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Mechanics Research, Inc.
15 North Broadway
Tacoma, Washington 98403

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16. ABSTRACT

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Total structural response stresses are summed and compared vs. a linear cyclic fatigue damage accumulation criterion. For the three steel structures considered, wind induced vibrations produce negligible reduction in service life. As a part of this study, a general computer program has been developed to predict stress responses of signal and luminaires to wind effects.

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Prepared by: Mechanics Research, Inc.
15 North Broadway
Tacoma, Washington 98403

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Phase 1

Aerodynamically Induced Stresses in Traffic Signals and Luminaire Supports

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Prepared by:

R. C. Lundquist

K. Diane Johnson

M. C. C. Bampton

Reviewed and Approved by:

R. T. Haelsig, R.C.E. No. 16538
Director, Mechanics Research, Inc.

MECHANICS RESEARCH INC.

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ABSTRACT

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KEY WORDS :

Computers
Drag Coefficients
Drag Forces
Dynamic Analysis
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Fatigue Effects
Finite Element Methods
Frequencies
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Gust Loads
Linear Damage Accumulation
Luminaires
Modal Analysis
Mode Shapes
Random Wind Loads
Simulated Wind Data
Static Wind Loads
Static Wind Stresses
Stiffness Methods
Stress Analysis Methods
Structural Analysis
Traffic Signals
von Karman Wind Effects
Vortex Shedding Loads
Wind Effects
Wind Idealizations

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Appendix B - WEFFLS Computer Program User Manual		Separately Bound

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I. INTRODUCTION & SUMMARY

I.1 Description of Problem

This research study for the California Division of Highways considers the aerodynamic and structural dynamic behavior of traffic signal and luminaire support responses to wind induced vibrations. A computer program has been developed to automatically evaluate these combined effects upon the service life of these structures.

The broad objectives of this study are:

- Development and checkout of an analytic tool for the prediction of stresses, deflections and dynamic responses of all elements of the support structure caused by aerodynamically induced forces.
- An assessment of several existing California traffic signal and lighting standards for structural design adequacy under wind loadings;
- Development of detail background data for preparation of an improved rational design criteria for traffic signals and luminaire supports.

The need for this study results from three factors:

- The present design criteria are largely empirical, and are based on physical testing, experience and design guidelines furnished by fabricators.
  - A static wind load criterion is utilized whereas the actual wind loading is dynamic.
- One type of luminaire supports in California have failed or exhibited distress due to fatigue produced by wind induced vibrations.
  - Extensive repairs of cracked tubular metal columns have been required. Collapse of such a standard would constitute a distinct safety hazard.
- Longer and more flexible standards and poles are being utilized.
  - Recent emphasis on highway safety has resulted in increased setback of signal and luminaire supports from the edge of

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pavement, so that longer, more flexible arms are required. furthermore, a possible substitution of aluminum in lieu of steel in future designs will result in more flexible structures.

I.2 Analytic Approach

Design of the majority of existing civil engineering structures for wind loadings has been based on equivalent static loading criteria, because only limited data was available concerning aerodynamic effects. Most of these structures have been stiff enough to exhibit little coupling with the aerodynamically applied wind forces. Some notable exceptions have included the first Tacoma Narrows Bridge, which failed catastrophically when a windstorm characterized by heavy gusts induced intolerable undulations in the structure.

Recent refinements in design methods, which have produced structures with increased flexibility and smaller margins of excess strength, have been paralleled by rapid increases in the understanding of aerodynamic effects. For these reasons, sound contemporary engineering can and should consider the coupled effects of aerodynamics, structural dynamics and strength.

The developed analysis method of traffic signals and luminaire supports considers these coupled effects.

The two dynamic forces of concern in a wind response study are drag and vortex shedding. Drag produces a force parallel to the direction of wind flow. Vortex shedding produces a force perpendicular to the direction of wind flow. The drag force is best represented by a mean force about which some randomly distributed gust fluctuation occurs. The vortex shedding force is best described by a steady state force related to the mean wind velocity. While this representation of vortex shedding ignores the unsteady component due to the random variation of wind velocity, it is as accurate as current state-of-the-art methods of prediction allow.

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The overall approach for the analysis is shown in Figure I-1. The computer program performs the entire analysis in a single pass. The starting point for a wind response analysis is to assume a mean wind velocity, then proceed through all analysis steps to obtain critical stresses for the three resultant load regimes: static, steady-state dynamic and random dynamic. Fatigue and useful life assessments may be determined from these stresses. Thus, for each selected mean wind velocity, the "consumed" or expended useful life of the structure can be determined for each unit of time during which this velocity exists, and the total useful life of the structure in a given geographical location may be determined if the wind velocity characteristics of the location are known.

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Flow Plan - Computer Program to Evaluate Wind Forces on Traffic Signals and Standards

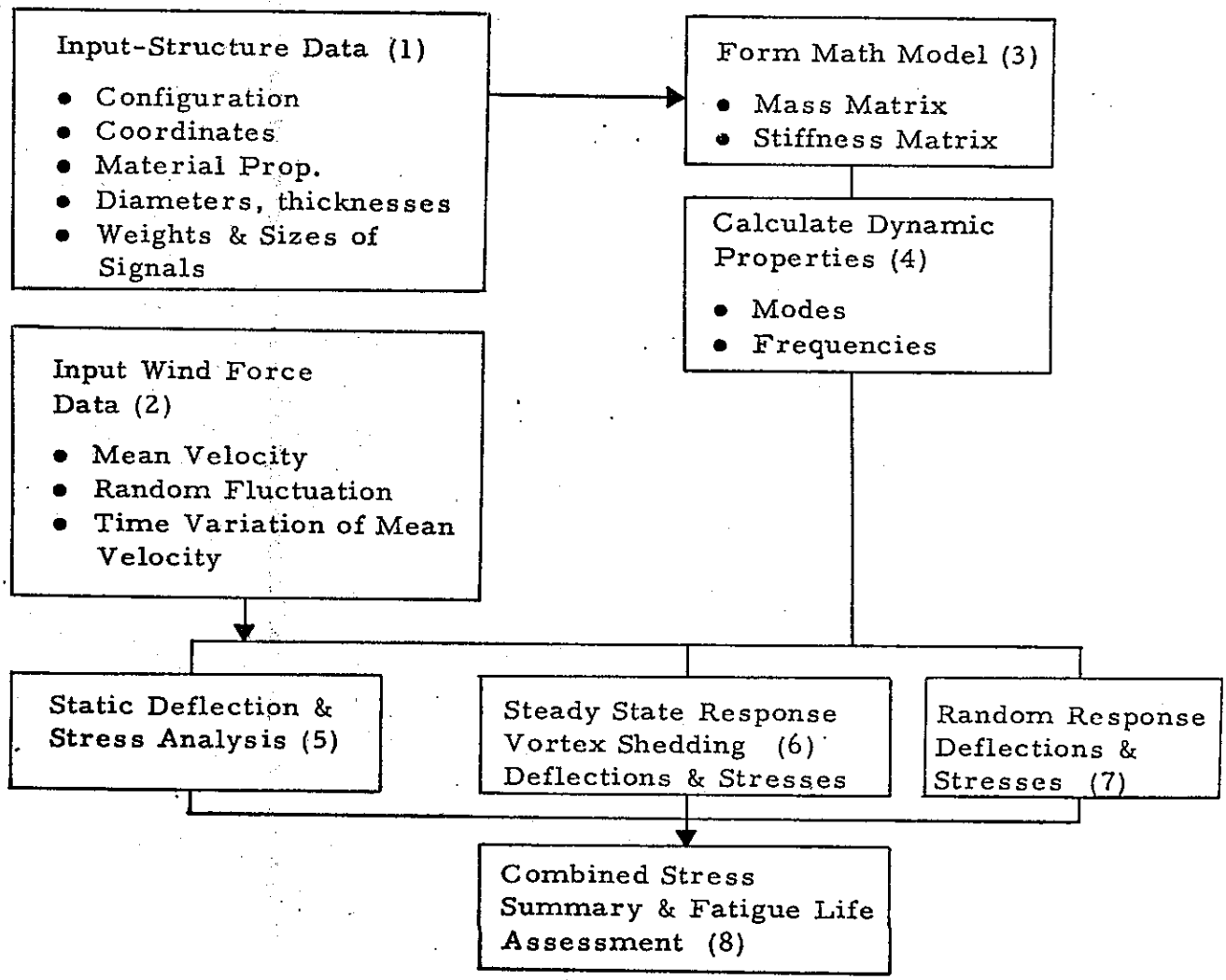

Figure I-1

Wind Force Computer Program

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I.3 Summary of Results

I.3.1 Key Findings

For the three analyzed structures (Traffic Signal and Lighting Standard Types XXI, XIX, XXVI), reference 2, the following outlines the key findings of this investigation.

1. All static and dynamic stresses for a typical fifty year period were found to be less than the endurance limit for carbon steel (26 ksi).
3. RMS random dynamic stresses resulted almost entirely from the first mode of the structure.
4. The interaction of the vonKarman vortex shedding forces with the natural modes of the structure was of a localized nature since all points of the structure were always loaded at different frequencies. This was due to the variation in diameter of the pole and variation of the wind velocity with height.

I.3.2 Conclusions

1. The vortex shedding stresses calculated in Reference 1 are rather conservative. The velocity causing excitation of the vonKarman vortex shedding phenomena is strongly dependent upon the specific diameter of the section in a tapered system. Only a slight portion of the body is subjected to a "tuned" steady state excitation. Hence, the applied generalized force is reasonably small.
2. Dynamic stresses for materials other than steel could be significant. The natural frequencies of an aluminum structure would be $1\sqrt{3}$ times the natural frequencies of a similar steel structure, and the random and steady state response would increase as can be seen from the analyses in Sections V.2 and V.3.
3. The design of the analyzed standards is adequate.

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I.3.3 Recommendations

1. A parametric study using the developed computer program to evaluate the adequacy of present design guidelines for various materials and various lighting standards.

2. A test program to verify the results and key assumptions of this analysis.

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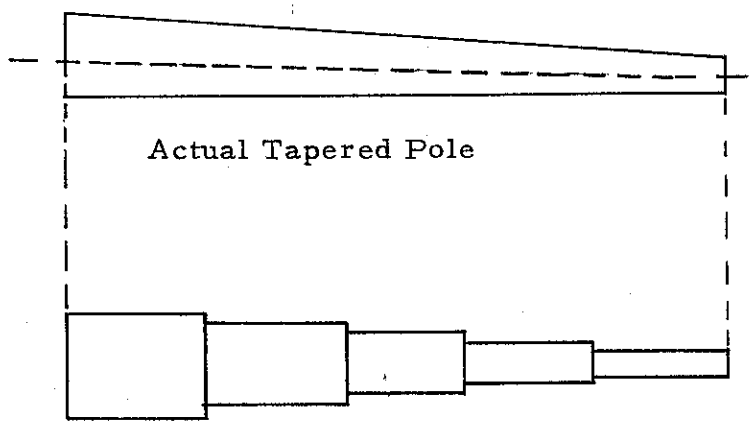
II. STRUCTURE IDEALIZATION AND MODELING

II.1 Analytic Assumptions

The response of the traffic signal/luminaire is determined utilizing finite element stiffness methods of analysis. In this method the pole and arm elements of the structure are subdivided into discrete uniform beam "elements". Each of these beam elements is assumed weightless, and all (inertia) and forces are concentrated at "node" points defining the ends of the beam elements. Where poles and arms taper, the taper is approximated by a series of uniform segments, as shown below.



Idealized Pole

A right handed global cartesian coordinate system is used to describe the structure geometry. The base of the pole, Node 1, is assumed as the origin. The analysis employs an X1, X2, X3 notation to describe these three coordinate axes. X3 is aligned with the pole vertical axis and directed upward from the base. X2 is aligned perpendicular to the plane of pole and arm. X1 is in the plane of the pole and arm and directed from the base outward in the direction of the arm tip.

The global coordinate axes are illustrated in Figure II.1.

Local element coordinate axes are employed to describe beam element end forces. This coordinate system is also illustrated in Figure II.1 for pole and arm members. ξ_1 is tangent to the beam element, directed from root to tip. ξ_2 and ξ_3 are perpendicular to ξ_1 and each other.

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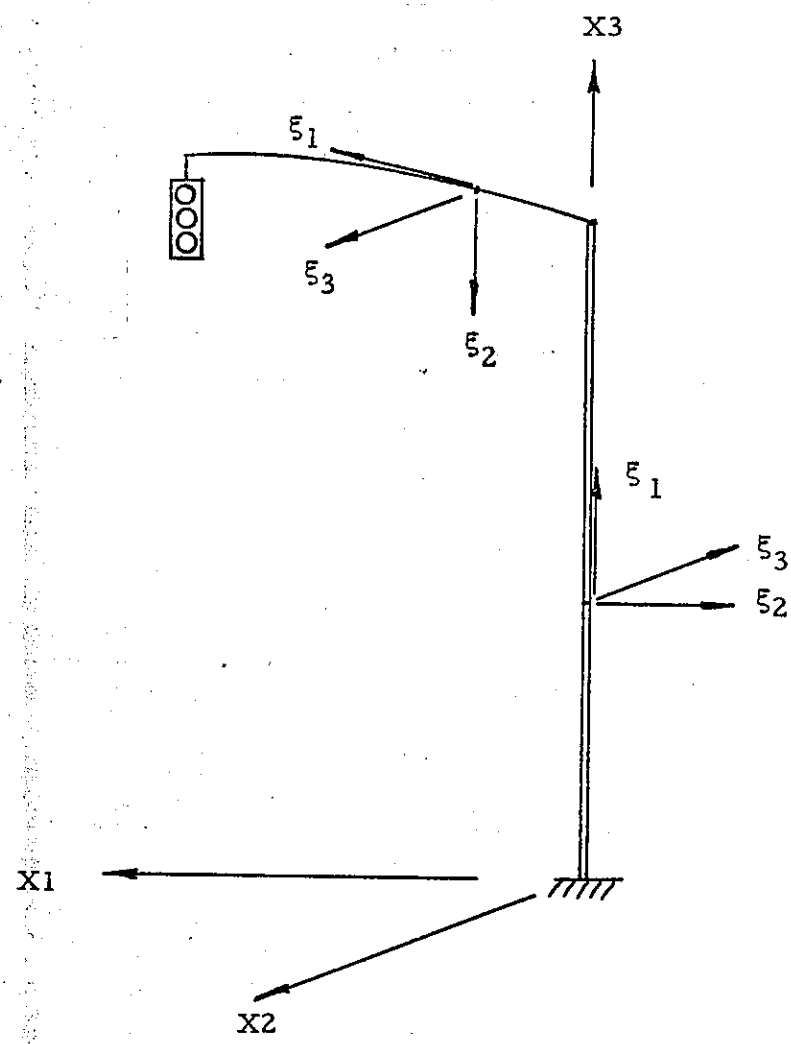

Figure II. 1 - Global and Local Coordinate Axes

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ξ_3 is always perpendicular to the plane of the pole and arm. For the pole, ξ_3 is opposite to X2; for the arms, ξ_3 is in the same direction as X2. Beam element end forces employ the ξ coordinate system and end A & B designations. Beam end A is closest to the root; end B is closest to tip.

The structure possesses a full six degrees of freedom at each node point. Translatory inertias (masses) are assigned to each of the three translatory degrees of freedom. Rotational inertias (mass moments of inertia) are considered only for signs and signals; and these are considered only for mass moments about axes X1 and X2. Forces are applied and treated in a similar fashion.

II. 2 Engineering Models

Models of traffic signal and lighting standards, Types XXI (Dwg. ES-17-5),* XIX (Dwg. ES-14-5), and XXVI (Dwg. ES-20-1) are shown in Figures II-2, II-3 and II-4, respectively. The individual nodal coordinates for each model are shown in Tables II-1, II-2 and II-3 respectively. Tables II-4, II-5 and II-6 present a tabulation of individual member properties for each structure. In this analysis, a modulus of elasticity of $E=30 \times 10^6$ psi and Poisson's ratio of $\nu = .3$ were used.

* Drawing numbers refer to Reference 2.

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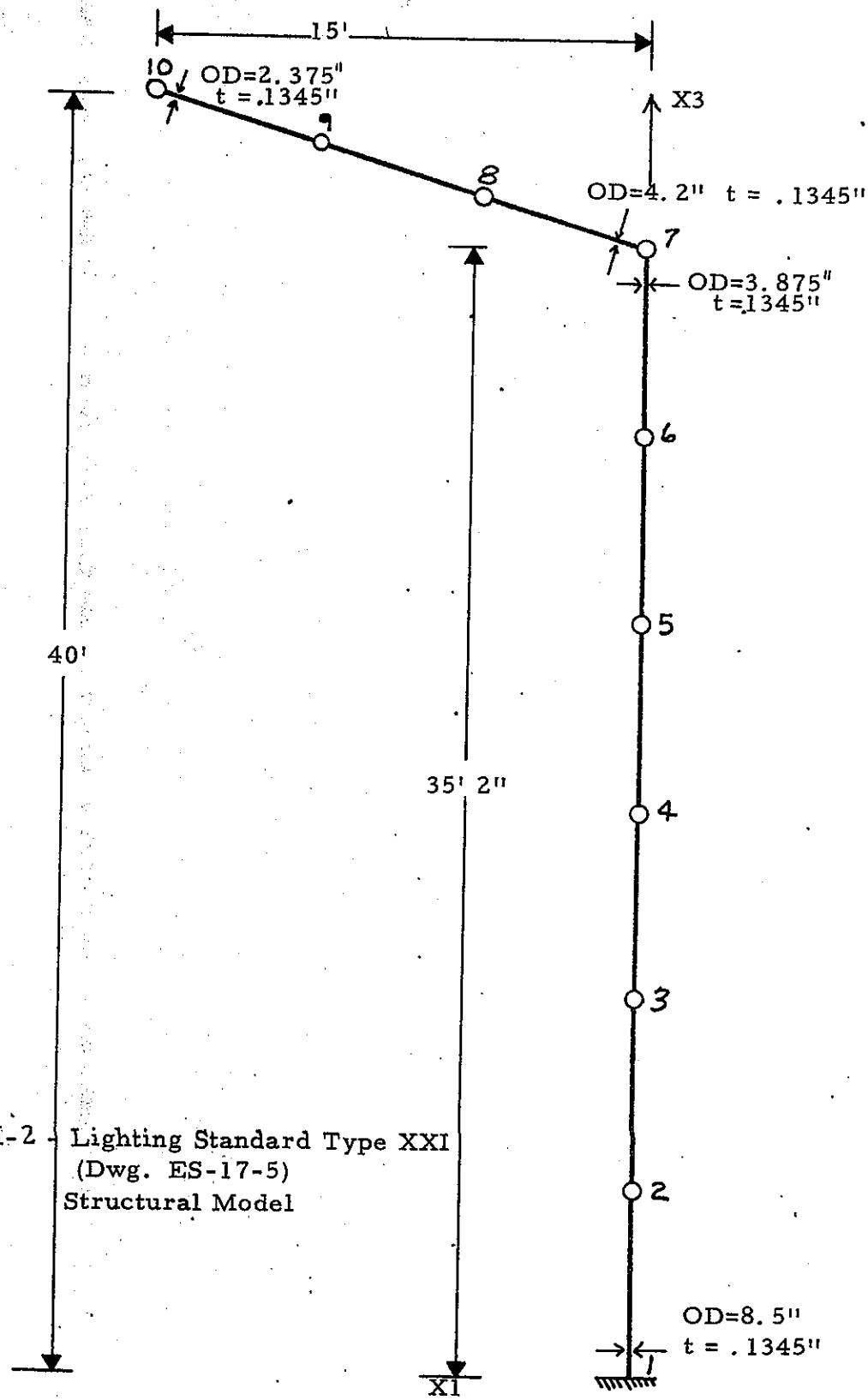

Figure II-2 - Lighting Standard Type XXI
(Dwg. ES-17-5)
Structural Model

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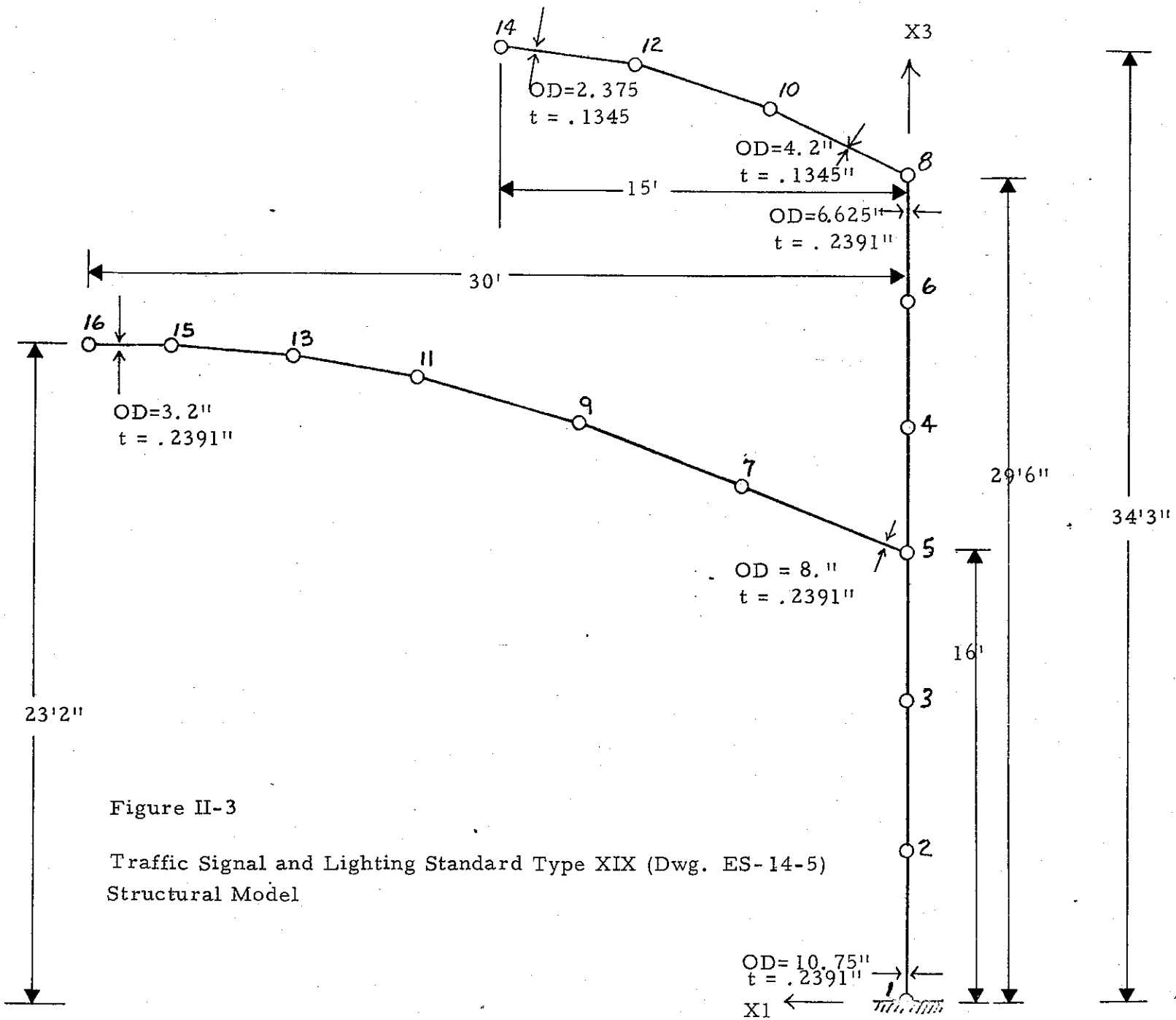

Figure II-3

Traffic Signal and Lighting Standard Type XIX (Dwg. ES-14-5)
Structural Model

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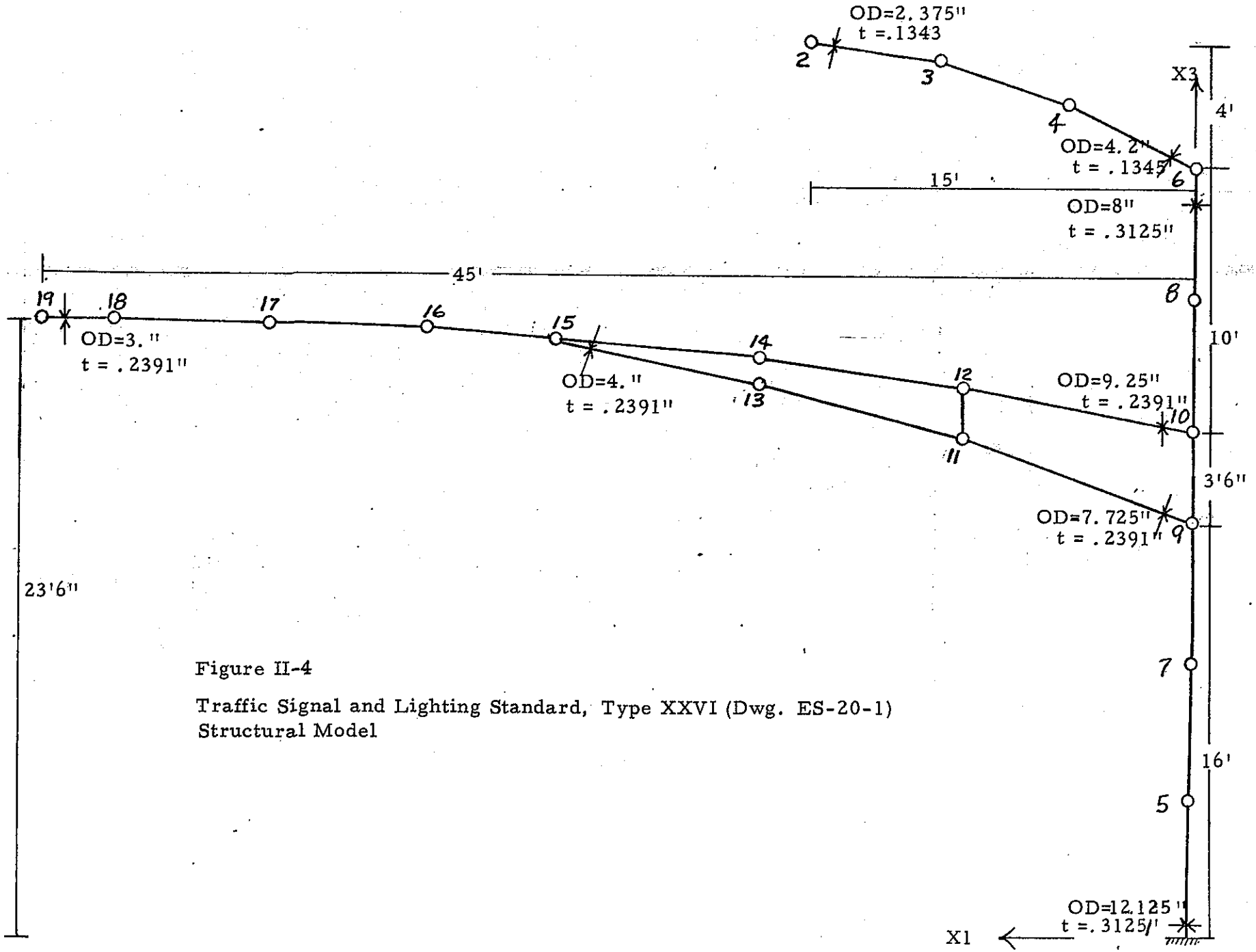

Figure II-4

Traffic Signal and Lighting Standard, Type XXVI (Dwg. ES-20-1)
Structural Model

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Each node has inertia in the three translational directions (X1, X2, X3). With the exception of the rotational inertia of signs and signals whose centers of gravity do not correspond with the centers of gravity of the nodes they are attached to, no rotational inertia terms have been included, because their effects are negligible with the fineness of the finite element grid used. Tables II-7, II-8 and II-9 present the nodal distribution of weight for each structure. For each structure, Node 1 has been assumed to be fully restrained in all translational and rotational directions, (i.e., the structure is cantilevered from Node 1, the foundation attachment location). All other nodes are allowed movement in all directions.

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JOINT COORDINATES (Inches)(See Figure II-1)

Joint	X1	X2	X3
1	0.	0.	0.
2	0.	0.	7.030000E+01
3	0.	0.	1.407000E+02
4	0.	0.	2.110000E+02
5	0.	0.	2.813000E+02
6	0.	0.	3.517000E+02
7	0.	0.	4.220000E+02
8	6.000000E+01	0.	4.413000E+02
9	1.200000E+02	0.	4.607000E+02
10	1.800000E+02	0.	4.800000E+02

Table II-1
Node Coordinates
Lighting Standard Type XXI

JOINT COORDINATES (Inches) (See Figure II-2)

Joint	X1	X2	X3
1	0.	0.	0.
2	0.	0.	6.400000E+01
3	0.	0.	1.280000E+02
4	0.	0.	2.460000E+02
5	0.	0.	1.920000E+02
6	0.	0.	3.000000E+02
7	7.200000E+01	0.	2.200000E+02
8	0.	0.	3.540000E+02
9	1.440000E+02	0.	2.470000E+02
10	6.000000E+01	0.	3.820000E+02
11	2.160000E+02	0.	2.660000E+02
12	1.200000E+02	0.	4.010000E+02
13	2.700000E+02	0.	2.750000E+02
14	1.800000E+02	0.	4.110000E+02
15	3.240000E+02	0.	2.780000E+02
16	3.600000E+02	0.	2.780000E+02

Table II-2
Node Coordinates

Traffic Signal and Lighting Standard Type XIX

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JOINT COORDINATES (Inches) (See Figure II-3)

Joint	X1	X2	X3
1	0.	0.	0.
2	1.800000E+02	0.	4.104000E+02
3	1.200000E+02	0.	4.020000E+02
4	6.000000E+01	0.	3.828000E+02
5	0.	0.	6.400000E+01
6	0.	0.	3.540000E+02
7	0.	0.	1.280000E+02
8	0.	0.	2.940000E+02
9	0.	0.	1.920000E+02
10	0.	0.	2.340000E+02
11	1.080000E+02	0.	2.304000E+02
12	1.080000E+02	0.	2.532000E+02
13	2.040000E+02	0.	2.544000E+02
14	2.040000E+02	0.	2.664000E+02
15	3.000000E+02	0.	2.736000E+02
16	3.600000E+02	0.	2.784000E+02
17	4.330000E+02	0.	2.802000E+02
18	5.060000E+02	0.	2.820000E+02
19	5.400000E+02	0.	2.820000E+02

Table II-3

Node Coordinates
Traffic Signal and Lighting Standard Type XXVI

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MEMBER PROPERTIES (See Figure II-1)

BAR NO.	JT A	JT B	AREA	J	I2	I3	SF2	SF3
1	1	2	33.74E-01	54.00E+00	27.00E+00	27.00E+00	50.00E-02	50.00E-02
2	2	3	30.53E-01	39.99E+00	19.99E+00	19.99E+00	50.00E-02	50.00E-02
3	3	4	27.32E-01	28.67E+00	14.33E+00	14.33E+00	50.00E-02	50.00E-02
4	4	5	24.11E-01	19.63E+00	98.15E-01	98.15E-01	50.00E-02	50.00E-02
5	5	6	20.90E-01	12.79E+00	63.94E-01	63.94E-01	50.00E-02	50.00E-02
6	6	7	17.69E-01	77.54E-01	38.77E-01	38.77E-01	50.00E-02	50.00E-02
7	7	8	15.91E-01	56.47E-01	28.23E-01	28.23E-01	50.00E-02	50.00E-02
8	8	9	13.33E-01	33.25E-01	16.63E-01	16.63E-01	50.00E-02	50.00E-02
9	9	10	10.76E-01	17.47E-01	87.40E-02	87.40E-02	50.00E-02	50.00E-02

Table II-4 - Member Properties Lighting Standard Type XXI

MEMBER PROPERTIES (See Figure II-2)

BAR NO.	JT A	JT B	AREA (in^2)	J (in^4)	I2 (in^4)	I3 (in^4)	SF2	SF3
1	1	2	76.45E-01	19.67E+01	98.33E+00	98.33E+00	50.00E-02	50.00E-02
2	2	3	70.66E-01	15.65E+01	78.27E+00	78.27E+00	50.00E-02	50.00E-02
3	3	5	65.75E-01	12.51E+01	62.54E+00	62.54E+00	50.00E-02	50.00E-02
4	4	5	60.32E-01	96.59E+00	48.30E+00	48.30E+00	50.00E-02	50.00E-02
5	4	6	55.64E-01	75.88E+00	37.94E+00	37.94E+00	50.00E-02	50.00E-02
6	5	7	54.89E-01	72.79E+00	36.40E+00	36.40E+00	50.00E-02	50.00E-02
7	6	8	50.97E-01	58.32E+00	29.16E+00	29.16E+00	50.00E-02	50.00E-02
8	7	9	47.65E-01	47.65E+00	23.83E+00	23.83E+00	50.00E-02	50.00E-02
9	8	10	15.46E-01	51.40E-01	25.70E-01	25.70E-01	50.00E-02	50.00E-02
10	9	11	40.41E-01	29.10E+00	14.55E+00	14.55E+00	50.00E-02	50.00E-02
11	10	12	13.25E-01	32.34E-01	16.17E-01	16.17E-01	50.00E-02	50.00E-02
12	11	13	33.93E-01	17.22E+00	86.11E-01	86.11E-01	50.00E-02	50.00E-02
13	12	14	10.33E-01	16.52E-01	82.60E-02	82.60E-02	50.00E-02	50.00E-02
14	13	15	28.20E-01	99.04E-01	49.52E-01	49.52E-01	50.00E-02	50.00E-02
15	15	16	23.98E-01	61.00E-01	30.50E-01	30.50E-01	50.00E-02	50.00E-02

Table II-5 - Member Properties Traffic Signal and Lighting Standard Type XIX

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MEMBER PROPERTIES (See Figure II-3)

BAR NO.	JT A	JT B	AREA (in^2)	J (in^4)	I2 (in^4)	I3 (in^4)	SF2	SF3
1	1	5	11.15E+00	36.58E+01	18.29E+01	18.29E+01	50.00E-02	50.00E-02
2	2	3	10.30E-01	16.52E-01	82.60E-02	82.60E-02	50.00E-02	50.00E-02
3	3	4	13.69E-01	33.39E-01	16.69E-01	16.69E-01	50.00E-02	50.00E-02
4	4	6	15.29E-01	53.84E-01	26.92E-01	26.92E-01	50.00E-02	50.00E-02
5	5	7	10.43E+00	29.93E+01	14.97E+01	14.97E+01	50.00E-02	50.00E-02
6	6	8	81.43E-01	13.38E+01	66.87E+00	66.87E+00	50.00E-02	50.00E-02
7	7	9	10.03E+00	25.01E+01	12.51E+01	12.51E+01	50.00E-02	50.00E-02
8	8	10	85.60E-01	16.56E+01	82.78E+00	82.78E+00	50.00E-02	50.00E-02
9	9	10	91.26E-01	20.05E+01	10.03E+01	10.03E+01	50.00E-02	50.00E-02
10	9	11	51.27E-01	59.34E+00	29.67E+00	29.67E+00	50.00E-02	50.00E-02
11	10	12	63.20E-01	11.11E+01	55.53E+00	55.53E+00	50.00E-02	50.00E-02
12	11	12	33.75E-01	15.40E-02	39.55E-03	22.78E+00	67.00E-02	67.00E-02
13	11	13	41.62E-01	31.76E+00	15.88E+00	15.88E+00	50.00E-02	50.00E-02
14	12	14	54.28E-01	70.43E+00	35.21E+00	35.21E+00	50.00E-02	50.00E-02
15	13	15	32.72E-01	15.46E+00	77.28E-01	77.28E-01	50.00E-02	50.00E-02
16	14	15	45.83E-01	42.42E+00	21.21E+00	21.21E+00	50.00E-02	50.00E-02
17	15	16	39.06E-01	26.26E+00	13.13E+00	13.13E+00	50.00E-02	50.00E-02
18	16	17	33.33E-01	16.33E+00	81.62E-01	81.62E-01	50.00E-02	50.00E-02
19	17	18	26.99E-01	86.88E-01	43.44E-01	43.44E-01	50.00E-02	50.00E-02
20	18	19	22.32E-01	49.21E-01	24.60E-01	24.60E-01	50.00E-02	50.00E-02

Table II-6 - Member Properties -Traffic Signal and Lighting Standard Type XXVI

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WEIGHTS (See Figure II-1)

JOINT	W1 (lbs)	W2 (lbs)	W3 (lbs)	W4	W5	W6
2	6.46400E+01	6.46400E+01	6.46400E+01	0.	0.	0.
3	5.81800E+01	5.81800E+01	5.81800E+01	0.	0.	0.
4	5.17300E+01	5.17300E+01	5.17300E+01	0.	0.	0.
5	4.52700E+01	4.52700E+01	4.52700E+01	0.	0.	0.
6	3.88100E+01	3.88100E+01	3.88100E+01	0.	0.	0.
7	3.36500E+01	3.36500E+01	3.36500E+01	0.	0.	0.
8	2.63600E+01	2.63600E+01	2.63600E+01	0.	0.	0.
9	2.17200E+01	2.17200E+01	2.17200E+01	0.	0.	0.
10	8.47000E+01	8.47000E+01	8.47000E+01	0.	0.	0.
TOTAL WEIGHTS=	4.25060E+02	4.25060E+02	4.25060E+02	0.	0.	0.

CENTER OF WEIGHT, X1 = 4.57206E+01 (in), X2 = 0. , X3 = 2.97663E+02 (in)

Table II-7 - Nodal Weights - Lighting Standard Type XXI

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WEIGHTS (See Figure II-2)

JOINT	W1 (lbs)	W2 (lbs)	W3 (lbs)	W4	W5	W6
2	1.34440E+02	1.34440E+02	1.34440E+02	0.	0.	0.
3	1.24340E+02	1.24340E+02	1.24340E+02	0.	0.	0.
4	8.92200E+01	8.92200E+01	8.92200E+01	0.	0.	0.
5	1.70070E+02	1.70070E+02	1.70070E+02	0.	0.	0.
6	8.20300E+01	8.20300E+01	8.20300E+01	0.	0.	0.
7	1.12490E+02	1.12490E+02	1.12490E+02	0.	0.	0.
8	6.52200E+01	6.52200E+01	6.52200E+01	0.	0.	0.
9	9.49200E+01	9.49200E+01	9.49200E+01	0.	0.	0.
10	2.68000E+01	2.68000E+01	2.68000E+01	0.	0.	0.
11	1.18400E+02	1.18400E+02	1.18400E+02	2.00000E+04	2.00000E+04	-0.
12	2.11500E+01	2.11500E+01	2.11500E+01	0.	0.	0.
13	4.81500E+01	4.81500E+01	4.81500E+01	0.	0.	0.
14	8.42600E+01	8.42600E+01	8.42600E+01	0.	0.	0.
15	7.90400E+01	7.90400E+01	7.90400E+01	0.	0.	0.
16	6.18800E+01	6.18800E+01	6.18800E+01	5.12000E+04	5.12000E+04	-0.
TOTAL WEIGHTS=	1.31241E+03	1.31241E+03	1.31241E+03	7.12000E+04	7.12000E+04	0.

CENTER OF WEIGHT, X1 = 9.71809E+01(in) X2 = 0. , X3 = 2.37938E+02(in

Table II-8 - Nodal Weights - Traffic Signal and Lighting Standard Type XIX

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WEIGHTS (See Figure II-3)

JOINT	W1 (lbs)	W2 (lbs)	W3 (lbs)	W4	W5	W6
2	8.39200E+01	8.39200E+01	8.39200E+01	0.	0.	0.
3	2.12600E+01	2.12600E+01	2.12600E+01	0.	0.	0.
4	2.68800E+01	2.68800E+01	2.68800E+01	0.	0.	0.
5	1.97520E+02	1.97520E+02	1.97520E+02	0.	0.	0.
6	8.44200E+01	8.44200E+01	8.44200E+01	0.	0.	0.
7	1.87290E+02	1.87290E+02	1.87290E+02	0.	0.	0.
8	1.43310E+02	1.43310E+02	1.43310E+02	0.	0.	0.
9	2.30680E+02	2.30680E+02	2.30680E+02	0.	0.	0.
10	2.27390E+02	2.27390E+02	2.27390E+02	0.	0.	0.
11	1.53940E+02	1.53940E+02	1.53940E+02	0.	0.	0.
12	1.84890E+02	1.84890E+02	1.84890E+02	0.	0.	0.
13	1.04700E+02	1.04700E+02	1.04700E+02	0.	0.	0.
14	1.37840E+02	1.37840E+02	1.37840E+02	0.	0.	0.
15	1.42520E+02	1.42520E+02	1.42520E+02	0.	0.	0.
16	1.18420E+02	1.18420E+02	1.18420E+02	3.48480E+04	3.48480E+04	0.
17	6.29900E+01	6.29900E+01	6.29900E+01	0.	0.	0.
18	8.68300E+01	8.68300E+01	8.68300E+01	0.	0.	0.
19	6.08500E+01	6.08500E+01	6.08500E+01	4.50000E+04	4.50000E+04	0.
TOTAL WEIGHTS=	2.25565E+03	2.25565E+03	2.25565E+03	7.98480E+04	7.98480E+04	0.

CENTER OF WEIGHT, X1 = 1.30693E+02 (in) X2 = 0. , X3 = 2.37760E+02 (in)

Table II-9 - Nodal Weights - Traffic Signal and Lighting Standard Type XXVI

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III. SIMULATED WIND DATA AND FORCES

To evaluate traffic signals and lighting standards for wind force, the maximum static wind forces (static drag) and two types of dynamic forces, random dynamic drag and vortex shedding, must be considered. The drag forces act in the direction of wind flow on both cylindrical and flat plate parts of the structure; the vortex shedding loads act in the direction transverse to the wind flow on the cylindrical parts of the structure. In the following sections the detailed methods and assumptions used in calculating the above types of forces for this study are presented. Also, the resultant forces for each specific traffic signal and lighting standard are shown.

III. 1 Wind Idealization

Since the mean wind velocity variation in the lower most thousand feet of height above ground level depends mainly on surface friction, the mean wind profile depends on roughness of the terrain, rather than storm conditions. References 3, 4, 5, and 6 recommend the 1/7th power law, which has been used in this analysis to determine the wind velocity at all elevations of concern, for highway type terrain. The 1/7th power law is:

$$V_Z = V_{30} \left(\frac{Z}{30} \right)^{1/7}$$

in which Z is the height above ground, V_Z is the wind speed at Z, and V_{30} is the wind speed at 30 ft.

In the fatigue analysis it is necessary to know the number of occurrences of extreme wind velocities for the required life of the structure. Figures III-1 and III-2 show the extreme mile wind velocities of the U.S. at 30 feet above the ground for a two-year and 50-year mean recurrence interval, respectively.

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The term, mile wind velocity, is defined as the average velocity of the wind averaged over the period of time it takes one mile of wind to pass by the wind speed indicator.

The recurrence interval for other mile wind velocities can be determined from the extreme mile wind velocities for two-year and 50-year intervals by use of a Fisher-Tippett distribution function described in References 3 and 4. The Fisher-Tippett distribution function is given by:

$$F(x) = \exp\left(\frac{x}{\beta}\right)^{-\nu} \qquad \text{(Reference 3)}$$

in which x is the extreme wind velocity, β and ν are the shape parameters of Fisher-Tippett distribution, and F is the distribution function or probability that an extreme value is less than x. The mean recurrence interval, "R", is given by the relationship:

$$R = 1/[1 - F(x)] \qquad \text{(Reference 4)}$$

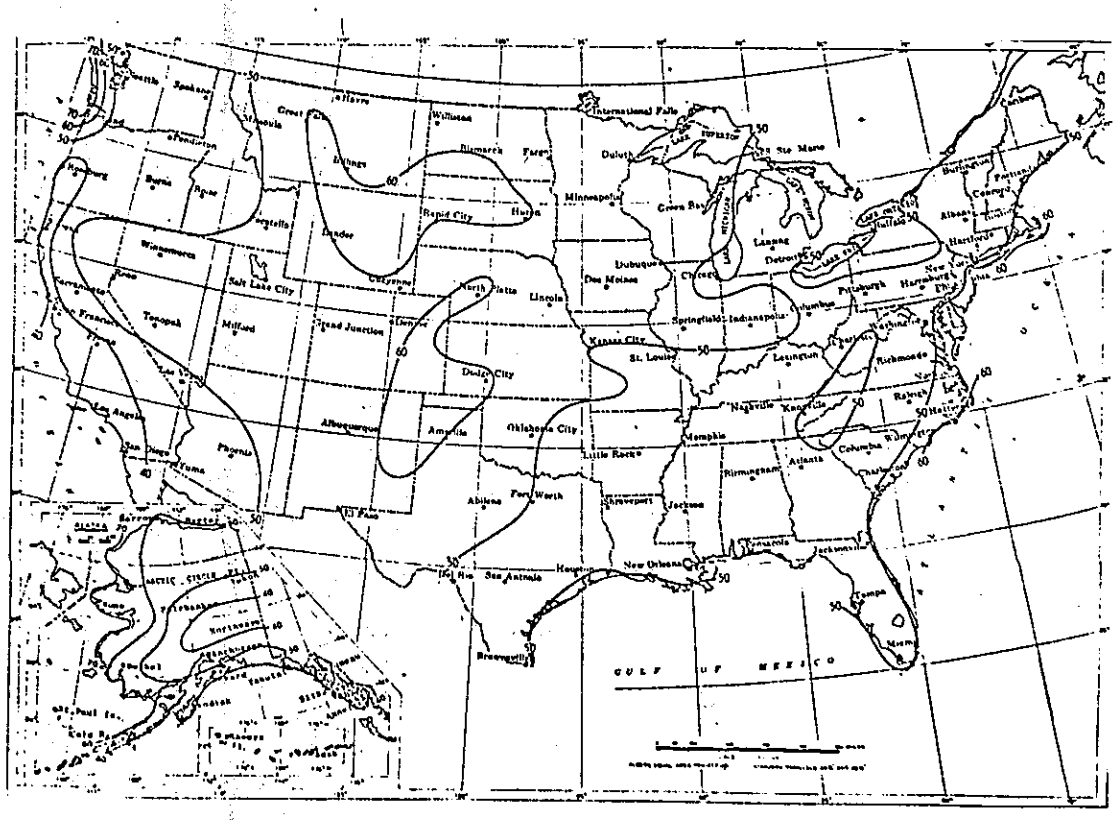

Figure III-1 - Isotach 0.50 Quantiles, in Miles per Hour: Annual Extreme - Mile 30 Ft above Ground, 2-Year Mean Recurrence Interval

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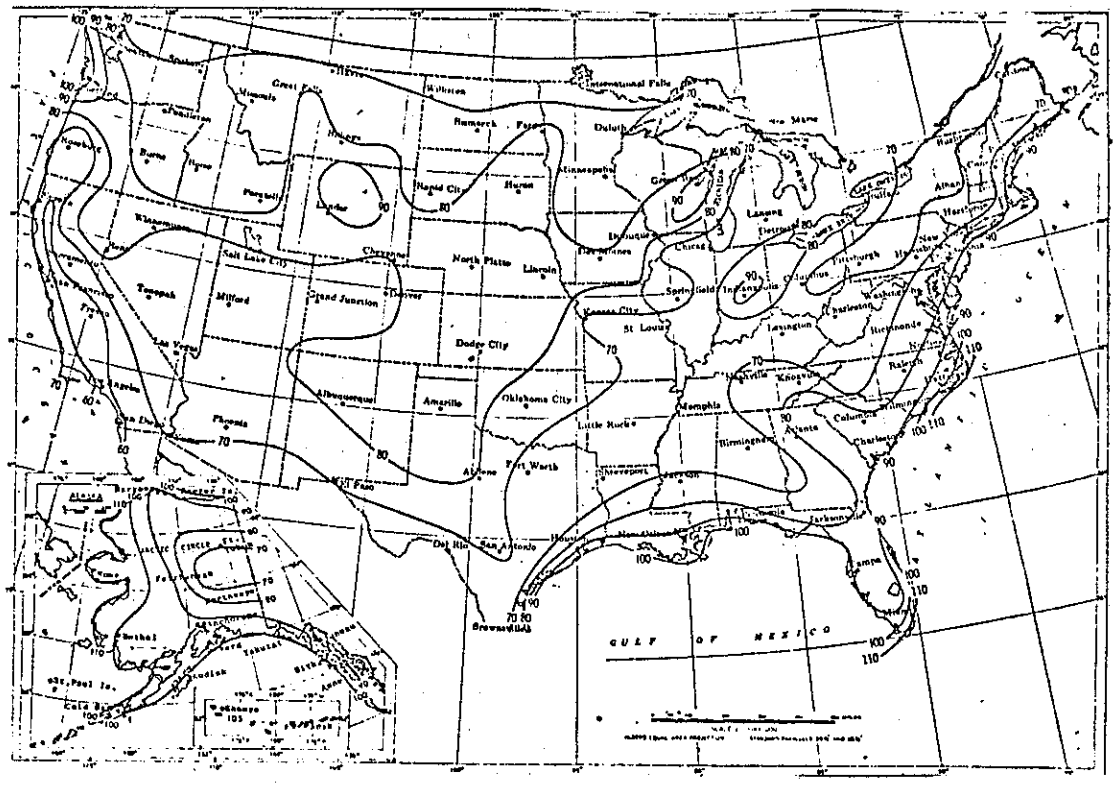

Figure III-2 - Isotach 0.02 Quantiles, in Miles per Hour: Annual Extreme-Mile 30 Ft above Ground, 50-Year Mean Recurrence Interval

Figure III-3 shows the probability paper developed in References 3 and 4 for the Fisher-Tippett distribution, Reference 4. This graph may be readily used to obtain the entire distribution function, F, and the recurrence interval, R, for any velocity. The process is to obtain the extreme wind speeds from Figures III-1 and III-2 for the desired geographical area and plot the wind velocity as a function of the recurrence interval on Figure III-3. A straight line connecting these points gives the value of R for any desired wind velocity. Based on data for the California area from Figures III-1 and III-2 and plotting it on Figure III-3 as shown, an 80 mph wind will occur once in fifty years; a 73 mph wind, twice; a 64.5 mph wind, 5 times; a 50 mph wind, 10 times; etc.

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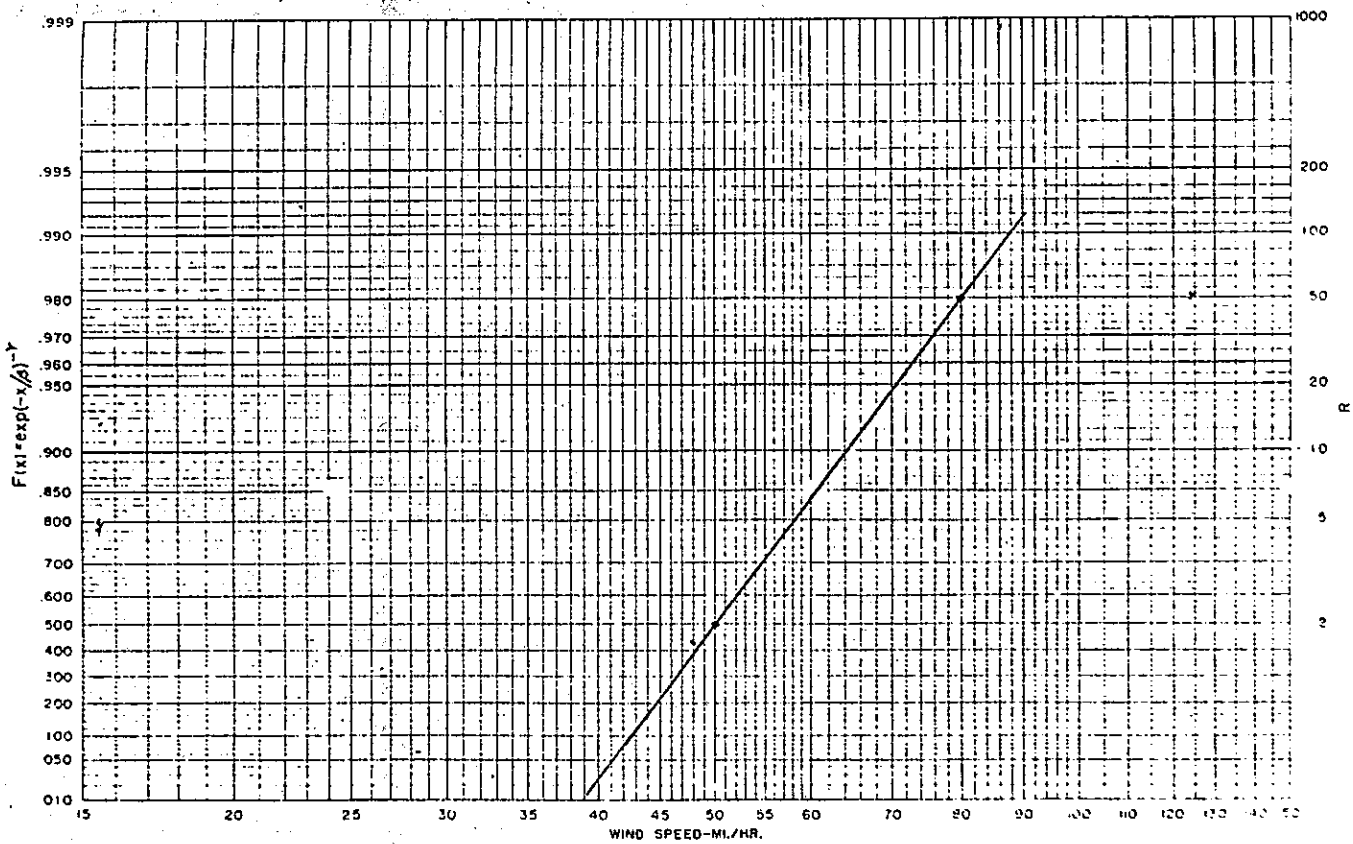

Figure III-3 - Maximum-Value Probability Paper, Fisher-Tippett Type II Distribution

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III. 2 Static Wind Loads

For the State of California, per Section III. 1, the fastest mile wind for a fifty-year mean recurrence interval is 80 mph; for a ten-year interval, 64.5 mph; and for a two-year interval, 50 mph. Applying a gust factor of 1.35, per Reference 7, to the fastest mile wind, the fastest wind speed for each of the above is as follows:

Recurrence Interval	2 years	10 years	50 years
Fastest Mile Wind	50 mph	64.5 mph	80 mph
Fastest Wind Speed	67.5 mph	87.1 mph	108 mph

The static drag forces are calculated by the following equation:

$$D = C_D \, qA,$$

where D is the drag force, C_D is the drag coefficient, A is the exposed area, and q is the dynamic pressure, which is calculated by the following equation:

$$q = 1/2 \, \rho \, V^2,$$

where V is the wind velocity and ρ is the air density. Figure III-4 shows C_D values for an infinite flat plate and for an infinite smooth cylinder in the Reynolds number range of interest, where the Reynolds number, R, in air at standard temperature and pressure, is given by:

$$R = 780 \, Vd.$$

In this equation, d is the diameter of the cylinder or width of flat plate, in inches, and V is the wind velocity in miles per hour. Drage coefficients for infinite smooth circular cylinders have been used for cylindrical sections in this problem due to their very large ℓ/d ratios. The drag coefficients for flat plates normal to the wind are constant for the Reynolds number range of interest. Table III-1 represents the drag coefficients for different A/B values (where A and B are the characteristic dimensions of the plate).

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Tables III-2, III-3 and III-4 show the detailed calculation of the static drag force for each wind speed for Type XXI (ES-17-5), Type XIX (ES-14-5) and Type XXVI (ES-20-1), respectively.

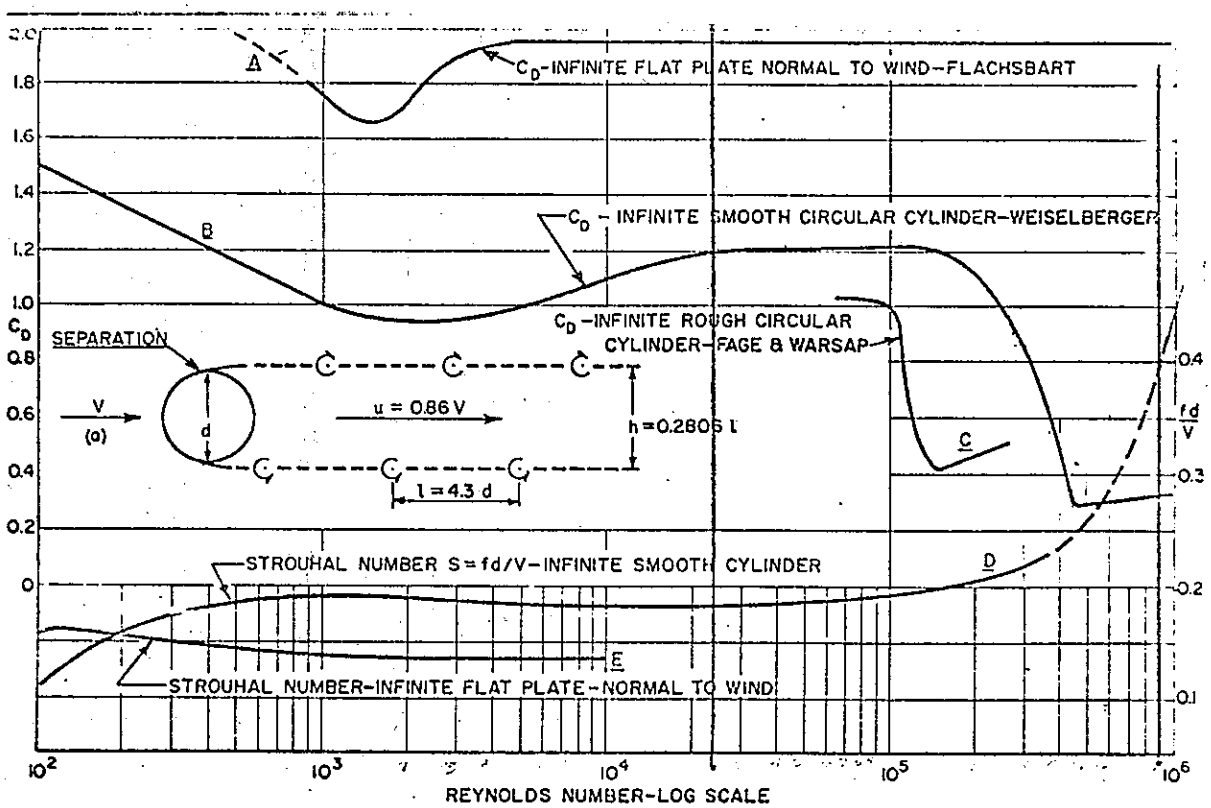

Figure III-4 - Reynolds Number versus Drag Coefficient and Strouhal Number

$\lambda = A/B$	1.0	2.0	5.0	10.0	∞
C_D	1.12	1.19	1.20	1.23	1.98

Table III-1 - Drag Coefficients Flat Plates Normal to Wind

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Table III-2 - Lighting Standard Type XXI (ES-17-5) Static Load Calculations

		Static Load Case 1 V_{30} = 67.5 mph				Static Load Case 2 V_{30} = 87.1				Static Load Case 3 V_{30} = 108 mph			
Node	A (ft^2)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)
2	3.779	53.46	.8	22.1	-	68.98	.4	16.6	-	85.5	.3	21.2	-
3	3.408	59.0	.8	24.3	-	76.13	.4	20.2	-	94.4	.3	23.3	-
4	3.037	62.5	.83	25.2	-	80.65	.53	26.8	-	100.0	.3	23.3	-
5	2.666	65.1	.92	26.6	-	84.05	.66	31.8	-	104.2	.29	21.5	-
6	2.295	67.3	1.0	26.6	-	86.81	.8	35.4	-	107.6	.58	39.5	-
7	2.074	69.1	1.1	27.8	-	89.1	.91	38.3	-	110.5	.70	45.3	-
8	1.575	69.5	1.15	22.4	-	89.67	1.0	32.4	-	111.2	.80	39.8	-
9	1.304	69.9	1.20	19.6	-	90.24	1.09	29.6	-	111.9	1.0	41.8	-
10	3.821	70.3	1.22	60.0	-	90.76	1.20	96.6	-	112.5	1.1	136.0	-

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Table III-3 - Traffic Signal and Lighting Standard Type XIX(ES-14-5) Static Load Calculations

		Static Load Case 1 V_{30} = 67.5 mph				Static Load Case 2 V_{30} = 87.1				Static Load Case 3 V_{30} = 108 mph			
Node	A (ft^2)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)
2	4.453	52.74	.4	12.7	-	68.06	.3	15.8	-	84.39	.32	25.96	-
3	4.124	58.23	.32	11.5	-	75.14	.31	18.5	-	93.17	.33	30.22	-
5	5.797	61.7	.32	18.1	-	79.62	.32	30.1	-	98.7	.33	47.7	-
4	2.974	63.9	.51	15.9	-	82.5	.31	16.1	-	102.3	.32	25.5	-
6	2.741	65.8	.60	18.2	-	84.9	.30	15.2	-	105.2	.31	24.1	-
8	3.071	67.3	.68	24.2	-	86.9	.29	17.2	-	107.7	.31	28.3	-
10	1.596	68.1	1.13	21.4	-	87.8	1.0	31.5	-	108.9	.82	39.7	-
12	1.272	68.5	1.20	18.3	-	88.5	1.08	27.5	-	109.7	.98	38.4	-
14	3.802	68.8	1.21	55.7	-	88.8	1.2	91.9	-	110.1	1.1	129.5	-
7	3.763	62.9	.68	25.9	-	81.2	.29	18.4	-	100.7	.31	30.2	-
9	3.190	64.0	.80	26.7	-	82.5	.53	29.5	-	102.3	.3	25.6	-
11 (ARM)	2.306	64.6	1.0	124.1	1990.	83.4	.70	194.4	3313.	103.4	.4	279.9	5094.
(SIG)	8.	63.9	1.19			82.5	1.19			102.3	1.19		
13	1.632	65.0	1.06	18.7	-	83.8	.88	25.8	-	103.9	.65	29.3	-
15 (SIGN	5.04	65.1	1.155	66.7	-	83.9	1.155	110.4	-	104.1	1.155	168.7	-
(ARM)	.305	65.1	1.13			83.9	1.0			104.1	.88		
16 (SIG)	8.	63.9	1.19	104.7	3184.	82.5	1.19	173.4	5301.	102.3	1.19	265.6	8151.
(ARM)	.400	65.1	1.2			83.9	1.07			104.1	.98		

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Table III-4 - Traffic Signal and Lighting Standard Type XXVI (ES-20-1)
Static Load Calculations

		Static Load Case 1 V_{30} = 67.5 mph				Static Load Case 2 V_{30} = 87.1				Static Load Case 3 V_{30} = 108 mph			
Node	A (ft^2)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)	V_Z (mph)	C_D	F_2 (lb)	M_1 (in-lb)
5	5.06	52.7	.29	10.5	-	68.1	.31	18.6	-	84.4	.32	29.5	-
7	4.74	58.2	.30	12.3	-	75.1	.31	21.2	-	93.2	.32	33.7	-
9	6.90	61.7	.29	19.5	-	79.1	.31	34.7	-	98.7	.32	55.0	-
10	6.59	63.5	.29	19.7	-	81.9	.31	35.1	-	101.6	.32	55.6	-
8	3.65	65.6	.30	12.1	-	84.6	.31	20.7	-	104.9	.32	32.9	-
6	2.96	67.3	.75	25.7	-	86.9	.30	17.1	-	107.7	.31	27.2	-
4	1.61	68.1	1.13	21.6	-	87.9	.93	29.6	-	109.0	.82	40.1	-
3	1.27	68.6	1.20	18.3	-	88.5	1.07	2.72	-	109.7	.95	37.2	-
2	3.86	68.8	1.20	56.	-	88.7	1.18	91.8	-	110.0	1.06	126.7	-
12	5.76	64.2	.48	29.1	-	82.8	.31	31.3	-	102.7	.32	49.7	-
14	4.61	64.7	.67	33.	-	83.4	.30	24.6	-	103.5	.31	39.1	-
15	4.80	64.9	.92	47.6	-	83.8	.72	62.0	-	103.9	.34	45.0	-
16 (SIG)	8.	64.2	1.19	124.2	2645.	82.8	1.19	197.1	4405	102.6	1.19	279.8	6773
(ARM)	2.33	65.1	.95			84.0	.72			104.1	.36		
17	2.15	65.1	1.08	25.2	-	84.0	.93	36.1	-	104.2	.70	41.8	-
18 (SIGN)	5.04	65.2	1.155	69.7	-	84.1	1.155	114.8	-	104.3	1.155	174.2	-
(ARM)	.5	65.2	1.18			84.1	1.05			104.3	.88		
19 (SIG)	8.	64.2	1.19	105.2	3006	82.8	1.19	174.3	5006	102.6	1.19	267.1	7696
(ARM)	.38	65.2	1.20			84.1	1.08			104.3	1.0		
11	4.75	63.3	.8	39.0	-	81.7	.4	32.5	-	101.3	.32	39.9	
13	3.53	64.2	1.0	37.3	-	82.9	.75	46.5	-	102.8	.4	38.2	

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III. 3 Random Dynamic Wind Loads

As the wind velocity fluctuates randomly (i. e., the instantaneous wind velocity is not predictable), the dynamic effects of the drag force on a structure must be determined using random response techniques. The mechanism whereby gust pressures are induced on ground based structures is still not completely understood. Therefore, although the results given herein are based on reported measurements of wind gust data, they must be considered to be only reasonable estimates at best. In order to define the power spectrum of the dynamic load, the spectra of the velocity fluctuations are first required. The velocity spectrum was calculated in reference 8 from a study of 90 strong-wind spectra and is evaluated as follows:

$$S_v(f) = \frac{4K\bar{V}_{30}x^2}{f(1+x^2)^{4/3}} ,$$

in which $S_v(f)$ is the velocity power spectrum at any height; f is the frequency, in cycles per second; $\bar{V}_{30}$ is the mean hourly wind speed (fps) at the standard reference height of 30 feet; K is the surface drag coefficient referenced to the mean speed at 30 feet (for highway type terrain K has a value of .005) and $x = \frac{4000\,f}{V_{30}}$ (cycles/ft).

To relate the load spectrum to the velocity spectrum, we use the following formula that describes the drag force:

$$D = (1/2\ \rho\ C_D A)\ V^2$$

or $$D = CV^2,$$

where $C = 1/2\ \rho\ C_D A$

ρ = density of air

C_D = drag coefficient

A = projected area.

It is assumed that the velocity consists of a mean flow with a small superimposed fluctuation. That is,

$$V = \bar{V} + v$$

Therefore, $D = \bar{D} + d \approx C\,(\bar{V}^2 + 2\,\bar{V}v)$

in which D, $\bar{D}$, d and V, $\bar{V}$, v are the total, mean, and fluctuating components of load and velocity, respectively, at any height.

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Since $\bar{D} = C\bar{V}^2$,

$$\frac{d}{\bar{D}} \quad \frac{2v}{\bar{V}}$$

hence $$\left(\frac{d}{v}\right)^2 = \frac{4\,\bar{D}^2}{\bar{V}^2} = 4\,C^2\bar{V}^2$$

Therefore at any height Z the power spectrum of the load, $\varphi(f)$, is as follows:

$$\varphi(f) = 4C_Z{}^2V_Z{}^2S_V(f),$$

where $\varphi(f)$ is in units of lbs^2/cps.

To convert from fastest mile wind speeds (derived from isotach charts) to mean hourly averages, first find the averaging period, t, for the fastest mile of wind by using the following formula

$$t = 3600/V_f,$$

in which t is in seconds and V_f is equal to the fastest mile velocity in miles per hour. Then, $\bar{V}_{30}$ is as fillows:

$$\bar{V}_{30} = V_f/F$$

where F is evaluated using Figure III-5.

For the state of California, based on data from Section III-1, the fastest mile wind for a fifty-year mean recurrence interval is 80 mph.

Therefore:

$$t = 3600/80 = 45 \text{ sec.}$$

From Figure III-5, F = 1.27

$$\bar{V}_{30} = 80/1.27 = 63 \text{ mph} = 92.4 \text{ fps}$$

For Lighting Standard Type XXI (Dwg. ES-17-5), the coefficient, $4C_Z{}^2V_Z{}^2$, for each node is evaluated in Table III-5 and the term, $S_V(f_n)$, is evaluated in Table III-6 for each natural frequency, f_n, of interest. The P.S.D. (Power Spectral Density) applied at each node is calculated by the following equation:

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$$PSD(f_n) = (4C_Z{}^2 V_Z{}^2)\,(S_V(f_n))$$

For Traffic Signal and Lighting Standard Type XIX (Dwg ES-14-5), the coefficients, $4C_Z{}^2V_Z{}^2$, and the terms, $S_V(f_n)$, are evaluated in Tables III-7 and III-8 respectively. For Traffic Signal and Lighting Standard Type XXVI (Dwg. ES-20-1), they are evaluated in Tables III-9 and III-10 respectively.

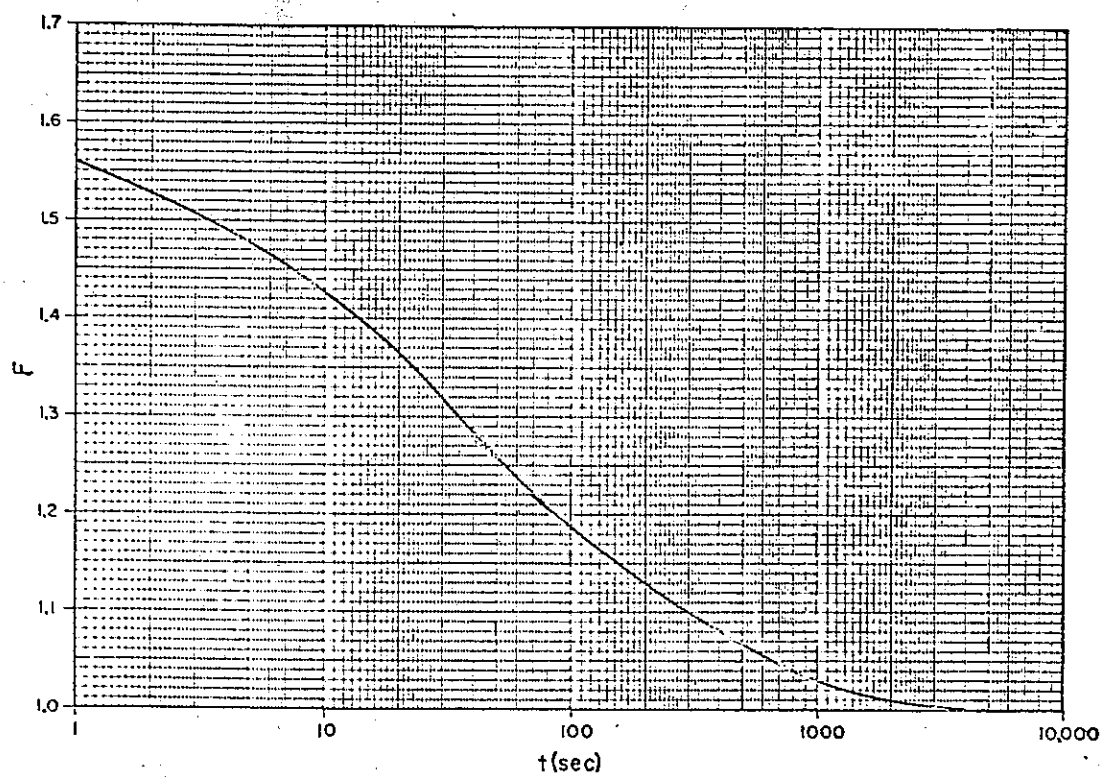

Figure III-5 - Ratio, F, of Probable Maximum Speed Averaged over Period, t, to That Averaged Over One Hour

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Node	X3 (in)	A (ft^2)	C_D	C_Z	$\bar{V}_Z$ (ft/sec)	$4C_Z{}^2V_Z{}^2$
2	70.3	3.779	.86	.003863	73.2	.3197
3	140.7	3.408	.88	.003565	80.7	.3308
4	211.	3.037	.90	.003249	85.5	.3087
5	281.3	2.666	.95	.003010	89.2	.2882
6	351.7	2.295	1.00	.002728	92.1	.2525
7	422.	2.074	1.06	.002612	94.5	.2435
8	441.3	1.575	1.12	.002096	95.2	.1592
9	460.7	1.304	1.20	.001860	95.8	.1269
10	480.	3.821	1.21	.005497	96.2	1.1189

Table III-5 - Calculation of $4C_Z{}^2V_Z{}^2$- Lighting Standard Type XXI

f(cps)	.6978	2.2054	7.3809	13.1776	20.8395	37.9121
$\bar{V}_{30}/f$	132.42	41.9	12.519	7.01	4.54	2.437
$x^2/(1+x^2)^{\frac{4}{3}}$	.1032	.0486	.02132	.0155	.01142	.0072
$S_V(f)$	.2733	.0407	.00536	.00217	.00104	.000351

Table III-6 - $S_V(f)$ at Natural Frequencies - Lighting Standard Type XXI

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Node	X3 (in)	A (ft^2)	C_D	C_Z	$\bar{V}_Z$ (ft/sec)	$4C_Z^2V_Z^2$
2	64	4.4533	.58	.003071	72.2	.1966
3	128	4.1244	.54	.002648	79.7	.1782
5	192	5.797	.59	.004066	84.5	.4722
4	246	2.9738	.68	.002121	87.5	.1378
6	300	2.7413	.72	.002346	90.0	.1783
8	354	3.0712	.75	.002738	92.2	.2549
10	382	1.5964	1.20	.002277	93.2	.1801
12	401	1.2720	1.20	.001814	93.8	.1158
14	411	3.8016	1.21	.005469	94.2	1.0616
7	220	3.7628	.75	.003355	86.1	.3338
9	247	3.1902	.92	.003489	87.6	.3737
11(ARM)	266	2.3060	1.02	.002796	88.5	.2449
(SIG.)	246	8.	1.19	.011319	87.5	3.9237
13	275	1.6324	1.09	.002115	88.9	.1414
15(SIGN)	278	5.04	1.155	.006921	88.9	1.5143
(ARM)	278	.3052	1.20	.000435	89.1	.0060
16(SIG.)	246	8.	1.19	.011319	87.5	3.9237
(ARM)	278	.4000	1.20	.000570	89.1	.0103

Table III-7 - Calculation of $4C_Z^2V_Z^2$ - Traffic Signal and Lighting Standard Type XIX

f(cps)	1.0412	1.5001	3.1132	6.4921	10.3942	11.6396
$\bar{V}_{30}/f$	88.74	61.60	29.68	14.23	8.890	7.9384
$x^2/(1+x^2)^{\frac{4}{3}}$	.0791	.0619	.03806	.02333	.01702	.01579
$S_V(f)$	.1404	.07626	.02259	.006641	.003026	.00251

Table III-8 - $S_V(f)$ at Natural Frequencies - Traffic Signal and Lighting Standard Type XIX

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Node	X3 (in)	A (ft^2)	C_D	C_Z	$\bar{V}_Z$ (ft/sec)	$4C_Z{}^2V_Z{}^2$
5	64.	5.06	.31	.001865	72.2	.0725
7	128.	4.74	.30	.001691	79.7	.0727
9	192.	6.90	.43	.003528	84.5	.3551
10	234.	6.59	.38	.002972	86.9	.2678
8	294.	3.65	.32	.001389	89.8	.0622
6	354.	2.96	.85	.002992	92.2	.3043
4	382.8	1.61	1.16	.002221	93.2	.1714
3	402.	1.27	1.20	.001812	93.9	.1158
2	410.4	3.86	1.22	.005599	94.1	1.1115
12	253.2	5.76	.6	.004109	87.9	.5215
14	266.4	4.61	.75	.004111	88.5	.5296
15	273.6	4.80	1.00	.005707	88.9	1.0286
16(SIG)	252.	8.	1.19	.011319	87.8	3.9523
16(ARM)	278.4	2.33	1.05	.002909	89.1	.2685
17	280.2	2.15	1.1	.002812	89.1	.2514
18(SIGN)	282.	5.04	1.155	.006921	89.2	1.5257
18(ARM)	282.	.5	1.2	.000713	89.2	.0162
19(SIG)	252.	8.	1.19	.011319	87.8	3.9523
19(ARM)	282.	.38	1.2	.000542	89.2	.0094
11	230.4	4.75	.87	.004914	86.7	.7257
13	254.4	3.53	1.0	.004197	87.9	.5448

Table III-9 - Calculation of $4C_Z{}^2V_Z{}^2$ - Traffic Signal and Lighting Standard Type XXVI

f(cps)	.8085	1.5540	2.6639	4.1579	9.1774	9.8473
$\bar{V}_{30}/f$	114.3	59.46	34.69	22.22	10.07	9.383
$x^2/(1+x^2)^{\frac{4}{3}}$	.0934	.0605	.0422	.0314	.01853	.01767
$S_V(f)$	.2135	.0719	.02927	.01395	.003731	.003316

Table III-10 - $S_V(f)$ at Natural Frequencies - Traffic Signal and Lighting Standard Type XXVI

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III. 4 Vortex Shedding Wind Loads

The commonly used expression for the alternating lateral force due to vortex shedding is:

$$F_K = qAC_K \sin 2\pi f_v t \qquad \text{(Reference 10)}$$

Where F_K is the vonKarman force; q is the dynamic pressure; A is the exposed area; C_K is the von Karman coefficient; f_v represents the frequency of shedding vortex pairs; and t is time. Figure III-6 (Reference 10) shows various reported values of C_K. The assumed variation of C_K with Reynolds Number used in this analysis is also shown in Figure III-6. The value of f_v is calculated as follows:

$$f_v = \frac{17.6\ SV}{d}, \qquad \text{(Reference 11)}$$

where S is the Strouhal number, V is the mean wind velocity (mph) and d is the diameter (inches) of the dylinder. For the Reynolds number range in this analysis, the Strouhal number is equal to .19, as shown in Figure III-4.

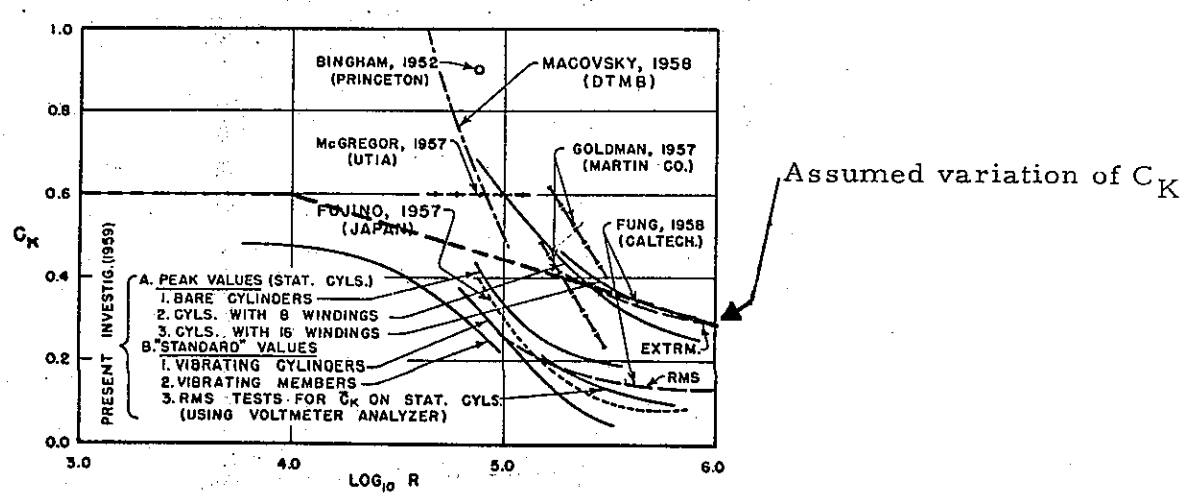

Figure III-6 - Reported Experimental Values of C_K

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The vortex shedding loads and frequencies calculated for the first three critical velocities for each of the three analyzed standards are shown in Tables III-11, III-12 and III-13. The critical velocities are calculated using the following equation :

$$\bar{V}_{CRIT} = \frac{f_n d_i}{17.6S}$$

Where:

$\bar{V}_{CRIT}$ =	Critical velocity at node i
f_n =	n^{th} natural frequency
S =	Strouhal number = .19
d_i =	Diameter of the cylindrical member at node i
Node i =	Node at which the nodal displacement vector is a maximum for the nth mode.

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Node	Degree of Freedom	$\bar{V}_{CRIT}$ = 12.42mph		$\bar{V}_{CRIT}$=11.634mph		$\bar{V}_{CRIT}$=30.824mph	
		qAC_K(lb)	f_v(cps)	qAC_K(lb)	f_v(cps)	qAC_K(lb)	f_v(cps)
2	X1	.468	4.25	.410	3.98	2.45	10.55
3	X1	.513	5.20	.451	4.87	2.69	12.91
4	X1	.513	6.18	.451	5.79	2.71	15.35
5	X1	.490	7.341	.430	6.88	2.63	18.22
6	X1	.450	8.81	.395	8.25	2.45	21.8656
7	X1	.428	10.34	.383	9.68	2.37	25.66
8	X3	.342	11.88	.300	11.13	1.86	29.48
9	X3	.293	14.40	.257	13.525	1.60	35.83
10	X3	.116	18.18	.102	17.03	.64	45.13

Table III - 11 Vortex Shedding Loads and Frequencies
Lighting Standard Type XXI

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Node	Degree of Freedom	$\bar{V}_{CRIT}$=6.83 mph		$\bar{V}_{CRIT}$=7.736 mph		$\bar{V}_{CRIT}$=14.13 mph	
		qAC_K(lb)	f_v(cps)	qAC_K(lb)	f_v(cps)	qAC_K(lb)	f_v(cps)
2	X1	.164	1.78	.207	2.02	.637	3.68
3	X1	.185	2.12	.234	2.40	.719	4.39
5	X1	.292	2.44	.369	2.77	1.136	5.05
4	X1	.162	2.73	.205	3.09	.629	5.64
6	X1	.159	3.04	.201	3.45	.619	6.30
8	X1	.188	3.41	.238	3.86	.735	7.05
10	X3	.108	6.47	.137	7.33	.423	13.39
12	X3	.089	7.84	.113	8.875	.350	16.2071
14	X3	.036	9.80	.046	11.10	.142	20.27
7	X3	.202	3.03	.255	3.43	.786	6.26
9	X3	.180	3.57	.227	4.04	.701	7.38
11	X3	.136	4.26	.172	4.82	.530	8.80
13	X3	.083	5.09	.105	5.76	.325	10.53
15	X3	.019	6.03	.024	6.83	.074	12.48
16	X3	.025	6.8805	.032	7.79	.099	14.23

Table III-12 - Vortex Shedding Loads and Frequencies
Traffic Signal and Lighting Standard Type XIX

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Node	Degree of Freedom	$\bar{V}_{CRIT}$ = 10.86 mph		$\bar{V}_{CRIT}$ = 9.03 mph		$\bar{V}_{CRIT}$ = 15.40 mph	
		qAC_K (lb)	f_v (cps)	qAC_K (lb)	f_v (cps)	qAC_K (lb)	f_v (cps)
5	X1	.408	2.49	.319	2.07	.781	3.53
7	X1	.463	2.94	.363	2.44	.888	4.17
9	X1	.769	3.68	.602	3.06	1.475	5.22
10	X1	.775	3.81	.607	3.17	1.487	5.40
8	X1	.457	4.03	.358	3.35	.877	5.71
6	X1	.394	5.89	.309	4.90	.757	8.35
4	X3	.243	10.26	.190	8.53	.469	14.55
3	X3	.199	12.46	.155	10.3613	.384	17.67
2	X3	.089	13.91	.070	11.57	.173	19.73
11	X3	.582	5.32	.455	4.43	1.119	7.55
12	X3	.702	4.30	.549	3.58	1.347	6.10
13	X3	.457	6.68	.357	5.56	.879	9.48
14	X3	.582	5.06	.455	4.21	1.118	7.17
15	X3	.629	6.42	.492	5.34	1.210	9.10
16	X3	.310	6.9427	.242	5.78	.597	9.85
17	X3	.293	9.26	.229	6.87	.564	11.7174
18	X3	.070	9.99	.055	8.31	.135	14.17
19	X3	.054	10.96	.042	9.11	.104	15.54

Table III-13 - Vortex Shedding Loads and Frequencies
Traffic Signal and Lighting Standard Type XXVI

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IV. STATIC STRESS ANALYSIS

IV. 1 Analytic Method

MRI's STARDYNE system used for the static wind loads analysis is formulated around the "Stiffness" or "Displacement" method of structural analysis The mathematical model is defined by the matrix equation

$$\left[K\right] \left\{\delta\right\} = \left\{F\right\} \qquad \text{(IV. 1-1)}$$

where

$\left[K\right]$ = stiffness matrix

$\left\{\delta\right\}$ = displacement vector

$\left\{F\right\}$ = external load vector

The displacement vector $\left\{\delta\right\}$ comprises all the non-restrained movements of each node point. The external load vector $\left\{F\right\}$ comprises the external loads applied to the node points in all nonrestrained directions of movement. An element of the $\left[K\right]$ matrix, K_{ij}, is defined as the force necessary to hold the structural element from moving in the ith degree of freedom when the jth degree of freedom is given a unit displacement and all of the other degrees of freedom of the structural element are restrained from moving.

The static analysis of the structure proceeds as follows:

1. An elemental stiffness matrix $\left[K\right]_i$ is defined for each elemental building block used in simulating the physical system. For each element, the equation,

$$\left[K\right]_i \left\{\delta\right\}_i = \left\{F\right\}_i, \qquad \text{(IV. 1-2)}$$

may be written. The spacial relationship of each element to the system coordinates is defined by the equation ,

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$$\{\delta\}_i = [C]_i \{\delta\} \qquad \text{(IV. 1-3)}$$

where $[C]_i$ is a rotational transformation matrix relating the element coordinate system to the global coordinate system. Equation IV.1-1 is obtained from the equation

$$\sum_i [C]_i^T [K]_i [C_i] \{\delta\} = \{F\} \qquad \text{(IV. 1-4)}$$

2. The system of linear equations in IV.1-1 is solved to yield the displacement vector $\{\delta\}$. Equations IV. 1-3 and IV.1-2 are employed in turn to compute $\{F\}_i$, which represents the internal forces on the ith elemental building block.

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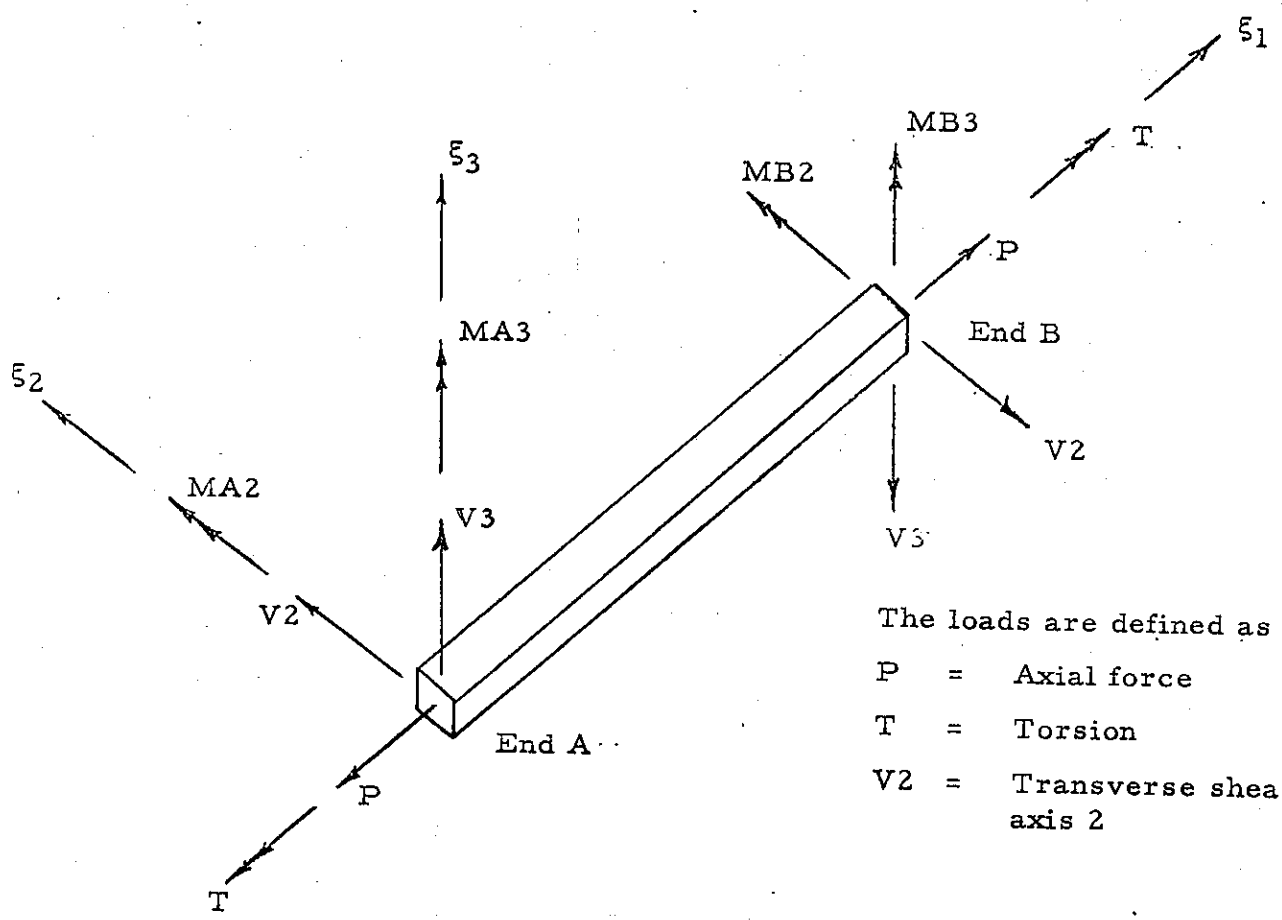
Beam Loads from STARDYNE

The member loads generated by the STARDYNE program are applied to a member A-B according to the convention shown below.



The loads are defined as follows:

P = Axial force

T = Torsion

V2 = Transverse shear force along axis 2

V3 = Transverse shear force along axis 3

M2 = Bending moment about axis 2

M3 = Bending moment about axis 3.

Individual Stresses

A. Axial Stress

$$\sigma_A = \frac{P}{A}$$

P = Axial force --(lbs)

A = Cross sectional area -- (in^2)

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B. Bending Stress

$$\sigma_i = \frac{M_i c_i}{I_i}$$

M_i = Bending moment about axis (i) (in-lb)

c_i = Distance from axis (i) to extreme fiber --(in)

I_i = Area moment of inertia about axis (i) --(in^4)

C. Torsional Shear Stress = S_s

$$\tau_T = \frac{TC}{K}$$

T = Torque (in-lbs)

C = O.D. /2

$$K = \frac{\pi[r_i^4 - (r_i - t)^4]}{2}$$

D. Transverse Shear Stress

$$\tau_i = \frac{V_i Q_i}{2 I_i t}$$

V_i = Transverse Shear Force (lbs)

Q_i = Static moment of area above the layer in question with respect to the neutral axis (in^3)

$$= 2r_i^3[\frac{t}{r_i} - (\frac{t}{r_i})^2 + \frac{1}{3}(\frac{t}{r_i})^3]$$

2t = Width of layer upon which shearing stress is acting (in)

Combined stresses are treated by using the conservative Tresca, or maximum shear, theory of ductile material failure. The Tresca failure criterion allows comparison of twice the maximum shear stress vs. the uni-axial yield stress of the material. In effect, this theory states that failure of the section occurs when the diameter of the largest Mohr's stress circle, which may be constructed for the particular stress state existing with the cross section, exceeds uni-axial material yield stress.

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The Tresca failure criteria has been accepted as a measure of design integrity by a number of design codes, particularly those associated with nuclear system structural elements; e.g., ASME Boiler Pressure Vessels Code, Section III Nuclear Vessels.

Stress comparisons are performed at both ends of a finite beam element and at three locations within the cross section:

1. At local cross section axis ξ_2:

$$2 * \tau_{max} = \left[\left(\frac{|\sigma_A| + |\sigma_3|}{2} \right)^2 + \left(|\tau_2| + |\tau_T| \right)^2 \right]^{1/2}$$

2. At local cross section axis ξ_3:

$$2 * \tau_{max} = \left[\left(\frac{|\sigma_A| + |\sigma_2|}{2} \right)^2 + \left(|\tau_3| + |\tau_T| \right)^2 \right]^{1/2}$$

3. At maximum cross section stress location:

$$2 * \tau_{max} = \left[\left(\frac{|\sigma_A| + \sqrt{\sigma_2^2 + \sigma_3^2}}{2} \right)^2 + \left(|\tau_T| + \sqrt{\tau_2^2 + \tau_3^2} \right)^2 \right]^{1/2}$$

The largest Tresca stress is reported for each finite beam element. The computer program, WEFFLS, developed for this analysis allows the user to define localized stress concentration factors for all stress components prior to the calculation of Tresca stress.

IV.2 Results

The static wind loads calculated in Section III.2 in conjunction with the structural data in Section II.2 were submitted to the STARDYNE computer system. The resulting static stresses for each structure and each recurrence interval are shown in Tables IV-1 through IV-9. Stresses were also calculated for the effect of the dead weight of the structure and are shown in Tables IV-10 through IV-12 for each analyzed lighting standard. Unity stress concentration factors have been employed through this analysis.

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	0.	-1097.	-13000.	0.	10310.	0.	150.	0.
2-3	0.	-1346.	-12610.	0.	9602.	0.	151.	0.
3-4	0.	-1691.	-11990.	0.	8633.	0.	150.	0.
4-5	0.	-2187.	-11130.	0.	7324.	0.	150.	0.
5-6	0.	-2939.	- 9757.	0.	5426.	0.	147.	0.
6-7	0.	-4158.	7579.	0.	2566.	0.	143.	0.
7-8	0.	3.	-10520.	0.	6079.	0.	128.	0.
8-9	0.	- 3.	- 8706.	0.	3741.	0.	119.	0.
9-10	0.	0.	- 5798.	0.	0.	0.	111.	0.

Table IV-1 - Lighting Standard Type XXI (ES-17-5)
Static Load Case 1
Recurrence Interval = 2 yrs. - V_{30} = 67.5 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	0.	-1731.	-18250.	0.	14790.	0.	193.	0.
2-3	0.	-2124.	-18080.	0.	14060.	0.	202.	0.
3-4	0.	-2669.	-17550.	0.	12860.	0.	210.	0.
4-5	0.	-3453.	-16590.	0.	11100.	0.	216.	0.
5-6	0.	-4640.	-14780.	0.	8345.	0.	218.	0.
6-7	0.	-6565.	-11660.	0.	4051.	0.	216.	0.
7-8	0.	4.	-16610.	0.	9703.	0.	199.	0.
8-9	0.	- 5.	-13890.	0.	6023.	0.	189.	0.
9-10	0.	0.	- 9335.	0.	0.	0.	179.	0.

Table IV-2 - Lighting Standard Type XXI
Static Load Case 2
Recurrence Interval = 10 yrs. - V_{30} = 87.1 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	0.	-2412.	-22660.	0.	18520.	0.	231.	0.
2-3	0.	-2960.	-22630.	0.	17850.	0.	241.	0.
3-4	0.	-3718.	-22280.	0.	16690.	0.	251.	0.
4-5	0.	-4811.	-21510.	0.	14790.	0.	265.	0.
5-6	0.	-6465.	-19680.	0.	11310.	0.	283.	0.
6-7	0.	-9146.	-15800.	0.	5644.	0.	289.	0.
7-8	0.	6.	-23140.	0.	13670.	0.	273.	0.
8-9	0.	- 6.	-19570.	0.	8479.	0.	266.	0.
9-10	0.	0.	-13140.	0.	0.	0.	252.	0.

Table IV-3 - Lighting Standard Type XXI (ES-17-5)
Static Load Case 3
Recurrence Interval = 50 years - V_{30} = 108 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	0.	-2923.	- 8182.	0.	6281.	0.	147.	0.
2-3	0.	-3400.	- 7336.	0.	5166.	0.	156.	0.
3-5	0.	-3967.	- 6003.	0.	3534.	0.	164.	0.
4-5	0.	- 578.	1581.	0.	-2289.	0.	51.	0.
4-6	0.	- 681.	- 1861.	0.	1114.	0.	49.	0.
5-7	0.	- 735.	-10160.	0.	7232.	0.	133.	0.
6-8	0.	- 814.	- 1331.	0.	556.	0.	47.	0.
7-9	0.	- 921.	- 9658.	0.	6055.	0.	143.	0.
8-10	0.	- 528.	-10720.	0.	5950.	0.	130.	0.
9-11	0.	- 846.	- 8708.	0.	4197.	0.	156.	0.
10-12	0.	- 241.	- 8076.	0.	3381.	0.	112.	0.
11-13	0.	- 662.	- 6266.	0.	3408.	0.	111.	0.
12-14	0.	0.	- 5476.	0.	0.	0.	109.	0.
13-15	0.	- 683.	5167.	0.	1441.	0.	121.	0.
15-16	0.	- 884.	- 2126.	0.	0.	0.	88.	0.

Table IV-4 - Traffic Signal and Lighting Standard Type XIX
Static Load Case 1
Recurrence Interval = 2 years - V_{30} = 67.5 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	0.	-4621.	-11880.	0.	9121.	0.	213.	0.
2-3	0.	-5374.	-10650.	0.	7498.	0.	226.	0.
3-5	0.	-6270.	- 8712.	0.	5130.	0.	238.	0.
4-5	0.	- 930.	2251.	0.	-3170.	0.	66.	0.
4-6	0.	-1095.	- 2650.	0.	1656.	0.	66.	0.
5-7	0.	-1208.	-15970.	0.	11570.	0.	201.	0.
6-8	0.	-1309.	- 1979.	0.	890.	0.	66.	0.
7-9	0.	-1516.	-15460.	0.	9819.	0.	223.	0.
8-10	0.	- 863.	-17230.	0.	9690.	0.	206.	0.
9-11	0.	-1403.	-14130.	0.	6893.	0.	250.	0.
10-12	0.	- 398.	-13150.	0.	5579.	0.	180.	0.
11-13	0.	-1100.	-10300.	0.	5642.	0.	182.	0.
12-14	0.	0.	- 9035.	0.	0.	0.	179.	0.
13-15	0.	-1137.	- 8555.	0.	2387.	0.	201.	0.
15-16	0.	-1472.	- 3520.	0.	0.	0.	146.	0.

Table IV-5 - Traffic Signal and Lighting Standard Type XIX
Static Load Case 2
Recurrence Interval = 10 years - V_{30} = 87.1 mph

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Member A-B	Axial Stress	Tor-sional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	0.	-6749.	-17150.	0.	13140.	0.	311.	0.
2-3	0.	-7850.	-15340.	0.	10760.	0.	329.	0.
3-5	0.	-9158.	-12500.	0.	7306.	0.	344.	0.
4-5	0.	-1297.	3163.	0.	-4478.	0.	95.	0.
4-6	0.	-1527.	- 3723.	0.	2313.	0.	93.	0.
5-7	0.	-1831.	-23440.	0.	17070.	0.	290.	0.
6-8	0.	-1825.	- 2765.	0.	1236.	0.	92.	0.
7-9	0.	-2302.	-22800.	0.	14670.	0.	322.	0.
8-10	0.	-1215.	-24010.	0.	13640.	0.	283.	0.
9-11	0.	-2148.	-21110.	0.	10440.	0.	369.	0.
10-12	0.	- 561.	-18510.	0.	7861.	0.	254.	0.
11-13	0.	-1689.	-15610.	0.	8635.	0.	272.	0.
12-14	0.	0.	-12730.	0.	0.	0.	252.	0.
13-15	0.	-1748.	-13090.	0.	3655.	0.	307.	0.
15-16	0.	-2264.	- 5392.	0.	0.	0.	224.	0.

Table IV-6 - Traffic Signal and Lighting Standard Type XIX
Static Load Case 3
Recurrence Interval = 50 years - V_{30} = 108 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-5	0.	-3153.	- 6258.	0.	4807.	0.	126.	0.
2-3	0.	0.	0.	0.	-5504.	0.	110.	0.
3-4	0.	- 285.	3295.	0.	-7909.	0.	111.	0.
4-6	0.	- 578.	5700.	0.	-10320.	0.	126.	0.
5-7	0.	-3611.	- 5504.	0.	3867.	0.	133.	0.
6-8	0.	- 443.	291.	0.	- 747.	0.	29.	0.
7-9	0.	-4148.	- 4313.	0.	2519.	0.	135.	0.
8-10	0.	- 374.	654.	0.	- 1093.	0.	31.	0.
9-10	0.	-2849.	- 2050.	0.	1368.	0.	73.	0.
9-11	0.	- 531.	- 9619.	0.	5189.	0.	127.	0.
10-12	0.	- 386.	- 8086.	0.	6514.	0.	58.	0.
11-12	0.	- 59.	4631.	0.	4898.	0.	-39.	0.
11-13	0.	- 509.	- 8003.	0.	4440.	0.	95.	0.
12-14	0.	- 406.	- 8876.	0.	6385.	0.	89.	0.
13-15	0.	- 658.	- 7325.	0.	2646.	0.	98.	0.
14-15	0.	- 290.	- 9070.	0.	6050.	0.	92.	0.
15-16	0.	- 769.	-10320.	0.	6287.	0.	166.	0.
16-17	0.	- 445.	- 8798.	0.	4636.	0.	119.	0.
17-18	0.	- 686.	- 7136.	0.	1536.	0.	129.	0.
18-19	0.	- 987.	- 2319.	0.	0.	0.	93.	0.

Table IV-7 - Traffic Signal and Lighting Standards Type XXVI
Static Load Case 1
Recurrence Interval - 2 years - V_{30} = 67.5 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-5	0.	-4802.	- 8953.	0.	6866.	0.	182.	0.
2-3	0.	0.	0.	0.	- 9023.	0.	180.	0.
3-4	0.	- 467.	5402.	0.	-12790.	0.	178.	0.
4-6	0.	- 939.	9217.	0.	-16380.	0.	196.	0.
5-7	0.	-5498.	- 7862.	0.	5516.	0.	191.	0.
6-8	0.	- 704.	459.	0.	- 1080.	0.	40.	0.
7-9	0.	-6372.	- 6152.	0.	3591.	0.	193.	0.
8-10	0.	- 594.	946.	0.	- 1558.	0.	43.	0.
9-10	0.	-4353.	- 2880.	0.	1935.	0.	102.	0.
9-11	0.	- 850.	-14540.	0.	8119.	0.	184.	0.
10-12	0.	- 628.	-12270.	0.	10170.	0.	78.	0.
11-12	0.	- 94.	7276.	0.	7702.	0.	-62.	0.
11-13	0.	- 826.	-12530.	0.	7117.	0.	145.	0.
12-14	0.	- 669.	-13860.	0.	10250.	0.	130.	0.
13-15	0.	-1071.	-11740.	0.	4347.	0.	156.	0.
14-15	0.	- 490.	-14560.	0.	9833.	0.	144.	0.
15-16	0.	-1277.	-16800.	0.	10310.	0.	267.	0.
16-17	0.	- 741.	-14430.	0.	7666.	0.	194.	0.
17-18	0.	-1142.	-11800.	0.	2544.	0.	213.	0.
18-19	0.	-1644.	- 3842.	0.	0.	0.	155.	0.

Table IV-8 - Traffic Signal and Lighting Standard Type XXVI
Static Load Case 2
Recurrence Interval = 10 years - V_{30} = 87.1 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-5	0.	-5746.	-10410.	0.	7994.	0.	210.	0.
2-3	0.	0.	0.	0.	-12450.	0.	249.	0.
3-4	0.	- 645.	7456.	0.	-17630.	0.	245.	0.
4-6	0.	-1294.	12710.	0.	-22540.	0.	269.	0.
5-7	0.	-6580.	- 9154.	0.	6462.	0.	219.	0.
6-8	0.	- 968.	631.	0.	- 1498.	0.	56.	0.
7-9	0.	-7625.	- 7208.	0.	4294.	0.	220.	0.
8-10	0.	- 817.	1311.	0.	- 2178.	0.	61.	0.
9-10	0.	-5295.	- 3580.	0.	2452.	0.	121.	0.
9-11	0.	-1106.	-16890.	0.	10150.	0.	193.	0.
10-12	0.	- 862.	-14620.	0.	12590.	0.	76.	0.
11-12	0.	- 152.	10690.	0.	11160.	0.	-90.	0.
11-13	0.	-1129.	-15650.	0.	9666.	0.	160.	0.
12-14	0.	- 960.	-17160.	0.	13160.	0.	144.	0.
13-15	0.	-1465.	-15950.	0.	5163.	0.	227.	0.
14-15	0.	- 772.	-18710.	0.	13660.	0.	154.	0.
15-16	0.	-1919.	-22730.	0.	14290.	0.	348.	0.
16-17	0.	-1139.	-20020.	0.	11710.	0.	238.	0.
17-18	0.	-1756.	-18030.	0.	3898.	0.	324.	0.
18-19	0.	-2527.	- 5888.	0.	0.	0.	237.	0.

Table IV-9 - Traffic Signal and Lighting Standard Type XXVI
Static Load Case 3
Recurrence Interval = 50 years - V_{30} = 108 mph

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	-126.	0.	0.	- 2919.	0.	2919.	0.	0.
2-3	-118.	0.	0.	- 3567.	0.	3567.	0.	0.
3-4	-111.	0.	0.	- 4453.	0.	4453.	0.	0.
4-5	-104.	0.	0.	- 5742.	0.	5742.	0.	0.
5-6	- 98.	0.	0.	- 7644.	0.	7644.	0.	0.
6-7	- 94.	0.	0.	-10680.	0.	10680.	0.	0.
7-8	- 26.	0.	0.	-13420.	0.	7921.	0.	-159.
8-9	- 25.	0.	0.	-11340.	0.	5027.	0.	-152.
9-10	- 24.	0.	0.	- 7792.	0.	0.	0.	-150.

Table IV-10 - Lighting Standard Type XXI (ES-17-5)
Static Load Case 4
Dead Weight of Structure

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-2	-172.	0.	0.	- 6732.	0.	6732.	0.	0.
2-3	-167.	0.	0.	- 7862.	0.	7862.	0.	0.
3-5	-160.	0.	0.	- 9136.	0.	9136.	0.	0.
4-5	- 61.	0.	0.	- 1647.	0.	1647.	0.	0.
4-6	- 50.	0.	0.	- 1940.	0.	1940.	0.	0.
5-7	- 34.	0.	0.	-11170.	0.	7341.	0.	-174.
6-8	- 39.	0.	0.	- 2318.	0.	2318.	0.	0.
7-9	- 30.	0.	0.	- 9780.	0.	5798.	0.	-158.
8-10	- 36.	0.	0.	-14580.	0.	8591.	0.	-164.
9-11	- 19.	0.	0.	- 8134.	0.	3865.	0.	-148.
10-12	- 24.	0.	0.	-11470.	0.	5096.	0.	-152.
11-13	- 9.	0.	0.	- 5506.	0.	2702.	0.	-109.
12-14	- 13.	0.	0.	- 8171.	0.	0.	0.	-162.
13-15	- 3.	0.	0.	- 3953.	0.	895.	0.	-100.
15-16	0.	0.	0.	- 1256.	0.	0.	0.	- 52.

Table IV-11 - Traffic Signal and Lighting Standard Type XIX
Static Load Case 4
Dead Weight of Structure

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Member A-B	Axial Stress	Torsional Shear Stress	Bending Stresses				Shear Stresses	
			End A		End B			
	σ_A	τ_T	σ_2	σ_3	σ_2	σ_3	τ_2	τ_3
1-5	- 202.	0.	0.	- 9469.	0.	9469.	0.	0.
2-3	- 11.	0.	0.	0.	0.	8168.	0.	163.
3-4	- 23.	0.	0.	- 4963.	0.	11180.	0.	150.
4-6	- 37.	0.	0.	- 8219.	0.	13960.	0.	157.
5-7	- 197.	0.	0.	-10840.	0.	10840.	0.	0.
6-8	- 27.	0.	0.	- 1205.	0.	1205.	0.	0.
7-9	- 187.	0.	0.	-12090.	0.	12090.	0.	0.
8-10	- 42.	0.	0.	- 1054.	0.	1054.	0.	0.
9-10	114.	0.	0.	-12500.	0.	- 460.	0.	-1393.
9-11	-1354.	0.	0.	- 4135.	0.	- 961.	0.	- 146.
10-12	1045.	0.	0.	2239.	0.	1832.	0.	151.
11-12	- 301.	0.	0.	71.	0.	1754.	0.	174.
11-13	-1675.	0.	0.	1480.	0.	1895.	0.	90.
12-14	1263.	0.	0.	- 1553.	0.	115.	0.	- 52.
13-15	-2125.	0.	0.	- 3097.	0.	1905.	0.	- 25.
14-15	1497.	0.	0.	- 162.	0.	6189.	0.	183.
15-16	- 7.	0.	0.	- 9903.	0.	5827.	0.	- 168.
16-17	- 2.	0.	0.	- 8041.	0.	3660.	0.	- 126.
17-18	- 1.	0.	0.	- 5635.	0.	907.	0.	- 109.
18-19	0.	0.	0.	- 1341.	0.	0.	0.	- 54.

Table IV-12 - Traffic Signal and Lighting Standard Type XXVI
Static Load Case 4
Dead Weight of Structure

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V. DYNAMIC ANALYSIS

The proper mathematical description of a structural frame, such as the Traffic Signal and Lighting Standards, results in a large number of second order differential equations. If a lumped parameter representation is employed, a separate equation is required for each important parameter i.e., inertia lump, or mass point. Additional equations are required to simulate important load paths, or interconnections, between the lumped parameters, points of load application and the external boundaries of the system.

Where these resultant differential equations are linear, important simplifying procedures based upon orthogonal functions are utilized. These procedures are embodied in the so-called "Modal Analysis" method described in succeeding paragraphs.

V.1 Modal Analysis

We have chosen to use this technique in conjunction with a stiffness, or displacement method, description of the structural system. The normal modes and frequencies, obtained from an eigenvalue solution of the equations of motion may be used to produce a response solution.

The modal analysis technique is a widely used method for the evaluation of structural dynamic response characteristics of complex, distributed, or lumped parameter linear systems.

MRI implements the modal analysis methods described herein using the STARDYNE Structural Analysis System. The greatest value of this method is the fact that the proper utilization of the mode shapes and natural frequencies resolves a complex problem of many coupled degrees of freedom into a set of linearly uncoupled, or independent, second order single degree of freedom systems. Each of these independent single degree of freedom systems can be solved in the presence of the excitation forces by using the wealth of technical information available regarding forced dynamic response of single degree of freedom order dynamic systems.

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V.1.1 Analytic Method

V.1.1.1 Normal Coordinates

In the analysis of multi-degree-of-freedom systems, the differential equations of motion are normally coupled either statically or dynamically. However, a set of coordinates exists in which the equations of motion are decoupled both statically and dynamically. These are called "Normal Coordinates" and they may be determined by a transformation of coordinates in which the transformation matrix is constructed of the system eigenvectors. When damping forces are present, it is a necessary condition that the damping coefficients be proportional to either the mass or stiffness constants of the system or a linear combination of both.

The equations of motion for a proportionally damped multi-degree-of-freedom system may be written in matrix form as follows:

$$\left[m\right]\left\{\ddot{x}\right\} + \left[c\right]\left\{\dot{x}\right\} + \left[k\right]\left\{x\right\} = \left\{F(t)\right\} \qquad \text{(V.1-1)}$$

where:

$\left[m\right]$ is the mass matrix

$\left[c\right]$ is the matrix of damping coefficients

$\left[k\right]$ is the stiffness matrix

$\left\{\ddot{x}\right\}$ is a vector of system coordinate acceleration

$\left\{\dot{x}\right\}$ is a vector of system coordinate velocities

$\left\{x\right\}$ is a vector of system coordinate displacements

$\left\{F(t)\right\}$ is the driving function

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Now apply the coordinate transformation

$$\{x\} = [\varphi]\{\eta\}, \qquad \text{(V.1-2)}$$

where

$[\varphi]$ is the matrix which transforms the system coordinates to a set of generalized independent coordinates,

and

$\{\eta\}$ is the vector of "Normal" coordinate displacements.

Also, apply a similar transformation to the velocity and acceleration term

$$\{\dot{x}\} = [\varphi]\{\dot{\eta}\} \qquad \text{(V.1-3)}$$

$$\{\ddot{x}\} = [\varphi]\{\ddot{\eta}\} \qquad \text{(V.1-4)}$$

If the above transformations are substituted into the equations of motion we get:

$$[m][\varphi]\{\ddot{\eta}\} + [c][\varphi]\{\dot{\eta}\} + [k][\varphi]\{\eta\} = \{F(t)\}. \qquad \text{(V.1-5)}$$

Now premultiply (5) by $[\varphi]^T$ and obtain:

$$[\varphi]^T[m][\varphi]\{\ddot{\eta}\} + [\varphi]^T[c][\varphi]\{\dot{\eta}\} + [\varphi]^T[k][\varphi]\{\eta\} = [\varphi]^T\{F(t)\}. \qquad \text{(V.1-6)}$$

From the orthogonality relationship of the normal modes we observe that :

$$[\varphi]^T[m][\varphi] = [M] \text{ the generalized mass} \qquad \text{(V.1-7)}$$

$$[\varphi]^T[k][\varphi] = [K] = [\omega_i^2][M] \text{ generalized stiffness} \qquad \text{(V.1-8)}$$

$$[\varphi]^T[c][\varphi] = [C] \qquad \text{(V.1-9)}$$

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$$\left[C\right] = \left[2\zeta\right]\left[K\right]\left[\omega\right]^{-1} \quad \text{for Modal Damping} \qquad (V.1\text{-}9a)$$

$$\left[C\right] = \left[G\right]\left[K\right] \quad \text{for Uniform Damping} \qquad (V.1\text{-}9b)$$

$$\left[C\right] = \frac{1}{\Omega}\left[S\right]\left[K\right] \quad \text{for Structural Damping} \qquad (V.1\text{-}9c)$$

The now decoupled equations of motion become

$$\left[M\right]\left\{\ddot{\eta}\right\} + \left[C\right]\left\{\dot{\eta}\right\} + \left[K\right]\left\{\eta\right\} = \left[\varphi\right]^T\left\{F(t)\right\} \qquad (V.1\text{-}10)$$

Premultiplying by $\left[M\right]^{-1}$ we get:

$$\left\{\ddot{\eta}\right\} + \left[M\right]^{-1}\left[C\right]\left\{\dot{\eta}\right\} + \left[\omega^2\right]\left\{\eta\right\} = \left[M\right]^{-1}\left[\varphi\right]^T\left\{F(t)\right\} \qquad (V.1\text{-}11)$$

The nth equation is

$$\ddot{\eta}_n + \frac{C_n}{M_n}\dot{\eta}_n + \omega_n^2\,\eta_n = \frac{\left\{\varphi^n\right\}^T\left\{F(t)\right\}}{M_n} \qquad (V.1\text{-}12)$$

V.1.1.2 Modal Damping

The modal damping term represents one "generalized dash pot" associated with each mode of the system as opposed to individual dash pots connected to discrete points on the structure. These generalized dash pots tend to dampen the motion of the generalized masses acting on the generalized springs of each mode. Each mode of the system can have a discrete value of modal damping. The equations of motion in generalized coordinates with modal damping are of the form

$$\ddot{\eta}_n + 2\zeta_n\,\omega_n\,\dot{\eta}_n + \omega_n^2\,\eta_n = \frac{\left\{\varphi^n\right\}^T\left\{F(t)\right\}}{M_n} \qquad (V.1\text{-}13)$$

thus, referring back to Equation V.1-12 we can see that C_n has the value

$$\frac{2\,\zeta_n\,K_n}{\omega_n}$$

and

$$\frac{C_n}{M_n} = \frac{2\zeta_n\,K_n}{M_n\,\omega_n} = 2\,\zeta_n\omega_n$$

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V.1.1.3 Modal Extraction

The preceding modal analysis is predicated upon the ability to extract sets of orthogonal modal vectors, $\{\varphi\}_n$, from the undamped homogeneous equations of motion. For this analysis we have used the "Householder-QR" technique. This technique consists of Householder's method to form a tri-diagonal dynamical matrix. Roots and vectors are subsequently found by application of a QR iteration.

The homogeneous, undamped equations of motion are obtained from Equation V.1-5 and rewritten as:

$$\left[[k] - \omega_n^2 \; \lceil m \rfloor \right] \{\varphi\}_n = \{0\}, \qquad \text{(V.1-14)}$$

where:

$[k]$ is the symmetric stiffness matrix (known)

$\lceil m \rfloor$ is the diagonal mass matrix (known)

ω_n^2 is the nth eigenvalue (unknown)

$\{\varphi\}_n$ is the nth eigenvector (unknown)

Prior to the application of the "Householder-QR" method, zeros are eliminated from the $\lceil m \rfloor$ matrix by transformation techniques. These transformation techniques express the dependency between the "zero-mass" equations and the "non-zero-mass" equations. By this method, the order of the resultant problem can be reduced significantly.

V.1.2 Results

Modal analysis was performed for each of the three Traffic Signal and Lighting Standards using the Householder-QR process of MRI's STARDYNE Structural Analysis System. The models described in Section II of this report were used for this analysis. Tables V-1, V-2 and V-3 show for Traffic Signal and Lighting Standards Types XXI, XIX, and XXVI, respectively, the generalized results of the first 12 normal modes for each structure. The participation factor, γ_n, corresponds to a generalized force for base motion acceleration.

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γ_n is calculated as follows:

$$\gamma_n = \frac{\sum_i m_i \varphi_{in}}{\sum_i m_i \varphi^2_{in}},$$

where

m_i = the mass associated with the ith DOF

φ_{in} = the normalized mode displacement of ith DOF and the nth mode

$\sum_i m_i \varphi^2_{in}$ = the generalized mass

It is a quantity not used in the response solution discussed below, but it gives good insight into the importance of each mode. Appendix A contains a complete tabulation of these modal vectors.

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Mode Number	Frequency (cps)	Generalized Weight (lbs)	γ_1	γ_2	γ_3
1	.698	115.9	.000	1.341	.000
2	.742	225.6	.854	.000	-.420
3	1.584	154.7	.914	.000	.643
4	2.205	105.4	.000	.901	.000
5	7.341	167.6	.611	.000	-.041
6	7.381	191.0	.000	.574	.000
7	13.178	54.7	.000	.411	.000
8	13.525	52.1	-.492	.000	.558
9	20.840	191.8	.000	-.371	.000
10	21.866	172.0	-.377	.000	-.154
11	37.788	129.0	-.280	.000	-.080
12	37.912	118.2	.000	-.291	.000

Table V-1 Generalized Modal Characteristics Lighting Standard Type XXI

Mode Number	Frequency (cps)	Generalized Weight (lbs)	γ_1	γ_2	γ_3
1	1.041	279.8	.000	1.573	.000
2	1.079	309.1	-.980	.000	1.036
3	1.500	133.9	.000	.184	.000
4	1.596	128.7	-.175	.000	.067
5	2.828	497.1	1.124	.000	.380
6	3.113	264.7	.000	1.151	.000
7	6.492	276.9	.000	-.114	.000
8	6.880	362.9	.041	.000	-.416
9	8.875	664.9	-.614	.000	-.240
10	10.394	1127.3	.000	.027	.000
11	11.640	96.0	.000	-1.013	.000
12	16.207	46.3	-.699	.000	.058

Table V-2 Generalized Modal Characteristics Traffic Signal and Lighting Standard Type XIX

Mode Number	Frequency (cps)	Generalized Weight (lbs)	γ_1	γ_2	γ_3
1	.809	251.3	.000	1.875	.000
2	1.060	318.4	-1.163	.000	1.355
3	1.554	105.2	.000	1.406	.000
4	1.735	107.2	-.137	.000	.353
5	2.627	257.7	1.666	.000	-.059
6	2.664	511.4	.000	-1.109	.000
7	4.158	522.5	.000	.558	.000
8	6.943	582.8	1.190	.000	.674
9	9.177	549.3	.000	-.159	.000
10	9.847	2129.6	.000	.013	.000
11	10.361	284.6	.581	.000	.150
12	11.717	366.8	-.291	.000	-.521

Table V-3 Generalized Modal Characteristics Traffic Signal and Li[illegible]
Standard Type XXVI

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γ_n is calculated as follows:

$$\gamma_n = \frac{\sum_i m_i \varphi_{in}}{\sum_i m_i \varphi^2_{in}},$$

where m_i = the mass associated with the ith DOF

φ_{in} = the normalized mode displacement of ith DOF and the nth mode

$\sum_i m_i \varphi^2_{in}$ = the generalized mass

It is a quantity not used in the response solution discussed below, but it gives good insight into the importance of each mode. Appendix A contains a complete tabulation of these modal vectors.

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Mode Number	Frequency (cps)	Generalized Weight (lbs)	γ_1	γ_2	γ_3
1	.698	115.9	.000	1.341	.000
2	.742	225.6	.854	.000	-.420
3	1.584	154.7	.914	.000	.643
4	2.205	105.4	.000	.901	.000
5	7.341	167.6	.611	.000	-.041
6	7.381	191.0	.000	.574	.000
7	13.178	54.7	.000	.411	.000
8	13.525	52.1	-.492	.000	.558
9	20.840	191.8	.000	-.371	.000
10	21.866	172.0	-.377	.000	-.154
11	37.788	129.0	-.280	.000	-.080
12	37.912	118.2	.000	-.291	.000

Table V-1 Generalized Modal Characteristics Lighting Standard Type XXI

Mode Number	Frequency (cps)	Generalized Weight (lbs)	γ_1	γ_2	γ_3
1	1.041	279.8	.000	1.573	.000
2	1.079	309.1	-.980	.000	1.036
3	1.500	133.9	.000	.184	.000
4	1.596	128.7	-.175	.000	.067
5	2.828	497.1	1.124	.000	.380
6	3.113	264.7	.000	1.151	.000
7	6.492	276.9	.000	-.114	.000
8	6.880	362.9	.041	.000	-.416
9	8.875	664.9	-.614	.000	-.240
10	10.394	1127.3	.000	.027	.000
11	11.640	96.0	.000	-1.013	.000
12	16.207	46.3	-.699	.000	.058

Table V-2 Generalized Modal Characteristics Traffic Signal and Lighting Standard Type XIX

Mode Number	Frequency (cps)	Generalized Weight (lbs)	γ_1	γ_2	γ_3
1	.809	251.3	.000	1.875	.000
2	1.060	318.4	-1.163	.000	1.355
3	1.554	105.2	.000	1.406	.000
4	1.735	107.2	-.137	.000	.353
5	2.627	257.7	1.666	.000	-.059
6	2.664	511.4	.000	-1.109	.000
7	4.158	522.5	.000	.558	.000
8	6.943	582.8	1.190	.000	.674
9	9.177	549.3	.000	-.159	.000
10	9.847	2129.6	.000	.013	.000
11	10.361	284.6	.581	.000	.150
12	11.717	366.8	-.291	.000	-.521

Table V-3 Generalized Modal Characteristics Traffic Signal and Lighting Standard Type XXVI

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V.2 Dynamic Random Gust Response

V.2.1 Analytic Method

The random loading associated with a gust environment gives rise to the requirement for power spectral density analysis procedures. As an initial step the spectra of wind velocities is defined (Reference III. 7) by the following equation (evaluated in Section III. 3).

$$S_V(f) = \frac{4K\bar{V}_1}{f} \cdot \frac{x^2}{[1+x^2]^{4/3}}$$

Where:

$$x = \frac{4000f}{\bar{V}_1}$$

f = Frequency in cycles per second

$\bar{V}_1$ = Mean hourly wind speed at 30 ft

K = Drag coefficient at 30 ft.

A basic assumption is that all points on the structure are completely correlated. That is, the gust excitation affects all points simultaneously with equal magnitude. Inserting the gust excitation into a standard response solution for a multi-degree-of-freedom system (Reference V-1) and using Parseval's theorem to transform from time domain to frequency domain, the following expression is achieved:

$$\sigma_Y^2 = \sum_{R=1}^{N} \varphi_{YR}^2 \cdot \frac{\Gamma_R^2}{f_R^3 \cdot M_R^2 \cdot C_R} \cdot S_v(f)$$

This expression is based on quantities pertinent to vibration mode φ_R and reflects the simplifications of

1) zero coupling between modes
2) zero phase angle
3) constant values for S_v at each frequency

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where,

φ_R = R^{th} mode shape

Γ_R = R^{th} participation factor

= $\varphi_R^T \cdot F_j$

F_j = Vector of forces at each node j due to unit $S_v(f)$

M_R = R^{th} generalized mass

C_R = Damping in the Rth mode

= 4 x structural damping coefficient (constant)

σ_Y is the root mean square deflection Y. A value of the R.M.S. stress x at a point can be obtained by using a matrix,

$$A_R = S \cdot \varphi_R$$

where,

S = Matrix of all elemental stresses due to unit nodal displacements

Then,

A_{XR} = Stress x due to unit mode R

Hence, σ_x^2 is obtained by replacing φ_{YR}^2 with A_{XR}^2

Therefore, $$\sigma_x = \left[\sum_{R=1}^{N} A_{XR}^2 \cdot \frac{\Gamma_R^2}{f_R^3 \cdot M_R^2 \cdot C_R} \cdot S_v(f) \right]^{\frac{1}{2}}$$

Fatigue life is estimated by obtaining an "apparent frequency" for the system in its random environment. This is computed by evaluation of the number of times that a certain level of stress is exceeded. The level of stress that is used is σ_x. Hence, the "apparent frequency" is given by

$$f_x = \frac{1}{2\pi} \cdot \frac{\sigma_1}{\sigma_x} \cdot e^{-\frac{1}{2}} \quad \text{cycles per second}$$

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where,

$$\sigma_1 = \left[\sum_{R=1}^{N} A_{XR}^2 \cdot \frac{\Gamma_R^2 \cdot f_R^2}{f_R^3 \cdot M_R^2 \cdot C_R} \cdot S_v(f) \right]^{\frac{1}{2}} \qquad \text{(Ref. V-1)}$$

V.2.2 Results

The power spectrum of the wind load calculated in Section III. 3 in conjunction with the structural models of Section II. 2, the random response analytics discussed above, and a damping coefficient of .05 (5% of critical) were used to calculate the RMS stresses. The RMS stresses for each structure are shown in Tables V-4 through V-6.

V.3 Vortex Shedding Response

V.3.1 Steady State Response Analytics

The driving function for the kth point of load application is:

$$F_k(t) = F_{ko} \sin(\omega_k t - \beta_k) \qquad \text{(V.3-1}$$

where:

F_{ko} = is the peak force applied at the kth applied load location.

ω_k = is the circular driving frequency of the kth applied load.

β_k = is an arbitrary phase angle related to the kth applied load.

Equation (V.1-13) upon subsitution of Equation (V.3-1) becomes:

$$\ddot{\eta}_n + 2\zeta_n \omega_n \dot{\eta}_n + \omega_n^2 \eta_n = \frac{\sum_k \varphi_{kn} F_{ko} \sin(\omega_k t - \beta_k)}{M_n} \qquad \text{(V.3-2)}$$

Standard solutions exist for the relation where (for example, see page 73, Scanlan and Rosenbaum):

$$\ddot{\eta}_n + 2\zeta_n \omega_n \dot{\eta}_n + \omega_n^2 \eta_n = \sin \omega t \qquad \text{(V.3-3)}$$

These solutions are of the form:

$$\eta_n = A_n \sin(\omega t - \psi_n) \qquad \text{(V.3-4)}$$

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			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.3031737E-09	.2390648E+02	.1810950E+03	.1496263E+03	.1640298E-06	.1367690E-06	.1707696E+01	.1423701E-08
2	2	3	.1059240E-09	.2926113E+02	.1852166E+03	.1464327E+03	.1791795E-06	.1374742E-06	.1830376E+01	.1530334E-08
3	3	4	.3293121E-09	.3692902E+02	.1881309E+03	.1410657E+03	.1762868E-06	.1371725E-06	.1989852E+01	.1641062E-08
4	4	5	.2030236E-09	.4593713E+02	.1782577E+03	.1229825E+03	.1728149E-06	.1300860E-06	.1939881E+01	.1495689E-08
5	5	6	.1992116E-09	.6315624E+02	.1726068E+03	.1018491E+03	.1316108E-06	.1305187E-06	.2183274E+01	.1588007E-08
6	6	7	.3374002E-09	.9956648E+02	.1459885E+03	.5588195E+02	.1853621E-06	.1124422E-06	.2292434E+01	.1890425E-08
7	7	8	.6479658E-09	.5858979E-01	.2319661E+03	.1418121E+03	.1413193E-06	.8880334E-07	.2253072E+01	.1307114E-08
8	8	9	.9175035E-09	.7078421E-01	.2059115E+03	.9266104E+02	.1289816E-06	.5662516E-07	.2277774E+01	.1452323E-08
9	9	10	.1097740E-08	.3041671E-10	.1462313E+03	.9269780E+00	.8940828E-07	.5667700E-09	.2260106E+01	.1381867E-08

Table V-4 RMS Random Dynamic Stress
$\bar{V}_{30}$ = 80 Mph Recurrence Interval 50 years
Lighting Standard Type XIX

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.2059498E-09	.4794982E+02	.1422114E+03	.1061687E+03	.1269025E-06	.1020780E-06	.2535794E+01	.1750524E-08
2	2	3	.2969926E-09	.5600382E+02	.1304098E+03	.8941832E+02	.1236297E-06	.9550655E-07	.2652696E+01	.1826028E-08
3	3	5	.5570033E-09	.6507533E+02	.1102597E+03	.6415569E+02	.1152914E-06	.8440312E-07	.2739542E+01	.1844483E-08
4	4	5	.2917882E-09	.1314903E+02	.2948621E+02	.4429473E+02	.2281999E-07	.3686948E-07	.9432227E+00	.9254329E-09
5	4	6	.8607194E-10	.1547987E+02	.3698457E+02	.2132786E+02	.2843570E-07	.2239890E-07	.9078404E+00	.3514693E-09
6	5	7	.2138847E-09	.7502653E+01	.1642890E+03	.1144499E+03	.8210123E-07	.6039774E-07	.1984756E+01	.8646058E-09
7	6	8	.1092730E-09	.1850045E+02	.2756578E+02	.1133227E+02	.2780459E-07	.1743785E-07	.8487232E+00	.5697619E-09
8	7	9	.1106870E-09	.9092791E+01	.1563571E+03	.9633430E+02	.8218460E-07	.5094900E-07	.2029645E+01	.1055597E-08
9	8	10	.1202731E-08	.1439515E+02	.2445136E+03	.1455159E+03	.1136932E-06	.6452814E-07	.2330821E+01	.1160515E-08
10	9	11	.2557710E-09	.6239850E+01	.1403996E+03	.7012277E+02	.7325774E-07	.3783132E-07	.2016064E+01	.1016040E-08
11	10	12	.7589718E-09	.6371900E+01	.2002339E+03	.8838789E+02	.8739244E-07	.3809674E-07	.2225934E+01	.9810197E-09
12	11	13	.5792145E-09	.5033884E+01	.1041381E+03	.5063137E+02	.5570242E-07	.2700290E-07	.1665731E+01	.8933823E-09
13	12	14	.9157573E-09	.1304555E-12	.1458312E+03	.9767078E+00	.6224400E-07	.4168805E-09	.2324494E+01	.9921453E-09
14	13	15	.5856819E-09	.5895526E+01	.7764989E+02	.1715634E+02	.4112357E-07	.1010824E-07	.1498593E+01	.7683439E-09
15	15	16	.5581109E-10	.8258706E+01	.2641179E+02	.7846928E+00	.1539056E-07	.8440734E-09	.8160868E+00	.4365876E-09

Table V-5 RMS Random Dynamic Stresses
$\bar{V}_{30}$ = 80 Mph Recurrence Interval 50 Years
Traffic Signal and Lighting Standard Type XIX

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			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/II-22	VQ/IT-33
1	1	5	.5140471E-09	.5911123E+02	.1044424E+03	.7549402E+02	.1197811E-06	.7519528E-07	.2251841E+01	.3502591E-08
2	2	3	.2947484E-08	.7831670E-12	.4815816E+00	.7113038E+02	.4850989E-08	.7164989E-06	.1144182E+01	.1152538E-07
3	3	4	.3795557E-08	.3642650E+01	.4180165E+02	.9481489E+02	.4277792E-06	.9169514E-06	.1067027E+01	.9867967E-08
4	4	6	.3326744E-08	.7413172E+01	.6737084E+02	.1131422E+03	.6658662E-06	.1053802E-05	.1081445E+01	.9294428E-08
5	5	7	.6414736E-09	.6768432E+02	.9265053E+02	.6038719E+02	.9555040E-07	.4767170E-07	.2325253E+01	.3577564E-08
6	6	8	.1546408E-08	.4654856E+01	.2765903E+01	.7446261E+01	.9082783E-07	.8621877E-07	.2599631E+00	.3343199E-09
7	7	9	.2713693E-09	.7549155E+02	.7336818E+02	.3844421E+02	.6201458E-07	.1311230E-07	.2316599E+01	.3549949E-08
8	8	10	.9609460E-09	.4076041E+01	.5901283E+01	.1097061E+02	.7650932E-07	.6582148E-07	.3119330E+00	.7691759E-09
9	9	10	.7576582E-09	.5248345E+02	.3247614E+02	.1801731E+02	.2440242E-07	.5121478E-07	.1362276E+01	.6741505E-08
10	9	11	.2292444E-08	.8645906E+01	.1835057E+03	.1012008E+03	.9500566E-08	.9606946E-08	.2042990E+01	.4663491E-09
11	10	12	.3139146E-08	.4543904E+01	.1624410E+03	.1275710E+03	.2905925E-07	.1335335E-07	.1159596E+01	.1394579E-08
12	11	12	.1747002E-08	.1652772E+01	.8484917E+02	.8970264E+02	.8516080E-07	.1119284E-06	.7177047E+00	.1944315E-07
13	11	13	.4865731E-08	.7181699E+01	.1581117E+03	.8782211E+02	.3054162E-07	.1801838E-07	.1570520E+01	.1082692E-08
14	12	14	.2959692E-08	.3795146E+01	.1756493E+03	.1230394E+03	.2437945E-07	.1758979E-07	.1648548E+01	.1312551E-08
15	13	15	.5920345E-08	.8301348E+01	.1465364E+03	.5208052E+02	.2843237E-07	.3822802E-07	.1576925E+01	.1711168E-09
16	14	15	.3383966E-08	.1469483E+01	.1765016E+03	.1158606E+03	.2296961E-07	.6646307E-07	.1566695E+01	.1131554E-08
17	15	16	.9528201E-09	.4559133E+01	.2017735E+03	.1242992E+03	.1181268E-06	.1030054E-06	.2636131E+01	.5444391E-09
18	16	17	.9061005E-09	.3392672E+01	.1760169E+03	.8220893E+02	.1427461E-06	.8158983E-07	.2142432E+01	.1395437E-08
19	17	18	.5689773E-09	.5223327E+01	.1295739E+03	.2085499E+02	.1278268E-06	.2951996E-07	.1873463E+01	.1693296E-08
20	18	19	.4498749E-09	.7743534E+01	.3325545E+02	.9606610E+00	.4605638E-07	.8030717E-08	.9674430E+00	.1075516E-08

Table V - 6 RMS Random Dynamic Stresses
$\overline{V}_{30}$ = 80 Mph Recurrence Interval 50 Years
Traffic Signal and Lighting Standard Type XXVI

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where

$$A_n = \frac{1/\omega_n^2}{\left[\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\zeta_n \frac{\omega}{\omega_n}\right)^2 \right]^{1/2}} \qquad \text{(V.3-4a)}$$

$$\psi_n = \tan^{-1} \left\{ \frac{2\zeta_n \left(\frac{\omega}{\omega_n}\right)}{1 - \left(\frac{\omega}{\omega_n}\right)^2} \right\} \qquad \text{(V.3-4b)}$$

Simple summation of these standard cases yields a solution to equation (V.3-2) of the

$$\eta_n = \frac{\sum_k \varphi_{kn} F_{ko} A_{kn} \sin(\omega_k t - \psi_{kn} - \beta_k)}{M_n} \qquad \text{(V.3-5)}$$

where

$$A_{kn} = \frac{1/\omega_n^2}{\left[\left(1 - \frac{\omega_k^2}{\omega_n^2}\right)^2 + \left(2\zeta_n \frac{\omega_k}{\omega_n}\right)^2 \right]^{1/2}} \qquad \text{(V.3.5a)}$$

$$\psi_{kn} = \tan^{-1} \left\{ \frac{2\zeta_n \left(\frac{\omega_k}{\omega_n}\right)}{1 - \left(\frac{\omega_k}{\omega_n}\right)^2} \right\} \qquad \text{(V.3-5b)}$$

Separating equation (V.3-5) into real (in phase) and imaginary (out of phase) parts:

$$\eta_n = \eta_n' + i\,\eta_n'' \qquad \text{(V.3-6)}$$

$$\eta_n' = \frac{\sum_k \varphi_{kn} F_{ko} A_{kn} \cos(\psi_{kn} + \beta_k)}{Mn} \qquad \text{(V.3-7)}$$

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$$\eta''_n = \frac{= \sum_k \varphi_{kn} F_{ko} A_{kn} \sin(\psi_{kn} + \beta_k)}{M_n} \qquad \text{(V.3-8)}$$

The real and imaginary displacement response at degree of freedom, i, is found as:

$$\mathrm{Re}\,(x_i) = \sum_n \varphi_{in}\, \eta'_n \qquad \text{(V.3-9)}$$

$$\mathrm{Im}\,(x_i) = \sum_n \varphi_{in}\, \eta''_n \qquad \text{(V.3-10)}$$

Maximum displacement response at degree of freedom, j, is found to occur at a phase angle of:

$$\psi_{\max j} = \tan^{-1} \left[\frac{\mathrm{Im}\,(xj)}{\mathrm{Re}\,(xj)} \right] \qquad \text{(V.3-11)}$$

and have a magnitude of

$$|xj|_{\max} = [\mathrm{Re}\,(xj)^2 + \mathrm{Im}\,(xj)^2]^{1/2} \qquad \text{(V.3-12)}$$

The corresponding consistent displacement vector at which xj is a maximum (all in phase) is:

$$\{x\} = [\varphi]\, \{\underline{\eta_{jn}}\} \qquad \text{(V.3-13)}$$

where:

$$\eta_{jn} = \frac{\sum_k \varphi_{kn} F_{ko} A_{kn} \cos(\psi_{kn} + \beta_k - \psi_{\max j})}{Mn} \qquad \text{(V.3-14)}$$

Since we do not, in general, know the phase relations, β_k, between points of loading application, we are forced to select a set of input loading phase angles, β_k, which maximize response:

$$\psi_{kn} + \beta_k - \psi_{\max j} = 0 \qquad \text{(V.3-15)}$$

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If we assume the mode, m, dominates:

$$\beta_k = \psi_{max\ j} - \psi_{km}$$

But, if the mth mode dominates:

$$\psi_{max\ j} = \psi_{km}$$

Hence, $\beta_k = 0.$ (V.3-16)

Thus, this will be the assumption used throughout this analysis.

V.3.2 Results

The loads and frequencies calculated in Section III.4, the structural model data of Section II.2, the modal vectors of Section V.1, and a damping coefficient of .05 were used in conjunction with the analytics discussed above to calculate the vortex shedding stresses. The steady state vortex shedding stresses for each structure and recurrence interval are shown in Tables V-7 through V-15 respectively.

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	.84357E-03	-.55592E-10	.47701E-06	.13829E-11	.22723E-04	-.27687E-13
3	.32550E-02	-.17837E-09	.10049E-05	.18704E-11	.44111E-04	-.65129E-13
4	.70381E-02	-.28891E-09	.15940E-05	.10711E-11	.61350E-04	-.11727E-12
5	.11742E-01	-.29059E-09	.22614E-05	-.10722E-11	.69682E-04	-.19343E-12
6	.16435E-01	-.10847E-09	.30324E-05	-.38476E-11	.60127E-04	-.31051E-12
7	.19225E-01	.24080E-09	.39420E-05	-.55049E-11	.14856E-04	-.50332E-12
8	.18899E-01	.29363E-09	.10178E-02	-.51917E-11	-.44467E-04	-.14749E-11
9	.17395E-01	.21282E-09	.56719E-02	-.43189E-11	-.10353E-03	-.41906E-11
10	.14930E-01	-.58022E-10	.13338E-01	-.35724E-11	-.13975E-03	-.65114E-11

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES				SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.2035615E+00	-.1845009E-07	.3428790E-05	-.1363023E-05	.4600416E+02	-.3273331E+02	-.1077518E-06	.6922172E+00
2	2	3	.2249593E+00	-.2258260E-07	.1868407E-05	.3393298E-06	.4140959E+02	-.2567297E+02	-.1031104E-06	.7349651E+00
3	3	4	.2513801E+00	-.2850037E-07	-.2682241E-06	.2003569E-05	.3373071E+02	-.1526277E+02	-.7255312E-07	.7721270E+00
4	4	5	.2848310E+00	-.3537530E-07	-.2411302E-05	.2765407E-05	.2014974E+02	.2322353E-01	-.1229754E-07	.7005774E+00
5	5	6	.3285524E+00	-.4874152E-07	-.3828649E-05	.2179533E-05	.1070694E+01	.2175644E+02	.5043667E-07	.6981465E+00
6	6	7	.3881366E+00	-.6835369E-07	-.3143145E-05	-.8787871E-07	-.2959248E+02	.5386525E+02	.8162778E-07	.6172212E+00
7	7	8	.3932652E+00	.2381878E-09	-.1567610E-06	.1738162E-05	.6669459E+02	-.4342780E+02	-.3934570E-07	.5788842E+00
8	8	9	.3767412E+00	-.1514958E-08	-.2462807E-05	.2001999E-05	.6296271E+02	-.2948885E+02	.9259941E-08	.6726581E+00
9	9	10	.3708846E+00	.4121782E-19	-.3129714E-05	-.1983964E-07	.4649934E+02	.2947650E+00	.4837190E-07	.7186795E+00

Table V-7 Steady State Vortex Shedding Stresses and Deflections

$\overline{V}_{CRIT}$ = 12.42 Mph

Lighting Standard Type XXI

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	.70397E-03	-.33634E-10	.24538E-06	.83634E-12	.19103E-04	-.15327E-13
3	.27627E-02	-.10782E-09	.51693E-06	.11290E-11	.38171E-04	-.36054E-13
4	.61144E-02	-.17436E-09	.81994E-06	.64055E-12	.55606E-04	-.64921E-13
5	.10557E-01	-.17457E-09	.11633E-05	-.66414E-12	.68740E-04	-.10708E-12
6	.15616E-01	-.62916E-10	.15598E-05	-.23532E-11	.72327E-04	-.17190E-12
7	.20239E-01	.15050E-09	.20277E-05	-.33632E-11	.55813E-04	-.27863E-12
8	.21037E-01	.18489E-09	-.24777E-02	-.31757E-11	.28694E-04	-.86024E-12
9	.21297E-01	.13871E-09	-.32818E-02	-.26486E-11	.13784E-05	-.25005E-11
10	.21107E-01	-.22350E-10	-.26883E-02	-.21971E-11	-.15469E-04	-.39041E-11

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES				SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.1047121E+00	-.1021377E-07	.2075504E-05	-.8225312E-06	.3790178E+02	-.2829381E+02	-.6535590E-07	.5011587E+00
2	2	3	.1157183E+00	-.1250148E-07	.1128097E-05	.2102175E-06	.3560519E+02	-.2419684E+02	-.6250482E-07	.5328168E+00
3	3	4	.1293075E+00	-.1577750E-07	-.1683087E-06	.1219907E-05	.3150394E+02	-.1805040E+02	-.4396633E-07	.5624794E+00
4	4	5	.1465118E+00	-.1958339E-07	-.1466392E-05	.1682903E-05	.2328634E+02	-.8436369E+01	-.7450021E-08	.5157176E+00
5	5	6	.1689976E+00	-.2698278E-07	-.2329975E-05	.1326540E-05	.1244058E+02	.4675672E+01	.3068912E-07	.5234847E+00
6	6	7	.1996409E+00	-.3783987E-07	-.1912987E-05	-.5102696E-07	-.5860282E+01	.2458400E+02	.4961837E-07	.4730314E+00
7	7	8	.2762722E+00	.1421104E-09	-.8559850E-07	.1048767E-05	.3030696E+02	-.2003456E+02	-.2396389E-07	.2555802E+00
8	8	9	.2645286E+00	-.9162608E-09	-.1485796E-05	.1210864E-05	.2903646E+02	-.1371825E+02	.5524774E-08	.3078197E+00
9	9	10	.2605594E+00	.3289499E-19	-.1892880E-05	-.1199920E-07	.2162776E+02	.1371010E+00	.2925577E-07	.3342720E+00

Table V - 8 Steady State Vortex Shedding Stresses and Deflections

$\bar{V}_{CRIT}$ = 11.634 Mph

Lighting Standard Type XXI

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	.47628E-03	-.54983E-10	.59770E-06	.13679E-11	.13216E-04	-.28304E-13
3	.19585E-02	-.17647E-09	.12380E-05	.18516E-11	.28345E-04	-.66580E-13
4	.45444E-02	-.28603E-09	.19636E-05	.10641E-11	.44079E-04	-.11989E-12
5	.81276E-02	-.28821E-09	.27854E-05	-.10505E-11	.55441E-04	-.19774E-12
6	.11975E-01	-.10903E-09	.37344E-05	-.37890E-11	.49411E-04	-.31744E-12
7	.13891E-01	.23506E-09	.48535E-05	-.54234E-11	-.17660E-05	-.51454E-12
8	.13100E-01	.28573E-09	.24688E-02	-.51123E-11	-.75610E-04	-.14794E-11
9	.10813E-01	.20406E-09	.95460E-02	-.42485E-11	-.15141E-03	-.41672E-11
10	.72819E-02	-.65625E-10	.20527E-01	-.35101E-11	-.19867E-03	-.64628E-11

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.2507951E+00	-.1886131E-07	.3390544E-05	-.1349462E-05	.2463229E+02	-.2116380E+02	-.1064643E-06	.1809188E+00
2	2	3	.2771289E+00	-.2308593E-07	.1849437E-05	.3324527E-06	.2629472E+02	-.2115335E+02	-.1019033E-06	.2401231E+00
3	3	4	.3096156E+00	-.2913560E-07	-.2614105E-06	.1976690E-05	.2724743E+02	-.1747139E+02	-.7171421E-07	.4087268E+00
4	4	5	.3507182E+00	-.3616376E-07	-.2378816E-05	.2728718E-05	.2249161E+02	-.4951392E+01	-.1215158E-07	.6091458E+00
5	5	6	.4044134E+00	-.4982789E-07	-.3777839E-05	.2150499E-05	.7949313E+01	.2100315E+02	.4977067E-07	.8854841E+00
6	6	7	.4775657E+00	-.6987718E-07	-.3101302E-05	-.8829888E-07	-.2819241E+02	.6615329E+02	.8058129E-07	.9590344E+00
7	7	8	.5800038E+00	.2368625E-09	-.1610199E-06	.1720937E-05	.8174391E+02	-.5533552E+02	-.3881118E-07	.6570479E+00
8	8	9	.5555792E+00	-.1498548E-08	-.2438533E-05	.1980289E-05	.8015446E+02	-.3849104E+02	.9208417E-08	.8372275E+00
9	9	10	.5471265E+00	.3329132E-19	-.3095811E-05	-.1962472E-07	.6066401E+02	.3845566E+00	.4784791E-07	.9376044E+00

Table V - 9 Steady State Vortex Shedding Stresses and Deflections
$\overline{V}_{CRIT}$ = 30.824 Mph
Lighting Standard Type XXI

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	-.14560E-03	-.18402E-12	.12226E-06	.55763E-14	-.44331E-05	.63559E-14
3	-.58859E-03	-.73696E-12	.25453E-06	.11493E-13	-.92676E-05	.14341E-13
4	-.22295E-02	-.28725E-11	.49440E-06	.25979E-13	-.17996E-04	.17890E-13
5	-.13517E-02	-.16772E-11	.39669E-06	.17688E-13	-.14409E-04	.24334E-13
6	-.33099E-02	-.44764E-11	.60032E-06	.32719E-13	-.21897E-04	.96857E-14
7	-.17853E-02	.50601E-12	.11152E-02	.12740E-13	-.16416E-04	.46864E-13
8	-.46122E-02	-.63841E-11	.71595E-06	.37252E-13	-.26201E-04	-.98735E-15
9	-.22570E-02	.45514E-11	.23731E-02	.87012E-14	-.18344E-04	.71698E-13
10	-.60169E-02	-.10922E-10	.30108E-02	.60998E-13	-.70537E-04	-.95495E-13
11	-.26230E-02	.10557E-10	.37598E-02	.59957E-14	-.19963E-04	.96450E-13
12	-.77543E-02	-.20664E-10	.84969E-02	.76393E-13	-.10758E-03	-.17500E-12
13	-.28073E-02	.16220E-10	.48655E-02	.50810E-14	-.20872E-04	.11328E-12
14	-.89760E-02	-.33886E-10	.15826E-01	.84303E-13	-.12937E-03	-.22247E-12
15	-.28711E-02	.22729E-10	.60124E-02	.47566E-14	-.21469E-04	.12576E-12
16	-.28711E-02	.27322E-10	.67879E-02	.47634E-14	-.21576E-04	.12847E-12

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES				SHEAR STRESSES	
MEMBER	JA	JP	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.5730881E-01	.5947177E-08	.1483902E-07	-.1229334E-07	-.1163807E+02	.9931735E+01	-.1789295E-09	-.1199342E+00
2	2	3	.6200439E-01	.6946107E-08	.1490779E-07	-.1195433E-07	-.1190310E+02	.9965260E+01	-.1843762E-09	-.1252132E+00
3	3	5	.6663384E-01	.8071239E-08	.1429248E-07	-.1172593E-07	-.1187894E+02	.9715005E+01	-.1520869E-09	-.1282290E+00
4	4	5	.5428262E-01	-.5673148E-08	-.1484219E-07	.2311388E-07	-.7479153E+01	.8941223E+01	-.5261832E-09	.9300599E-01
5	4	6	.5884690E-01	-.6678787E-08	.1875713E-07	-.9776552E-08	-.9029024E+01	.7486498E+01	-.5201605E-09	-.8934401E-01
6	5	7	-.1239662E-01	.1993544E-08	-.3845787E-07	.2800994E-07	-.3545367E+01	.2307778E+01	.4156330E-09	-.4923298E-01
7	6	8	.6423659E-01	-.7982018E-08	.1280258E-07	-.4826228E-08	-.9150042E+01	.7585318E+01	-.4166628E-09	-.8173689E-01
8	7	9	-.1133349E-01	.2426826E-09	-.3815189E-07	.2488217E-07	-.3163047E+01	.1764100E+01	.4487413E-09	-.4727246E-01
9	8	10	-.1346796E-01	-.6236834E-08	.1054702E-06	-.6273927E-07	-.4846250E+02	.2948002E+02	-.1005650E-08	-.4467424E+00
10	9	11	-.1253731E-01	.1607986E-08	-.3620258E-07	.1944859E-07	-.2551952E+01	.1106712E+01	.4804157E-09	-.4144184E-01
11	10	12	-.3853816E-01	-.2787235E-08	-.8633711E-07	.3867500E-07	.3986956E+02	-.1768832E+02	.9484458E-09	.4413925E+00
12	11	13	-.1077990E-01	.9294067E-09	.2884485E-07	-.1457342E-07	.1636052E+01	-.7215048E+00	-.4442423E-09	.2846812E-01
13	12	14	-.7656152E-01	.7671141E-22	-.6379037E-07	-.4272374E-09	.2888917E+02	.1934858E+00	.1016794E-08	.4604822E+00
14	13	15	-.1128336E-01	.1563263E-09	.2232255E-07	-.5222854E-08	.1105409E+01	-.2111679E+00	-.4235879E-09	.2215184E-01
15	15	16	-.6220488E-02	.3742868E-11	.8013023E-08	.2380665E-09	.3290931E+00	.2097673E-01	-.2475910E-09	.1050457E-01

Table V-10 Steady State Vortex Shedding Stresses and Deflections

$\overline{V}_{CRIT}$ = 6.83 Mph

Traffic Signal and Lighting Standard Type XIX

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	-.13742E-03	-.16909E-12	.11625E-06	.51193E-14	-.41926E-05	.58648E-14
3	-.55778E-03	-.67613E-12	.24203E-06	.10531E-13	-.88189E-05	.13233E-13
4	-.21002E-02	-.26287E-11	.43830E-06	.23698E-13	-.16227E-04	.16723E-13
5	-.12869E-02	-.15370E-11	.37720E-06	.16183E-13	-.13816E-04	.22454E-13
6	-.30482E-02	-.40898E-11	.50453E-06	.29770E-13	-.18794E-04	.94281E-14
7	-.17319E-02	.46974E-12	.11446E-02	.11741E-13	-.17730E-04	.42993E-13
8	-.41406E-02	-.58233E-11	.57682E-06	.33816E-13	-.21564E-04	-.62887E-16
9	-.22691E-02	.41762E-11	.25770E-02	.81161E-14	-.21731E-04	.65758E-13
10	-.51701E-02	-.98327E-11	.22066E-02	.54841E-13	-.49657E-04	-.84357E-13
11	-.27207E-02	.96903E-11	.42895E-02	.56541E-14	-.25391E-04	.88753E-13
12	-.53638E-02	-.18494E-10	.59758E-02	.68615E-13	-.72966E-04	-.15588E-12
13	-.29607E-02	.14913E-10	.57281E-02	.47726E-14	-.27660E-04	.10468E-12
14	-.71848E-02	-.30313E-10	.10902E-01	.75792E-13	-.86614E-04	-.19894E-12
15	-.30466E-02	.20941E-10	.72744E-02	.44035E-14	-.29269E-04	.11665E-12
16	-.30466E-02	.25205E-10	.83365E-02	.43407E-14	-.29627E-04	.11930E-12

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	.5449383E-01	.5487681E-08	.1365808E-07	-.1125036E-07	-.1094370E+02	.9455829E+01	-.1692329E-09	-.1045786E+00
2	2	3	.5895871E-01	.6409432E-08	.1356132E-07	-.1091696E-07	-.1130845E+02	.9618595E+01	-.1708651E-09	-.1091898E+00
3	3	5	.6336066E-01	.7447633E-08	.1305729E-07	-.1068430E-07	-.1143778E+02	.9550906E+01	-.1406172E-09	-.1118114E+00
4	4	5	.3394099E-01	-.5044792E-08	-.1340717E-07	.2099124E-07	-.4952901E+01	.6071119E+01	-.4824417E-09	.7049649E-01
5	4	6	.3679433E-01	-.5939047E-08	.1695966E-07	-.8746725E-08	-.6011410E+01	.4859294E+01	-.4756979E-09	-.6673122E-01
6	5	7	-.8340875E-02	.1253185E-08	-.3497585E-07	.2554608E-07	-.6751245E+01	.4662205E+01	.3751291E-09	-.8310488E-01
7	6	8	.4016366E-01	-.7097933E-08	.1147152E-07	-.4262927E-08	-.5957628E+01	.4812045E+01	-.3765573E-09	-.5984211E-01
8	7	9	-.7258563E-02	.2260005E-08	-.3479577E-07	.2292754E-07	-.6364168E+01	.3961413E+01	.4010450E-09	-.8457178E-01
9	8	10	-.1765541E-01	-.5609990E-08	.9372329E-07	-.5619379E-07	-.3079849E+02	.1858904E+02	-.8832364E-09	-.2873426E+00
10	9	11	-.1040110E-01	.1515566E-08	-.3334430E-07	.1832810E-07	-.5560138E+01	.2711370E+01	.4305854E-09	-.8168759E-01
11	10	12	-.3321584E-01	-.2528750E-08	-.7732219E-07	.3509793E-07	.2514478E+02	-.1107674E+02	.8402360E-09	.2799452E+00
12	11	13	-.1050531E-01	.8716018E-09	.2715790E-07	-.1393499E-07	.3980809E+01	-.1901526E+01	-.4116041E-09	.6472414E-01
13	12	14	-.5746362E-01	-.1981711E-21	-.5787455E-07	-.3876160E-09	.1809361E+02	.1211823E+00	.9224980E-09	.2884051E+00
14	13	15	-.1314175E-01	.1254738E-09	.2132114E-07	-.5113634E-08	.2899177E+01	-.6518000E+00	-.4014868E-09	.5567124E-01
15	15	16	-.7788242E-02	-.3460851E-10	.7827091E-08	.2325424E-09	.9997345E+00	-.2543157E-01	-.2418460E-09	.2923598E-01

Table V - 11 Steady State Vortex Shedding Stresses and Deflections

$\bar{V}_{CRIT}$ = 7.736 Mph

Traffic Signal and Lighting Standard Type XIX

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	.65412E-03	.77489E-12	-.40413E-06	-.23223E-13	.19817E-04	-.23824E-13
3	.26180E-02	.30374E-11	-.84138E-06	-.46336E-13	.40792E-04	-.53754E-13
4	.95817E-02	.11328E-10	-.14944E-05	-.98337E-13	.72068E-04	-.67241E-13
5	.59435E-02	.67567E-11	-.13113E-05	-.68847E-13	.62223E-04	-.91211E-13
6	.13750E-01	.173595E-10	-.16929E-05	-.12263E-12	.81798E-04	-.36727E-13
7	.79197E-02	-.13792E-11	-.50825E-02	-.50565E-13	.77875E-04	-.17710E-12
8	.18439E-01	.24502E-10	-.19097E-05	-.13947E-12	.91388E-04	.29715E-14
9	.10249E-01	-.16746E-10	-.11294E-01	-.34857E-13	.93290E-04	-.27482E-12
10	.22387E-01	.41272E-10	-.84594E-02	-.22999E-12	.18263E-03	.34777E-12
11	.12166E-01	-.39851E-10	-.18556E-01	-.24371E-13	.10677E-03	-.37203E-12
12	.26654E-01	.76491E-10	-.21932E-01	-.28499E-12	.25466E-03	.62255E-12
13	.13167E-01	-.61655E-10	-.24564E-01	-.21853E-13	.11480E-03	-.43574E-12
14	.29507E-01	.12310E-09	-.39047E-12	-.31088E-12	.29940E-03	.77785E-12
15	.13522E-01	-.86601E-10	-.30946E-01	-.22680E-13	.12037E-03	-.48086E-12
16	.13522E-01	-.10413E-09	-.35309E-01	-.24965E-13	.12160E-03	-.48999E-12

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES				SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	2	-.1894360E+00	-.2229178E-07	-.6373743E-07	.4925933E-07	.5276813E+02	-.4365303E+02	.1017631E-08	.6406782E+00
2	2	3	-.2049592E+00	-.2503607E-07	-.6033974E-07	.4450924E-07	.5260273E+02	-.4227909E+02	.1003500E-08	.6670595E+00
3	3	5	-.2202661E+00	-.3025339E-07	-.5385480E-07	.4068956E-07	.5071660E+02	-.3929004E+02	.7801380E-09	.6771089E+00
4	4	5	-.1017404E+00	.2110122E-07	.5302015E-07	-.8197867E-07	.1937897E+02	-.2569211E+02	.1842125E-08	-.4015949E+00
5	4	6	-.1102998E+00	.2484168E-07	-.6687963E-07	.3597491E-07	.2376101E+02	-.1742650E+02	.1790019E-08	.3668986E+00
6	5	7	.8496682E-01	-.7902922E-08	.1432138E-06	-.1095651E-06	.2741381E+02	-.1823625E+02	-.1338590E-08	.3650962E+00
7	6	8	-.1204078E+00	.2968903E-07	-.4658900E-07	.1859985E-07	.2163463E+02	-.1566232E+02	.1477748E-08	-.3119772E+00
8	7	9	.7673627E-01	-.9634495E-08	.1439168E-06	-.8990736E-07	.2495525E+02	-.1443511E+02	-.1686852E-08	.3554911E+00
9	8	10	.1899261E+00	.2156345E-07	-.3939644E-06	.2226136E-06	.1010352E+03	-.5937313E+02	.4032645E-08	.9804937E+00
10	9	11	.8582271E-01	-.6373474E-08	.1439845E-06	-.7448986E-07	.2083703E+02	-.9640059E+01	-.1992740E-08	.3210701E+00
11	10	12	.2335021E+00	.9120178E-08	.3065551E-06	-.1263204E-06	-.8036031E+02	.3467357E+02	-.3586557E-08	-.9091372E+00
12	11	13	.7444443E-01	-.3983286E-08	-.1107099E-06	.5327056E-07	-.1420225E+02	.6602094E+01	.1787977E-08	-.2365783E+00
13	12	14	.3141414E+00	.6648322E-21	.2097300E-06	.1397974E-08	-.5666363E+02	-.3795059E+00	-.3327076E-08	-.9031964E+00
14	13	15	.3017099E-01	-.1413106E-08	-.8201541E-07	.1733981E-07	-.1008090E+02	.2223702E+01	.1602122E-08	-.1946359E+00
15	15	16	.4488002E-01	-.1259653E-08	-.2695269E-07	-.8007629E-09	-.3415744E+01	.8470589E-01	.8327998E-09	-.9995470E-01

Table V - 12 Steady State Vortex Loading Stresses and Deflections

$\overline{V}_{CRIT}$ = 14.13 Mph

Traffic Signal and Lighting Standard Type XIX

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	-.38850E-01	.10855E-10	.39280E-01	.74287E-12	-.28246E-03	.27306E-11
3	-.36569E-01	-.11475E-09	.22996E-01	.96401E-12	-.24905E-03	.11510E-11
4	-.32263E-01	-.12060E-09	.95417E-02	.10203E-11	-.19159E-03	-.21339E-12
5	-.98322E-03	-.17003E-10	.89275E-06	.44594E-12	-.30126E-04	.64980E-13
6	-.27684E-01	-.87338E-10	.13190E-05	.38279E-12	-.11998E-03	.29705E-12
7	-.39999E-02	-.50498E-10	.18473E-05	.50528E-12	-.63435E-04	.14438E-12
8	-.20597E-01	-.68256E-10	.11979E-05	.19948E-12	-.11595E-03	.38105E-12
9	-.92290E-02	-.71630E-10	.28395E-05	.63230E-13	-.99160E-04	.23942E-12
10	-.13771E-01	-.67949E-10	.10827E-05	-.26986E-12	-.11126E-03	.44891E-12
11	-.13325E-01	-.40935E-10	.11617E-01	-.34282E-11	-.11096E-03	-.79914E-12
12	-.15862E-01	.41257E-10	.11618E-01	-.49005E-11	-.10956E-03	.36673E-12
13	-.15878E-01	-.23445E-10	.21996E-01	-.92669E-11	-.11154E-03	-.19666E-11
14	-.17372E-01	.11569E-09	.22376E-01	-.11141E-10	-.11434E-03	-.11451E-11
15	-.18312E-01	.12125E-10	.34430E-01	-.21404E-10	-.14528E-03	-.31325E-11
16	-.19150E-01	-.54186E-10	.44897E-01	-.36396E-10	-.19942E-03	-.34185E-11
17	-.19571E-01	-.15180E-09	.61942E-01	-.61110E-10	-.26031E-03	-.14719E-11
18	-.20088E-01	.21204E-10	.82929E-01	-.10753E-09	-.30429E-03	.14550E-11
19	-.20088E-01	.84194E-10	.93406E-01	-.14567E-09	-.31018E-03	.20427E-11

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES				SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	5	.4184767E+00	.6882606E-07	.1933537E-05	-.5226164E-06	-.8791528E+02	.7801533E+02	-.1097053E-06	-.7697648E+00
2	2	3	-.3070248E+00	-.1010143E-19	.1442792E-07	.2131027E-05	-.3022495E+00	-.4464274E+02	-.3427905E-07	-.7181096E+00
3	3	3	3 4	-.2205368E+00	.1091318E-06	-.1271800E-05	.7910350E-06	.2659287E+02	-.6342411E+02	.9670369E-08 -.74084
4	4	6	-.1927322E+00	.1196305E-06	.5869604E-06	.1880917E-05	-.4594664E+02	.7995273E+02	-.5814814E-07	.8012516E+00
5	5	7	.4474427E+00	.7880813E-07	.8925408E-06	.5863129E-06	-.9144944E+02	.8045477E+02	-.1064981E-06	-.7917695E+00
6	6	8	.6054570E-01	-.6751910E-07	-.4570130E-07	.7205228E-06	-.6643700E+01	.1018654E+02	-.3708159E-07	.1946800E+00
7	7	9	.4650963E+00	.8789846E-07	-.4002410E-06	.1725724E-05	-.9177049E+02	.8004563E+02	-.8774942E-07	-.7762076E+00
8	8	10	.5759973E-01	-.5912334E-07	-.5153021E-06	.1610804E-05	-.8405583E+01	.1284151E+02	-.6651159E-07	.2693199E+00
9	9	10	-.1254835E+01	.2774029E-06	-.8231732E-06	.1470373E-05	-.1022737E+03	-.1895429E+02	-.6056597E-07	-.1134283E+02
10	9	11	.8352009E+01	-.1288932E-05	.1739227E-08	.3538649E-06	-.2401562E+02	-.2276047E+01	-.8812566E-08	-.6515589E+00
11	10	12	-.6832346E+01	-.2073457E-05	.1861028E-05	.1410210E-06	-.2184011E+02	-.1782342E+02	-.6613640E-07	-.1310259E+01
12	11	12	.1577473E+01	.2207615E-06	.4648781E-06	.1191339E-05	-.2794378E+02	-.4454744E+02	-.6809969E-08	-.7153346E+01
13	11	13	.1226558E+02	-.1997310E-05	-.1366207E-06	.3583826E-06	.1645854E+02	.1746885E+02	-.4950515E-08	.7573802E+00
14	12	14	-.9560514E+01	-.2825783E-05	-.3231689E-06	.1166659E-05	.6598834E+01	-.4408753E+01	-.2640589E-07	.6856161E-01
15	13	15	.1565061E+02	-.3273954E-05	.2609935E-06	-.1475343E-05	.2795271E+02	-.1939665E+02	.2023004E-07	.1425368E+00
16	14	15	-.1125215E+02	-.3932711E-05	-.2141105E-05	.2501776E-06	.5536398E+01	-.5538499E+02	.4880865E-07	-.1286693E+01
17	15	16	-.1326228E+00	-.7775293E-05	.8452525E-07	-.2374895E-05	.9019386E+02	-.5605898E+02	.7769774E-07	.1157980E+01
18	16	17	-.1266549E+00	-.9058941E-05	.1901518E-05	-.2979789E-05	.7899667E+02	-.3732703E+02	.2458706E-07	.9501635E+00
19	17	18	-.1094394E+00	-.1394706E-04	.4590219E-05	-.1780962E-05	.5880919E+02	-.1004263E+02	-.4838622E-07	.8399478E+00
20	18	19	-.6131346E-01	-.2064316E-04	.1703329E-05	.4920462E-07	.1594474E+02	-.6193980E+00	-.4955199E-07	.4333161E+00

Table V - 13 Steady State Vortex Shedding Stresses

$\overline{V}_{CRIT}$ = 10.86 Mph

Traffic Signal and Lighting Standard Type XXVI

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	-.21126E-01	.12873E-11	.35638E-01	.74619E-12	-.29483E-03	.35427E-11
3	-.18793E-01	-.16020E-09	.18976E-01	.10559E-11	-.24309E-03	.13305E-11
4	-.14843E-01	-.15721E-09	.66336E-02	.11341E-11	-.15727E-03	-.57833E-12
5	-.40131E-03	-.28616E-10	.41390E-06	.74768E-12	-.12279E-04	.38729E-14
6	-.11659E-01	-.10145E-09	.11838E-05	.25995E-12	-.55542E-04	.98709E-13
7	-.16281E-02	-.84247E-10	.85645E-06	.82617E-12	-.25747E-04	.86055E-14
8	-.84724E-02	-.91046E-10	.99062E-06	.15682E-13	-.50510E-04	.21264E-12
9	-.37450E-02	-.11683E-09	.13165E-05	.32124E-13	-.40050E-04	.14270E-13
10	-.55835E-02	-.10568E-09	.80680E-06	-.61233E-12	-.45602E-04	.30470E-12
11	-.54131E-02	-.11850E-09	.47231E-02	-.55809E-11	-.44777E-04	-.17359E-11
12	-.64312E-02	.27595E-10	.47236E-02	-.81353E-11	-.44068E-04	.24694E-12
13	-.64549E-02	-.98224E-10	.89394E-02	-.15223E-10	-.44832E-04	-.29428E-11
14	-.70343E-02	.14373E-09	.90423E-02	-.18342E-10	-.45698E-04	-.16550E-11
15	-.73960E-02	.33872E-10	.13722E-01	-.35131E-10	-.54181E-04	-.42360E-11
16	-.76947E-02	-.21786E-10	.17454E-01	-.59545E-10	-.69000E-04	-.48570E-11
17	-.78354E-02	-.16694E-09	.23155E-01	-.99694E-10	-.85195E-04	-.27715E-11
18	-.80016E-02	.25286E-10	.29891E-01	-.17512E-09	-.96610E-04	.54648E-12
19	-.80016E-02	.59394E-10	.33208E-01	-.23710E-09	-.98035E-04	.12215E-11

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES	
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	5	.1940163E+00	.4102108E-08	.3269861E-05	-.8482304E-06	-.3598179E+02	.3164596E+02	-.1882926E-06	-.3371303E+00
2	2	3	-.1852775E+00	-.1525523E-19	.2020682E-07	.2984580E-05	-.4680445E+00	-.6913094E+02	-.4800905E-07	-.1112019E+01
3	3	4	-.7388468E-01	.1528430E-06	-.1781234E-05	.1104438E-05	.4122744E+02	-.9322269E+02	.1361346E-07	-.1045862E+01
4	4	6	-.1321046E-01	.1673751E-06	.8186001E-06	.2556589E-05	-.6762593E+02	.1112159E+03	-.7952621E-07	.1027068E+01
5	5	7	.2074454E+00	.4697051E-08	.1477046E-05	.1071979E-05	-.3716413E+02	.3234573E+02	-.1835653E-06	-.3469921E+00
6	6	8	.9660962E-01	-.9158574E-07	-.6441084E-07	.9566103E-06	-.9415065E+01	.1161992E+02	-.4902655E-07	.1211572E+00
7	7	9	.2156296E+00	.5238844E-08	-.7566728E-06	.3062190E-05	-.3696981E+02	.3181829E+02	-.1526295E-06	-.3410402E+00
8	8	10	.9190757E-01	-.8019738E-07	-.6825284E-06	.2162368E-05	-.9873109E+01	.1236146E+02	-.8984602E-07	.1510763E+00
9	9	10	-.3640409E+00	.3845837E-06	-.1708686E-05	.2728837E-05	-.3870721E+02	-.4791133E+00	-.9545150E-07	-.3666510E+01
10	9	11	.2640373E+01	-.2081737E-05	.5217418E-06	.9480899E-06	-.1140394E+02	-.2694704E+01	-.3642530E-07	-.3493919E+00
11	10	12	-.2168999E+01	-.3362576E-05	.2742819E-05	-.2273982E-06	-.9536680E+01	-.5921501E+01	-.8309530E-07	-.5106510E+00
12	11	12	.6677218E+00	.3754589E-06	.3682500E-07	.1297229E-05	-.3925789E+01	-.1231491E+02	-.5485312E-08	-.1602612E+01
13	11	13	.3622400E+01	-.3239650E-05	-.7655616E-06	.1273525E-05	.4739244E+01	.4836692E+01	-.1133954E-07	.2137690E+00
14	12	14	-.2843787E+01	-.4587351E-05	.7064792E-07	.1206812E-05	.2681120E+01	-.1068736E+01	-.3999156E-07	.5047654E-01
15	13	15	.4625533E+01	-.5337208E-05	.1560891E-05	-.2138890E-05	.7735746E+01	-.5383994E+01	.9628987E-08	.3917820E-01
16	14	15	-.3343420E+01	-.6414203E-05	-.2500001E-05	.9597155E-07	.1344448E+01	-.1536093E+02	.6205284E-07	-.3617937E+00
17	15	16	-.5409319E-01	-.1266803E-04	.4351846E-06	-.3151864E-05	.2502937E+02	-.1500205E+02	.9215973E-07	.3401633E+00
18	16	17	-.4857091E-01	-.1472658E-04	.2150012E-05	-.3723568E-05	.2118656E+02	-.9752278E+01	.3588068E-07	.2607280E+00
19	17	18	-.4201641E-01	-.2267291E-04	.5729708E-05	-.2372527E-05	.1537793E+02	-.2489791E+01	-.5782358E-07	.2219834E+00
20	18	19	-.2272590E-01	-.3354862E-04	.1956461E-05	.5651693E-07	.3967441E+01	-.4379635E-01	-.5691592E-07	.1109390E+00

Table V-14 Steady State Vortex Shedding Stresses

$\bar{V}_{CRIT}$ = 9.03 Mph

Traffic Signal and Lighting Standard Type XXVI

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STEADY STATE DEFLECTIONS

1	0.	0.	0.	0.	0.	0.
2	-.81399E-02	.24526E-11	.32815E-02	-.12880E-12	-.10930E-04	-.44045E-12
3	-.80371E-02	.22698E-10	.25472E-02	-.16405E-12	-.14884E-04	-.18863E-12
4	-.76972E-02	.23712E-10	.14851E-02	-.17343E-12	-.21322E-04	.30154E-13
5	-.22276E-03	.29808E-11	.25248E-06	-.78902E-13	-.69828E-05	-.93798E-14
6	-.69844E-02	.18158E-10	.48208E-07	-.74543E-13	-.28749E-04	-.44784E-13
7	-.94588E-03	.90263E-11	.52243E-06	-.93939E-13	-.15639E-04	-.20842E-13
8	-.52493E-02	.14294E-10	.62738E-07	-.45769E-13	-.29095E-04	-.57649E-13
9	-.22818E-02	.13343E-10	.80303E-06	-.25428E-13	-.26131E-04	-.34561E-13
10	-.34945E-02	.13390E-10	.76556E-07	.28468E-13	-.29405E-04	-.68043E-13
11	-.33557E-02	.95334E-11	.30601E-02	.53550E-12	-.29890E-04	.13089E-12
12	-.40485E-02	-.35592E-11	.30604E-02	.77409E-12	-.29493E-04	-.59117E-13
13	-.40131E-02	.64612E-11	.57668E-02	.14785E-11	-.29886E-04	.30160E-12
14	-.44605E-02	-.16053E-10	.59546E-02	.17802E-11	-.31201E-04	.17011E-12
15	-.47471E-02	-.14487E-11	.95573E-02	.34346E-11	-.48155E-04	.47671E-12
16	-.50545E-02	.77543E-11	.13400E-01	.58480E-11	-.77963E-04	.52985E-12
17	-.52303E-02	.23080E-10	.20530E-01	.98243E-11	-.11340E-03	.24636E-12
18	-.54640E-02	-.24580E-11	.30009E-01	.17294E-10	-.14017E-03	-.18788E-12
19	-.54640E-02	-.10863E-10	.34862E-01	.23430E-10	-.14417E-03	-.27558E-12

DYNAMIC MEMBER STRESSES

			AXIAL STRESS	TORSIONAL SHEAR STRESS	BENDING STRESSES					SHEAR STRESSES
MEMBER	JA	JB	P/A	TC/J	MC/I-2A	MC/I-2B	MC/I-3A	MC/I-3B	VQ/IT-22	VQ/IT-33
1	1	5	.1183495E+00	-.9935048E-08	-.3349985E-06	.9957801E-07	-.1905118E+02	.1940877E+02	.1830499E-07	.2780419E-01
2	2	3	.5741632E-02	.3504579E-20	-.2300179E-08	-.3397402E-06	.3577390E-01	.5283864E+01	.5464957E-08	.8499462E-01
3	3	4	-.2023576E-02	-.1739840E-07	.2027375E-06	-.1282082E-06	-.3152951E+01	.6932799E+01	-.1499124E-08	.7602998E-01
4	4	6	-.6931510E-02	-.1917702E-07	-.9497357E-07	-.2889693E-06	.5032849E+01	-.8023917E+01	.9046464E-08	-.7047557E-01
5	5	7	.1265402E+00	-.1137596E-07	-.1632973E-06	-.8569061E-07	-.2214902E+02	.2252533E+02	.1793060E-07	.2709980E-01
6	6	8	-.7264665E-02	.1034106E-07	.6978409E-08	-.1132975E-06	.6845742E+00	-.7610938E+00	.5842259E-08	-.4204765E-02
7	7	9	.1315306E+00	-.1268815E-07	.5280227E-07	-.2766940E-06	-.2505861E+02	.2540115E+02	.1482204E-07	.2267695E-01
8	8	10	-.6908895E-02	.9055185E-08	.8084888E-07	-.2554459E-06	.6551927E+00	-.7511597E+00	.1060037E-07	-.5826477E-02
9	9	10	-.5189103E+00	-.4433668E-07	.1310371E-06	-.2400765E-06	-.3412454E+02	-.1157997E+02	.1020239E-07	-.4276391E+01
10	9	11	.3405489E+01	.2069128E-06	-.8234879E-08	-.6725458E-07	-.4990713E+01	.1935363E+01	.1870777E-08	-.7571754E-01
11	10	12	-.2676422E+01	.3335257E-06	-.2967731E-06	-.9820439E-08	-.7652830E+01	-.7860786E+01	.1012812E-07	-.5124822E+00
12	11	12	.3767588E+00	-.3597767E-07	-.6038641E-07	-.1781097E-06	-.2226894E+02	-.2696597E+02	.9806392E-09	-.4858442E+01
13	11	13	.5679358E+01	.3211221E-06	.3728215E-07	-.7288728E-07	.9123041E+01	.9116371E+01	.7948332E-09	.4071686E+00
14	12	14	-.4315857E+01	.4547250E-06	.3496020E-07	-.1721481E-06	.7262152E+00	-.3201797E+01	.4294739E-08	-.7749939E-01
15	13	15	.7226161E+01	.5269709E-06	-.6712610E-07	.2302973E-06	.1456986E+02	-.1106920E+02	-.2718294E-08	.5831812E-01
16	14	15	-.5101010E+01	.6335330E-06	.3222547E-06	-.3620591E-07	.4067496E+01	-.2932224E+02	-.7383496E-08	-.6518759E+00
17	15	16	.1796207E-01	.1251936E-05	-.1545483E-07	.3613558E-06	.4827050E+02	-.3225295E+02	-.1173423E-07	.5433738E+00
18	16	17	.7616530E-03	.1457817E-05	-.2780631E-06	.4505950E-06	.4526564E+02	-.2243844E+02	-.3934125E-08	.5205125E+00
19	17	18	.8766229E-03	.2244442E-05	-.6938725E-06	.2738100E-06	.3529875E+02	-.6595014E+01	.7235092E-08	.4943887E+00
20	18	19	-.3566490E-02	.3321777E-05	-.2541887E-06	-.7342830E-08	.1041107E+02	-.8623858E+00	.7394668E-08	.2699842E+00

Table V - 15 Steady State Vortex Shedding Stresses

$\overline{V}_{CRIT}$ = 15.40 Mph

Traffic Signal and Lighting Standard Type XXVI

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VI. FATIGUE EVALUATION

VI. 1 Analytic Method

The fatigue lives of the three traffic signal and lighting standards were evaluated using the cumulative damage theory (Reference 13, 14, and 15) as follows:

$$UF = \sum_i \left(\frac{C_i}{CA_i}\right)$$

Where:

UF = Usage factor (i.e., life of structure used)

C_i = The number of cycles at stress intensity S_i

CA_i = The allowable number of cycles at stress intensity, S_i

The CA_i terms were evaluated using the S-N diagram shown in Figure VI-1, and an ultimate strength of 58 KSI. For static stresses the numbers of applied cycles are 1, 4, and 20 for fifty-, ten- and two-year recurrence intervals, respectively. For RMS stresses of the number of applied cycles for a fifty-year period is as follows:

$$C_i = \left(\frac{\sigma_1}{S_{RMS}}\right)\left(e^{-\frac{1}{2}}\right)\left(\frac{3600}{2\pi}\right)(F) \qquad \text{(Ref. 12)}$$

where:

S_{RMS} = 2. x max RMS Shear Stress

F = 1, 4, or 20 for a fifty-, ten-or two-year recurrence intervals, respectively

$$\sigma_1 = \left\{ \sum_R (S_R)^2 \frac{\Gamma_R^2 \, S_{v_R}}{f_R M_R^2 8.C} \right\} \qquad \text{(Ref. 12)}$$

S_R = 2 x Max Shear Stress for the Rth Mode

$$\Gamma_R = \left\{\varphi_i\right\}_R^T \left\{(2\, C_Z V_Z)_i\right\}$$

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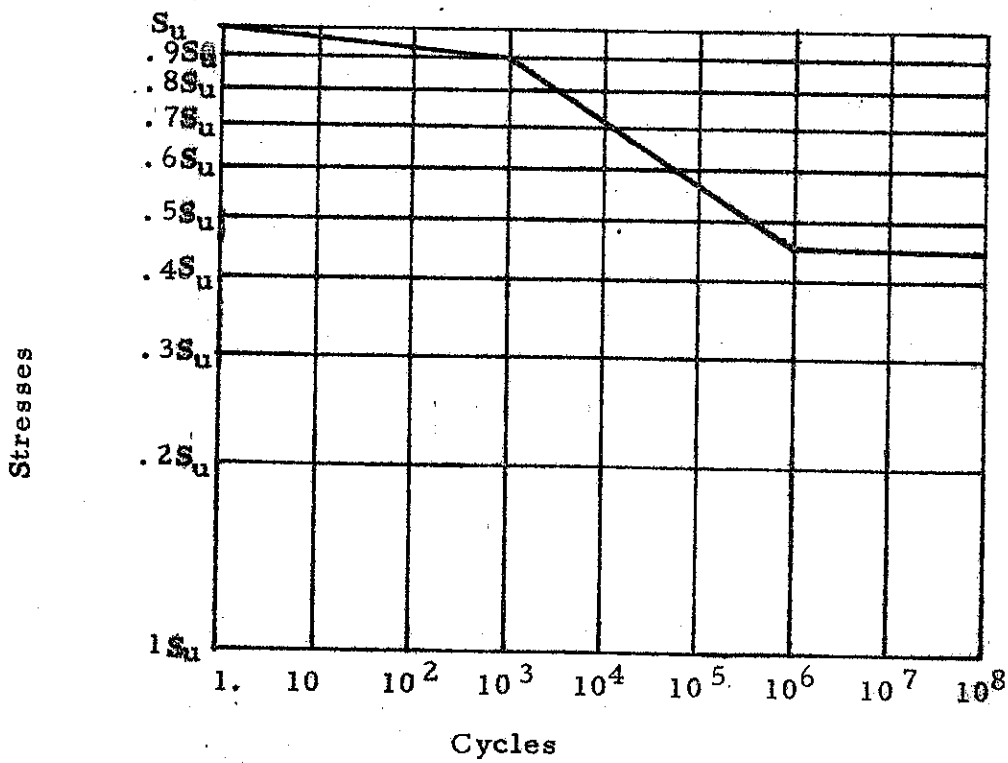

Figure VI-1 - SN Curve For Carbon Steel
(S_u = Ultimate Strength)

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$\left\{(2C_Z V_Z)_i\right\} S_{v_R}$ = Applied Load Spectrum (See Section III. 3)

f_R = Natural frequency of the Rth mode

M_R = Generalized Weight of the Rth mode

C = Damping Coefficient

$\left\{\varphi_i\right\}_R$ = Normalized modal displacement vector

For steady state stresses, the number of applied cycles is as follows:

$$C_i = \left(\frac{50}{R}\right) \left(\frac{3600\, f_{CRIT}}{V_{CRIT}}\right)^*$$

Where:

V_{CRIT} = The critical mile wind velocity (mph)

R = The recurrence interval for V_{CRIT}

f_{CRIT} = The critical natural frequency used to calculate V_{CRIT}

* This equation is based upon the engineering assumption that the contribution to response is small except in the vicinity of the natural frequency of each mode (there is a V_{CRIT} for each mode). This assumption is valid for lightly damped systems.

VI. 2 Results

Table VI-2 shows the maximum static stress intensities and allowable number of cycles calculated for each standard for 2-, 10- and 50-year recurrence intervals.

Traffic Signal and Lighting Standard Type	Maximum Stress Intensity (ksi)		
	2 Year Recurrence Interval	10 Year Recurrence Interval	50 Year Recurrence Interval
XIX	10.80	17.36	24.20
XXI	13.24	18.67	24.61
XXV	10.48	17.08	23.17

Table VI-2

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The maximum RMS stress intensities and applied cycles are tabulated in Table VI-3 for each standard for a fifty-year recurrence interval

Standard Type	XIX	XXI	XXVI
Stress Intensity (KSI)	.247	.233	.203
C_i	1172.	830.	960.

Table VI-3

The maximum, steady state, von Karman Vortex Shedding stresses and applied cycles are tabulated in Table VI-4 for each standard for each critical velocity.

Traffic Signal and Lighting Standard Type	VCRIT (mph)	Maximum Stress Intensity (KSI)	Applied Cycles (C)
XIX	6.83	.049	1.813×10^5
	7.74	.031	2.584×10^5
	14.13	.102	2.065×10^5
XXV	11.63	.038	2.093×10^5
	12.42	.067	1.064×10^5
	30.82	.083	1.277×10^5
XXVI	9.03	.111	2.065×10^5
	10.86	.106	1.151×10^5
	15.40	.049	1.370×10^5

Table VI-4

The above stress intensities are less than the endurance limit of carbon steel (26 KSI). Therefore, none of the fatigue life of the three analyzed standards has been consumed during a fifty year period.

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Appendix B

Computer Program User Manual for Wind Effects on Luminaires and Traffic Signals

MRI-TR-2430-2 December 1971
Revised May 1972

Prepared for

California Division of Highways
Bridge Department
P.O. Box 1499
Sacramento, California 95807

Prepared by

Mechanics Research, Inc.
15 N. Broadway
Tacoma, Washington 98403

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P.O. Box 1499
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Prepared by

Mechanics Research, Inc.
15 N. Broadway
Tacoma, Washington 98403

Written by: K. Diane Johnson

R. C. Lundquist

Approved by: R. T. Haelsig, P.E.

MECHANICS RESEARCH INC.

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I. INTRODUCTION

WEFFLS is a structural analysis program to evaluate the wind effects on traffic signals and luminaire supports. The program performs a static analysis, random response analysis and a steady state dynamic analysis of von Karmen vortex shedding. The program also performs a cumulative usage assessment to determine structure service life.

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II. PROGRAM ANALYTICS

A. General

The response of the traffic signal/luminaire is determined utilizing finite element stiffness methods of analysis. In this method the pole and arm elements of the structure are subdivided into discrete uniform beam "elements." Each of these beam elements is assumed weightless and all (inertia) and forces are concentrated at "node" points defining the ends of the beam elements. Where poles and arms taper, the taper is approximated by a series of uniform segments.

A right handed global ctaresian coordinate system is used to describe the structure geometry. The base of the pole is assumed as the origin. Program notation employs an X1, X2, X3 notation to describe these three coordinate axes. X3 is aligned with the pole vertical axis and directed upward from the base. X2 is aligned perpendicular to the plane of pole and arm. X1 is in the plane of the pole and arm and directed from the base outward in the direction of the arm tip.

The global coordinate axes are illustrated in Figure II. 1.

Local element coordinate axes are employed to describe beam element end forces. This coordinate system is also illustrated in Figure II. 1 for pole and arm members. ξ_1 is tangent to the beam element, directed from root to tip. ξ_2 and ξ_3 are perpendicular to ξ_1 and each other. ξ_3 is always perpendicular to the plane of the pole and arm. For the pole, ξ_3 is opposite to X2; for the arms, ξ_3 is in the same direction as X2. Beam element end forces employ the ξ coordinate system and end A&B designations. Beam end A is closest to the root; end B is closest to tip.

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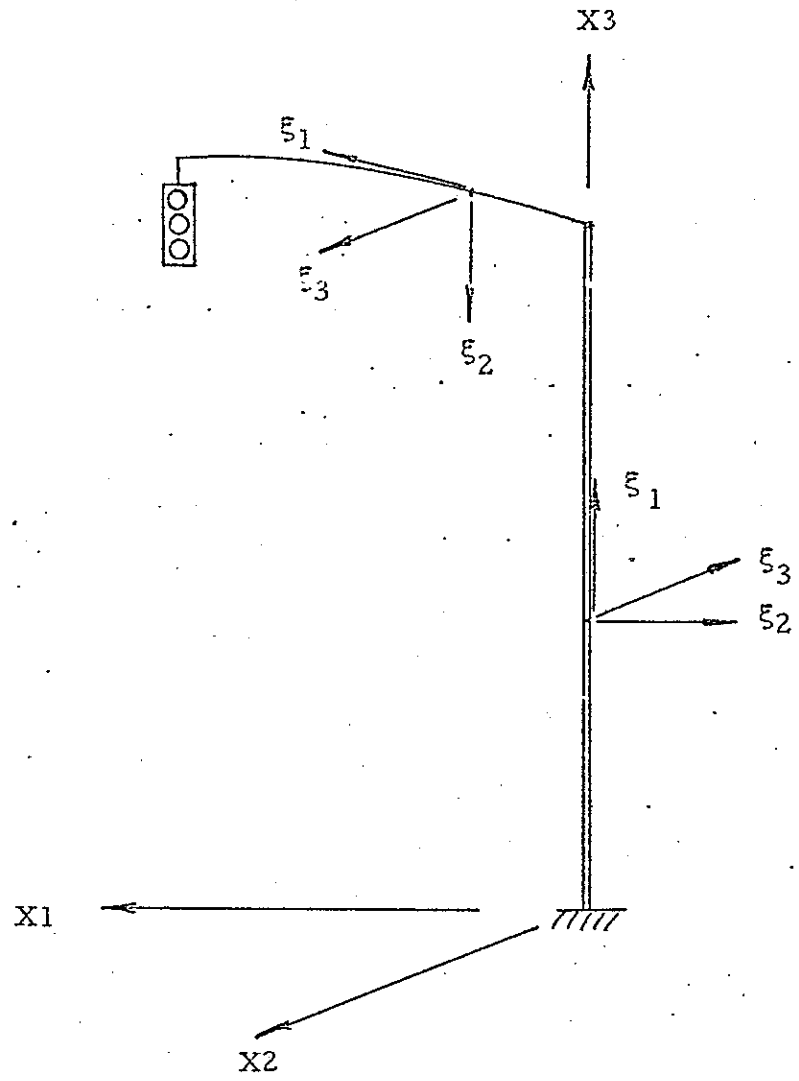

Figure II. 1 - Global and Local Coordinate Axes

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The structure possesses a full six degrees of freedom at each node point. Translatory inertias (masses) are assigned to each of the three translatory degrees of freedom. Rotational inertias (mass moments of inertia) are considered only for signs and signals; and these are considered only for mass moments about axes X1 and X2. Forces are applied and treated in a similar fashion.

B. Wind Force Idealization

The 1/7th power law has been used to determine wind velocities versus elevation. The spatial (geographic) characteristics of winds are typically reported, or normalized, by defining winds at 30' elevation. As a consequence winds applied to the structure are given by:

$$V_Z = V_{30} \left(\frac{Z}{30}\right)^{\frac{1}{7}}$$

Where: V_Z = Wind velocity at height Z (ft).

V_{30} = Wind velocity at 30' height.

Fatigue assessments are determined by the number of occurrences of extreme winds over the life of the structure. These are input to the program for a 2, 10, and a 50 year recurrence level. This is similar to a 2 year and a 50 year rain fall or earthquake prediction; e.g., once in 2 years, once in 50 years.

Static wind drag forces are applied to the structure utilizing the relation:

$$D = \frac{1}{2} C_D \rho V^2 A$$

Where: D = drag force (lbs)

C_D = input drag coefficient (dimensionless)

ρ = air density (stored in program)

V = wind velocity at elevation of element (computed)

A = projected area of contributing member to the loaded node (computed)

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A similar approach is employed for random dynamic winds. The velocity spectrum for winds is derived from a study of 90 strong-wind spectra. Section III. 3 of the basic report provides a detailed summary of random response analysis techniques.

Von Karman vortex shedding phenomona induces steady state oscillations of the structure perpendicular to the wind flow. The magnitude of this applied force is:

$$F_K = q\, AC_K \sin 2\pi f_v t$$

Where: F_K = the force applied to the structure

q = dynamic pressure

$= \frac{1}{2} \rho v^2$

C_K = the Von Karman coefficient

f_v = the vortex shedding frequency. (other terms have been previously defined)

C. Static Stress Analysis

Static analysis uses the direct stiffness method of structural analysis.

The mathematical model is defined by the matrix equation

$$[K] \{\delta\} = \{F\}$$

Where:

$[K]$ = stiffness matrix (known from geometry and materials data input)

$\{\delta\}$ = displacement vector (unknown)

$\{F\}$ = external load vector (known from winds data input & geometry)

Having solved for the unknown displacements, $\{\delta\}$, the internal loads on the beam elements $\{F\}_i$ are found using the associated element stiffness matrix, $[K]_i$. Associated stresses are computed by simple strength of materials relations: P/A, Mc/I, VQ/It, Tc/J.

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WEFFLS has the ability to analyze both circular and non-circular cross-sections; however, stress analysis is performed only for circular cross-sections. For non-circular sections, WEFFLS reprints element loads in the stress print segment.

Procedures for use of non-circular cross sections are not entirely obvious and therefore require some additional explanation. The only data entry point for general non-circular section data is within the "Non-circular Brace Data" (BRAN). As a consequence the following input steps are taken to input all non-circular section data:

1. Input material and geometry (Nodes) as usual.
2. Input non-zero "dummy" data for the pole, if non-circular.
3. Input arm, sign luminaire and brace data as usual, if circular sections.
4. Input BRAN data for all non-circular sections.

The above described treatment of non-circular sections applies to all forms of analysis: static and dynamic.

D. Dynamic Analysis

The modal superposition method of dynamic analysis is employed within WEFFLS. The detailed methology is described within Section V. 1 of the basic report. In essence the total dynamic response of the structure is obtained by summing the individual responses of certain orthogonal functions of the structure. These orthogonal functions are termed "normal modes" of the structure and are characterized by an associated natural frequency and normalized displacement configuration, or normal mode. The total deflection response of the structure is given by:

$$\{x(t)\} = [\varphi] \{\eta(t)\}$$

Where:

$\{x(t)\}$ = a vector of time dependent displacements of the structure

$[\varphi]$ = a matrix of orthogonal modes, determined from the properties (stiffness and mass) of the structure

$\{\eta(t)\}$ = a vector of time dependent generalized displacement

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coordinates, determined by the various response solutions for the specific dynamic excitations imposed upon the structure.

The normal modes of the structure are determined from the mass and stiffness properties of the structure using the Householder-QR transformation procedure. The program presently computes and processes 12 normal modes in all response calculations.

Stresses are obtained for dynamic responses in a way very similar to that used for statics as described in Section II. 3 of this document.

E. Fatigue Evaluation

A straight forward linear cumulative damage assessment process is applied to determine consumed useful life of the structure:

$$UF = \sum_i \left(\frac{C_i}{CA_i}\right)$$

Where:

UF =	Usage factor (ratio of useful life consumed)
C_i =	Number of cycles at stress of S_i
CA_i =	Total number of allowable cycles at stress of S_i; as determined from an S-N diagram.

A comprehensive discussion of fatigue procedures is contained in Section VI of the basic report.

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III. PROGRAM ORGANIZATION AND STRUCTURE

WEFFLS is designed to run as an unsegmented in-core program requiring three external scratch files. It is logically segmented into four parts and could be overlayed if core requirements exceed that available.[1]

The program was developed and the example problems executed on a CDC 6600 computer. Core requirements and arithmetic accuracy will differ from program execution on an IBM 360-65. To maintain accuracy, double precision arithmetic is used in matrix multiplication and in the extracting of eigenvector and eigenvalues.

A. Core Requirements

Labeled Common	31,200
Program Object Code	12,100
System Object Code	230
	43,530

B. Flow Diagram

The Flow Diagram is shown on the following pages.

C. Program Description

1. Labeled Common

The major core requirements of WEFFLS depend upon the number of joints and members allowed in the structure. In the descriptions of labeled common, the core required will be indicated as varying so that the programmer desiring to alter the program's size capability can use this description as a guide.

In the current version of WEFFLS:

N = # of unrestrained joints = 20

M= # of members = 40

1. See Table 1.

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Common	Description
/STIF/	Used for developing the structure stiffness matrix and for storing the modal stress vector AK(N,N) , AL(N,6), AM(N)
/EIGN/	Used in computing and storing the eigenvectors (BETA), eigenvalues (OMEGA) and generalized mass GM BETA(N,N), OMEGA(80), GM(MS) Where MS = number of mode shapes used in computations = 12
/SKRACH/	A skratch array used throughout the program SCRTH(N,4)
/JAM/	Member connectivity, member properties and joint coordinates JM(M), JTB(M), A(M,10), X(N+2,3)
/CONST/	Problem constants and heading information
/IO/	Input, output parameters
/DRAG/	Drag coefficient data

2. Program and Subprogram Descriptions

WEFFLS - The main program prints header information, reads and prints input data, generates joint coordinates, sets up member properties, forms member stiffness matrix and static loads and computes joint displacements. STRES is called to compute static member stresses and store them on tape 10. WEFFLS then calls STEIG, RANDMR, SST, and UFACT for the remainder of the analysis. Tape 8 is used as scratch storage for the stiffness matrix.

STEIG - Subprogram to compute the eigenvectors, eigenvalues and generalized mass of the structure. Twelve mode shapes are retained and printed. Tape 9 is used as a scratch tape.

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RANDMR -	Subprogram to compute and print the random response stresses and store them on Tape 9. STRES is called to compute the modal stress vectors and store them in /STIF/AK.
SST -	Subprogram for the computation of steady state deflections and stresses. SST finds the critical modes and critical velocities and calls STEADY to compute and print the deflections. STRES computes, prints and stores on Tape 8 the dynamic member stresses.
UFACT -	Subprogram to find and print the structure usage factors. If the life of the structure exceeds 100 years the specific value is not printed. Maximum member shear stresses and their associated applied cycles are outputed for random response and steady state usage factors calculations.

The following subroutines are listed in alphabetic order:

BMSECT -	Computes beam stress properties for circular and rectangular beams for use in member stress computation.
CDRAG -	Find the drag coefficient for a circular member
CVCK -	Calculates the von Karman coefficient for a given Reynolds number.
EIGQR2 -	Compacts the dynamical matrix into a tri-diagonal form. (Householder algorithm)
ERROR -	Prints error messages and stops execution
EXTRCT -	Forms the dynamical matrix and calls HSHLD3 and EIGQR2 for the solution of the eigenvectors and eigenvalues.
HSHLD3 -	Compacts the dynamical matrix into a tri-diagonal form. (Householder algorithm)
INTRP -	Perform interpolations of linear - linear to log - log.
MATINV -	Computes the resultant matrix $[A^{-1}] \cdot [B]$, given $[A]$ and $[B]$.
PLACD -	Computes the drag coefficient for a traffic sign or signal.

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RESPON -	Calculates the amplitude and phase angle given excitation frequency, natural frequency and damping for steady-state deflections.
SDRAG -	Find the drag coefficient for a rectangular member.
SHRMAX -	Find the maximum shear for circular and rectangular members.
STEADY -	Calculates the structural dynamic for multi-point steady state excitation.
STFMUL -	Matrix multiplication routine. Uses double precision arithmetic.
STRES -	Computes, prints and saves on tape the static and dynamic member stresses given joint displacements. Computes the modal stress vector and stores it in /STIF/ AK(M*8,MS) Where M = # of members MS = # of mode shapes
STRIX5 -	Computes each member stiffness matrix and adds it to the structural stiffness matrix
SWL -	Calculates the static wind force on the traffic signal and lighting standard given a maximum wind velocity.

Required system library routines:

DBLE -	Single to double precision conversion
EXP -	Exponentiation
SINCOS -	Sin, cos functions
SNGL -	Double to single precision
SQRT -	Square root function

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Main Program and Static Analysis	Eigenvectors and Eigenvalues	RMS Stresses	Steady-State Stresses	Usage Factor
WEFFLS				
STRIX5				
MATINV				
STRES				
ERROR				
STFMUL	STEIG	RANDMR	SST	UFACT
SWL	EXTRCT		RESPON	SHRMAX
CDRAG	HSHLD3	(500)*	STEADY	
SDRAG	EIGQR2		CVCK	
PLACD				
INTRP	(1400)*		(500)*	(700)*
BMSECT				
(9000)*				

Table 1 - Program Organization and Core Requirements

*Note: Object Code Lengths are rounded up to nearest hundred words

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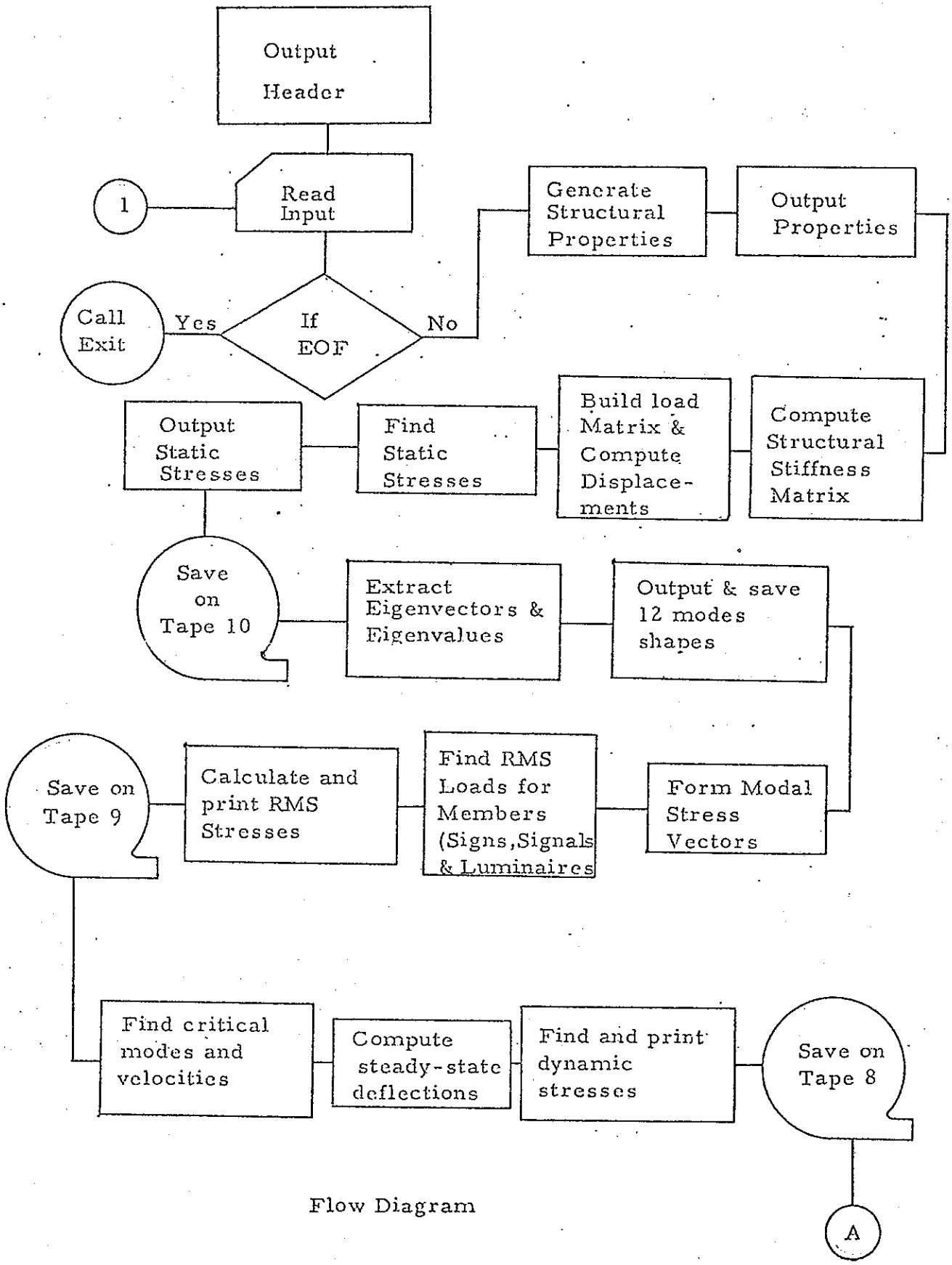

Flow Diagram

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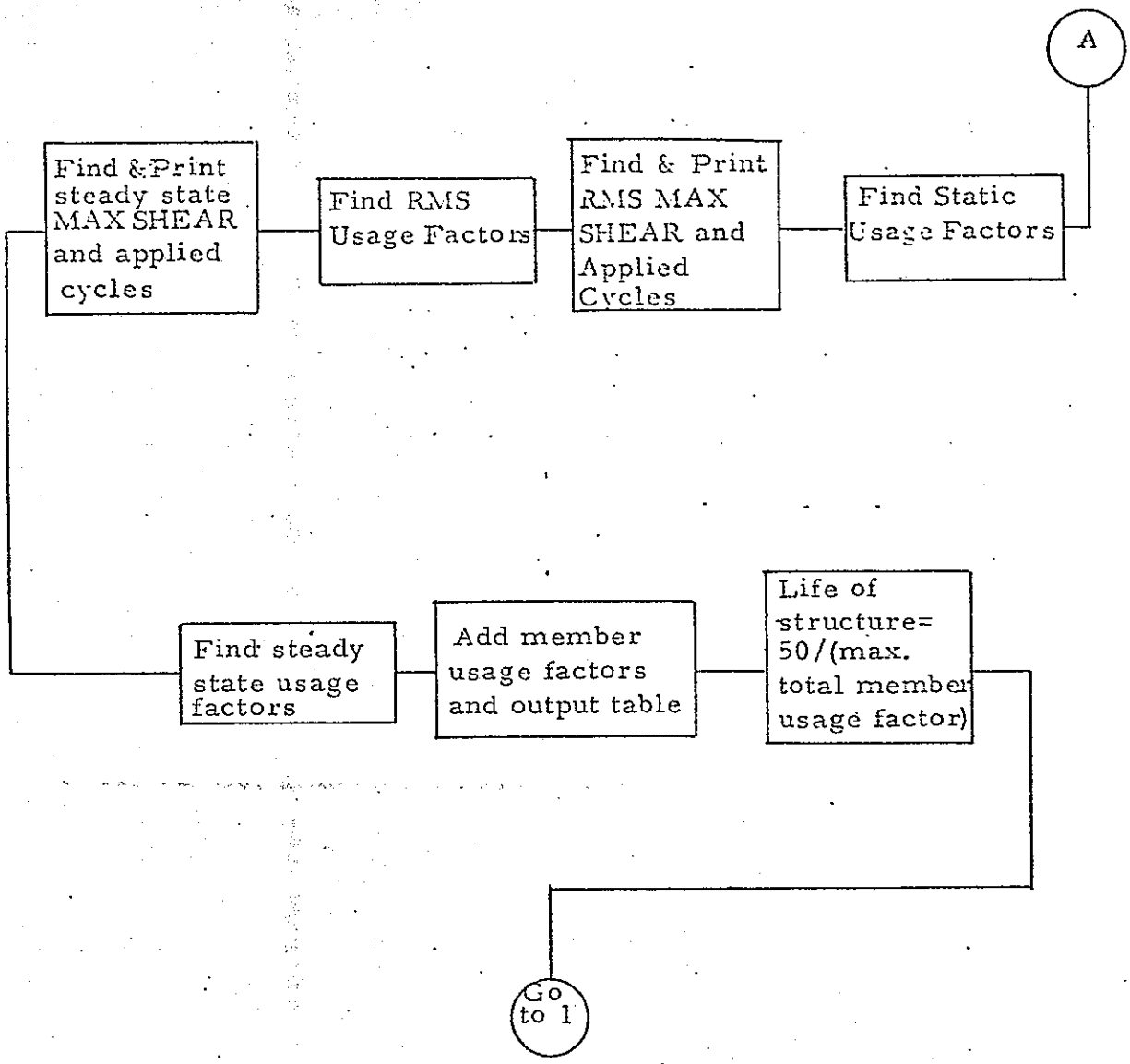

Flow Diagram (Cont.)

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IV. USER INPUT INSTRUCTIONS

A. Description Card

This card may contain alphanumeric (BCD) information in columns 1-80 which should describe the model being analyzed.

B. Material Property Data (A4, 4X, 3F8.0, F4.0, 8I4, F8.0)

4	8	16	24	32
MATL		E	PR	RHO

Where: The word MATL should appear in columns 1-4

E = Modulus of Elasticity (ksi)

PR = Poisson's Ratio

RHO = Weight density (lbs/in^3)

36	40	44	48	52	56	60	64	68	76
SA	S1	S2	S3	S4	S5	S6	S7	S8	DAMP

SA = Material Allowable Strength in ksi

SI = Maximum stress (in ksi) for a fatigue life of 10^I cycles (S-N cycle data)

DAMP = Damping Coefficient

C. Nodes (4X, I4, 2F8.0)

8	16	24
N	X1	X3

Where: N = Node Number - Node numbers must be in numerical sequence. If node numbers are omitted, node points will be generated at equal intervals along a straight line between the defined node points. The pole portion of the light standard must be numbered consecutively from the base to the tip. The luminaire and signal arms must also be numbered consecutively. The base node of the pole must always be node number 1.

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X1, X3= Node Coordinates (inches) - X3 is the vertical location of the node and X1 is the horizontal location. The origin of the coordinate system is always the base of the standard.

D. Pole Data (A4, I4, 4F8.0)

4	8	16	24	32	40
POLE	NT	BOD	BTH	TOD	TTH

Where: The word POLE should appear in columns 1-4.

NT = Node number of pole tip. The program assumes the base of the pole to be node number 1. Thus the pole will be made up at the following bars: 1-2, 2-3, 3-4, . . . , (NT-1)-NT.

BOD = Outer diameter (inches) of the pole at node 1.

BTH= Wall thickness (inches) of the pole at node 1.

TOD= Outer diameter (inches) of the pole at node NT.

TTH= Wall thickness (inches) of the pole at node NT.

Pole outer diameter and thickness at the pole nodes will be calculated by a linear interpolation of the properties at node 1 and NT.

E. Arm Data (A4, 4I4, 4X, 4F8.0)

4	8	12	16	20	24	32	40	48	56
ARMM	AN	NP	NF	NT		BOD	BTH	TOD	TTH

Where:

ARMM= The word ARMM should appear in column 1-4

AN = Arm Number. In monotomically increasing order commencing with one (maximum of three)

NP = Pole node number to which arm is attached.

NF = Node number of first node.

NT = Node number of the arm tip

BOD = Outer diameter (inches) of arm at node NP

BTH = Wall thickness (inches) of arm at node NP

TOD = Outer diameter (inches) of arm at node NT

TTH = Wall thickness (inches) of arm at node NT

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The program assumes the arm to be made up of the following beams: NP-NF, NF-(NF+1), - (NF+1)-(NF+2), . . . , (NT-1)-NT. The cross-section properties of the arm nodes will be calculated by a linear interpolation of arm base and tip properties.

F. Sign and Signal Data (A4, 2I4, 12X, 4F8.0)

4	8	12	24	32	40	48	56
SIGN	SN	N		A	B	WT	DEL3

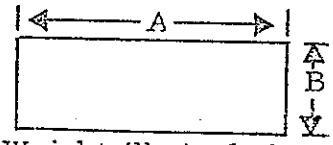
Where:

SIGN = The word SIGN should appear in columns 1-4

SN = Sign-signal number. In monotomically increasing order commencing with one. (Maximum of 5)

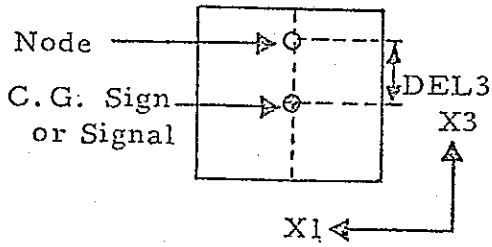
N = Node number to which the sign or signal is attached.

A, B = Sign or signal dimensions (inches)



WT = Weight (lbs) of sign or signal

DEL3= Vertical distance (inches) of the CG of sign or signal to the node (i. e.



G. Luminaire Data

4	8	12	24	32	40	48
LUMN		N		A1	A2	WT

Where:

LUMN= The word LUMN should appear in columns 1-4

N = Node number to which luminaire is attached

A1 = Luminaire area (in^2) in the X1-X2 plane

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A2 = Luminaire area (in^2) in the X2-X3 plane

WT = Weight (lbs) of luminaire

H. Circular Brace Data (A4, 3I4, 8A, 2F8.0)

4	8	12	16	24	32	40
BRAC	NS	NA	NB		A	B

Where:

BRAC = The word BRAC should appear in columns 1-4

NS = Brace number

NA, NB = Node numbers to which the brace is attached

A = Outer diameter of circular brace

B = Wall thickness of circular brace

I. Non-Circular Brace Data (A4, 4X, 3I4, 4X, 5F8.0)

4	8	12	16	20	24	32	40	48	56	64	72
BRAN		NA	NB	NTYPE		A	B	I2	I3	J	AR

Where:

BRAN = The word BRAN must appear in columns 1-4

NA, NB = Node numbers to which the non-circular brace is attached

NTYPE = Cross section type for which there must be a set of drag coefficient data

$1 \leqslant NTYPE \leqslant 3$

A = Cross sectional dimension in X1-X3 plane

B = Cross sectional dimension perpendicular to the X1-X3 plane

I_2 = Moment of inertia about the ξ_2 axis (see below)

I_3 = Moment of inertia about the ξ_3 axis (see below)

J = Torsional Moment

AR = Cross sectional area

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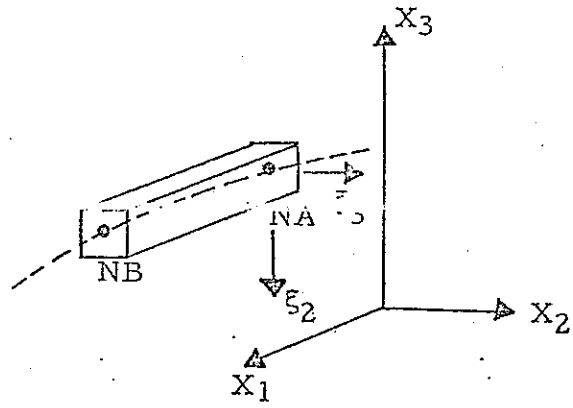
The ξ_3 axis is perpendicular to the longitudinal axis of the member, NA-NB, and is perpendicular to the plane, X1-X3, of the light standard. The ξ_2 axis is perpendicular to the longitudinal axis of member, NA-NB, and is in the plane, X1-X3) of the light standard. The orientation of the ξ_2 & ξ_3 axes are further identified in the following sketch:



J. Wind Data (A4, 20X, 6F8.0)

4	24	32	40	48	56	64	72
WIND		V2	G2	V10	G10	V50	G50

Where:

WIND = The word WIND must appear in columns 1-4

V2 = Maximum mile wind velocity* (mph) for a two year recurrance level

G2 = Gust factor for V2**

V10 = Maximum mile wind velocity* (mph) for a ten year recurrance level

G10 = Gust factor for V10**

V50 = Maximum mile wind velocity* (mph) for a fifty year recurrance level.

G50 = Gust factor for V50**

* For an elevation 30 feet above ground

**Gust factor to be multiplied times the mile wind velocity to find the maximum wind velocity.

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K. Drag Coefficient Data

This data must be included if non-circular brace cross-sections are used. There must be one set of drag coefficient data for each NTYPE ≥ 1. (Maximum of 3).

4	8	12
DRAG	NTYPE	N

Where:

DRAG = The word DRAG must appear in columns 1-4

NTYPE = The cross-section type ($1 \leq$ NTYPE ≤ 3)

N = Number of data cards to follow

Card 2 (2E8.0)

REYN	CDN

⋮

I = 1, N

Where:

REYN = Reynolds number

CDN = Drag Coefficient

L. Stress Concentration Factor Data

One card is input for each bar that has any non-unity stress concentration factors. Only those values that are to be reset need to be entered on the card. (4X, I4, 8F8.0)

	8	16	24	32	40	48	56	64	72
	NB	AXIAL	TORSION	M2A	M2B	M3A	M3B	V2	V3

Where:

NB = Bar number stress concentration factors

AXIAL= Axial

TORSION = Torsional

M2A = Moment about axis 2 at end A (ref. Fig. II.1 - page 3)

M2B = Moment about axis 2 at end B

M3A = Moment about axis 3 at end A

M3B = Moment about axis 3 at end A

V2 = Shear in the 2 axis direction

V3 = Shear in the 3 axis direction

M. END Card

This card must be the last card in the data set.

3
END

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V. EXAMPLE PROBLEMS

Example Input

The following is an example of the data input needed to analyze the specified traffic signals and lighting standards using this computer code.

These examples correspond to the three cases solved in the basic report and include analyses input for standard types: XIX, XXI, and XXVI.

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FORTRAN CODING FORM

EXAMPLE — TRAFFIC SIGNAL & LIGHTING STANDARD TYPE XIX (ES-14-5)

FORTRAN STATEMENT

TRAFFIC SIGNAL AND LIGHTING STANDARD TYPE XIX (DWG ES-14-5) EXAMPLE

MATL		30.E6	.3	.283	20.	15.	10.	8.	7.	6.	5.	4.	3.
	1	0.	0.										
	4	0.	192.										
	7	0.	354.										
	10	180.	411.										
	11	72.	220.										
	13	216.	266.										
	15	324.	278.										
	16	360.	278.										
POLE	7.	10.75	.2391	6.625	.2391								
ARMM	1	7 8 10		4.2	.1345	2.375	.1345						
ARMM	2	4 11 16		8.0	.2391	3.2	.2391						
SIGN	1	13	24.	48.	50.	-20.							
SIGN	2	15	22.	33.	47.8	0.							
SIGN	3	16	24.	48.	50.	-32.							
LUMN	10	3.3	3.3	75.									
WIND		80.	28.	50.	17.5								

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FORTRAN CODING FORM

WEFFLS data
TYPE XXI

FORTRAN STATEMENT

LIGHTING:		STANDARD	TYPE: XXI		DWG: E3-17-5									
MATL		30.E6	.3	.283	36.	56	54	52	41	32	26	26	26	.05
	1	0.00	0.00											
	7	0.00	422.00											
	10	180.00	480.00											
POLE	7	8.5	.1345	3.875	.1345									
ARMM	1	7.	8.	10	4.2	.1345	2.375	.1345						
LUMN	1	10	475.2	475.2	75.									
WIND			50.	1.35	64.5	1.35	80.	1.35						

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TRAFFIC SIGNAL AND LIGHTING STANDARD TYPE XXVI (DWG ES-20-1)

MATL		30.E6	.3	.203	36.	.56	.54	.52	.41	.32	.26	.26	.26	.05
	1	0.	0.											
	4	0.	192.											
	5	0.	234.											
	7	0.	354.											
	8	60.	382.0											
	9	120.	402.0											
	10	100.	410.4											
	11	108.	253.2											
	13	300.	273.6											
	14	360.	278.4											
	16	506.	282.0											
	17	540.	282.0											
	18	108.	230.4											
	19	204.	254.4											
POLE	7	12.125	.3125	8.000	.3125									
ARM	1	8 10		4.2	.1345	2.375	.1345							
ARM	2	5 11 17		9.25	.2391	3.	.2391							
SIGN	1	14		24.	42.	50.	-26.4							
SIGN	2	16		22.	33.	47.8	0.							

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SIGN	3	17		24.	48.	50.	-30.			
LUMN	1	10		39.6	39.6	75.				
BRAC	1	4	18	7.04	.2391					
BRAC	2	18	19	5.76	.2391					
BRAC	3	19	13	4.50	.2391					
BRAN	4	11	18	9.	.375	.03955	22.78	.154	[illegible]	
WIND				50.	1.35	64.5	1.35	80.	1.35	
DRAG	1	2								
10.E3		1.								
10.E6		1.								

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SIGN	3	17		24.	48.	50.	-30.			
LUMN	1	10		39.6	39.6	75.				
BRAC	1	4	18	7.04	.2391					
BRAC	2	18	19	5.76	.2391					
BRAC	3	19	13	4.50	.2391					
BRAN	4	11	18	9.	.375	.03955	22.78	.154	5.375	
WIND				50.	1.35	64.5	1.35	80.	1.35	
DRAG	1	2								
10.E3		1.								
10.E6		1.								

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