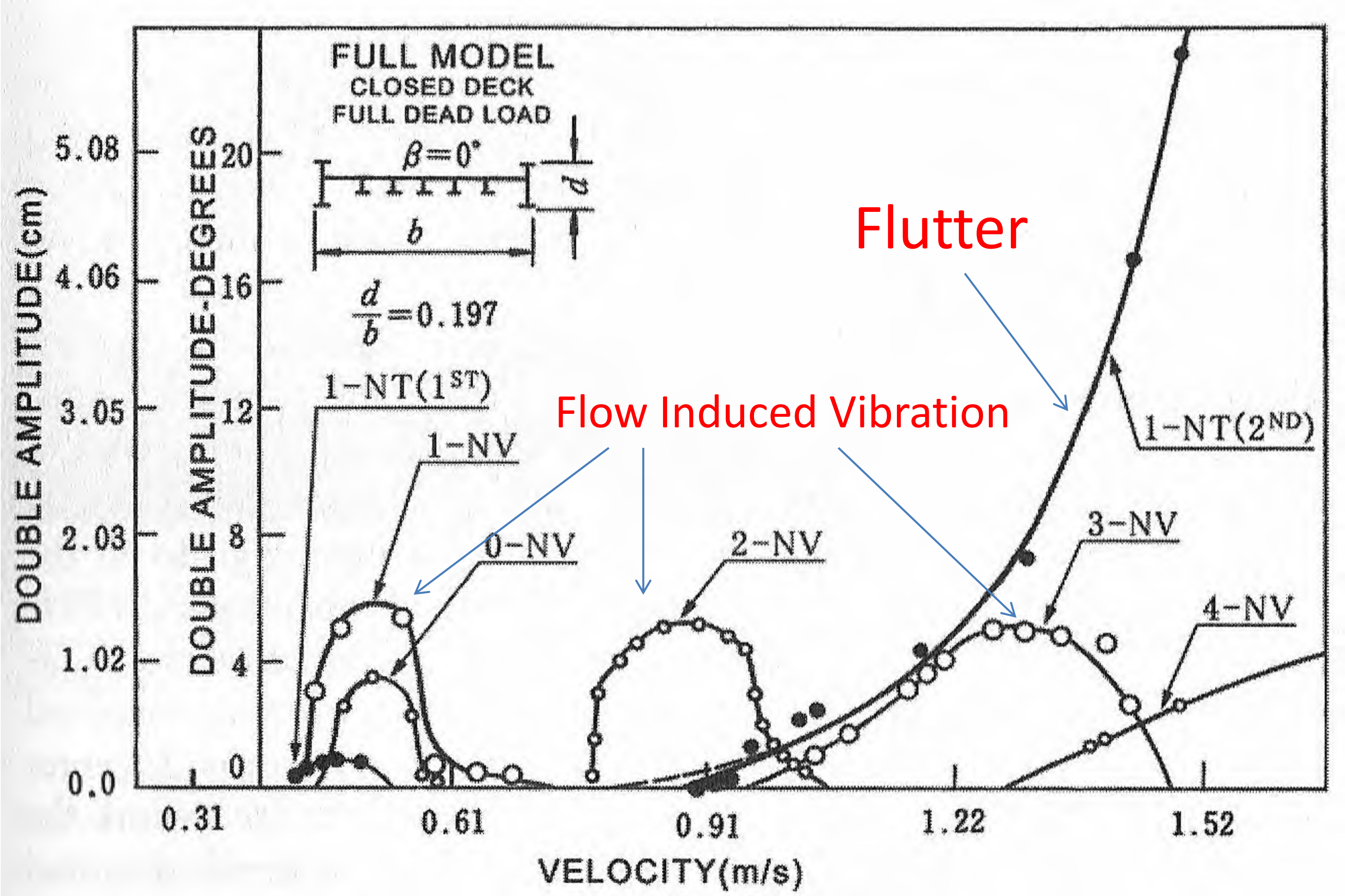
$$(A_2^*)_{crit} = 2I\zeta_\alpha/\rho B^4,$$

$$= \quad 14.48\zeta_\alpha .$$

OTN flutter conditions as a function of Mechanical damping

ζ_n	A_2^*	U/nB	Proto Type Velocity U_{cr} (m/s)
0.003	0.043	3.20	7.6
0.005	0.072	3.50	8.3
0.010	0.145	4.30	10.2
0.015	0.217	5.15	12.2
0.020	0.290	5.75	30.6

Results of Wind Tunnel Tests of Original Tacoma Bridge



Flutter

Flow Induced Vibration

The results of wind tunnel tests

- !-NT(2nd) Ucr = 0.99 m/s x √50
  = 7.0 m/s …… Proto-Type

▪ f_{model} = 1.44 Hz
$f_{proto\text{-}type}$ = 1.44/ √50
= 0.20 Hz …… The same value
of observation

■ 2.20 m/s x √50 = 15.6 m/s

Original Tacoma Bridge was collapsed at ■.

Conclusion

- The cause of the collapse of original Tacoma Narrow Bridge was flutter.
- Prof.R.H.Scalan made clear it by using aero-dynamic theory.
- Flutter is destructive phenomena, therefore we must check that it will not occur below wind design speed.