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OFF-HIGHWAY MACHINERY PRACTICE

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LATTICED CRANE BOOM SYSTEMS - ANALYTICAL PROCEDURE

1. PURPOSE:

The purpose of this recommended practice is to establish criteria for the analytical evaluation of the basic structural competence of wire rope supported, latticed crane boom systems. The criteria and procedures specified include the evaluation of elastic stability for the overall boom system and individual members of the system.

2. SCOPE:

This recommended practice applies to wire rope supported, latticed crane boom systems mounted on mobile construction type cranes for lift crane service.

3. APPLICATIONS:

This calculation procedure references and is related to SAE J987 tests. Tests of selected loading conditions from the ratings determined by this procedure or other limitations will verify calculated Class III and Class I (8.4.7 and J987 - 9.1) stresses and overall deflections. The testing also evaluates Class II areas not necessarily calculated by this procedure.

Intended uses of this document include the following:

3.1 A production boom system (serially produced) can be rated by this analytical procedure, but must be verified by test procedures as specified in SAE J987.

3.2 A production boom system that has been rated by 3.1 may be used on another machine provided that this same analytical procedure shows that its stress levels will be less than in the original test application, and provided that the supporting structure is as rigid as the structure used in 3.1. If these conditions are met, no additional SAE J987 testing is required.

3.3 A specially designed boom system (not serially produced), similar to a known and tested design, may be rated using this analytical procedure. An overload test, as specified in SAE J987, should be applied.

4. DEFINITIONS:

4.1 Boom: A member hinged to the front of the rotating upper structure with the outer end supported by ropes leading to a gantry, A-frame or live mast. Its purpose is to support a lifted load.

4.2 Boom Systems: A boom or boom and jib combination and the associated suspension system and supporting structure.

4.3 Buckling Ratio: Critical buckling is the loading condition where stress and deflection become undefined. P_{cr}/P is the ratio of the boom compression at buckling to the boom compression at rated load. W_{cr}/RL is the ratio of the lifted load at P_{cr} to rated load.

4.4 Chords: The main load-carrying members placed at the extreme corners of the boom or jib cross section.

4.5 Gantry: A gantry (A-frame) is a structure mounted on the revolving upper structure of the machine to which the boom supporting ropes are attached.

4.6 Jib: An extension mounted near the boom point to provide added length for lifting loads. The jib may be in line with the bottom or offset to various angles.

4.7 Lacing Members: Structural truss members at angles to and supporting the chords in a lattice boom. They are open or closed members used to transmit shear loads and to maintain the geometry of the lattice boom.

4.8 Lattice Boom (or Jib): Constructed in the form of a truss with lacing members between the chords.

4.9 Live Mast: Hinged structural member extending above the upper structure used for supporting a boom. Head of live mast is usually supported and raised or lowered by the boom hoist ropes.

4.10 Mobile Construction Type Lifting Crane: Comprised of a boom system and hoisting mechanism attached to an upper structure that is rotatably mounted to a mobile undercarriage. It is used for the purpose of lifting loads in the utilization and load spectrum of construction industry hook type lifting applications.

4.11 Mathematical symbols used are defined in SAE J987.

5. RATED LOAD CALCULATION FOR BOOM:

5.1 Forces and Loadings: The forces considered to act on the boom structure for stress calculations shall include boom deadweight loads, hoist rope and boom suspension deadweight loads, hoist and boom suspension forces, rated load, boom foot inclination, side load produced by hoist drum offset, and a horizontal side load applied to the load equal to 2% of the rated load.

5.1.1 The horizontal side load (2% of rated load) provides for the normal rating conditions associated with machine operation during lifting crane service.

5.1.2 The dynamic effects of vertical acceleration or deceleration of the load are provided for by the required strength margins.

5.1.3 Consideration of factors beyond the manufacturer's normally specified operating conditions has not been provided for. The factors include traveling with a load, out-of-level operation, duty cycles, wind effects on the boom and the lifted load, etc.

5.1.4 Boom foot inclination results from deformation of supporting structure. When the rated load on a leveled crane is swung to some positions (i.e., corner), the boom foot support may become out of level due to this deformation (see also 3.2). This inclination can be determined by calculation or previous test experience on a similar supporting structure.

5.1.5 The parts of hoist line used in this calculation should be the minimum required for the load being lifted. The boom suspension shall be as specified by the manufacturer.

5.2 Stress and Deflection Criteria: It is assumed that the calculation procedure used is sufficiently accurate (see 8.4.6) to determine S_{ra} per SAE J987. Also, the boom rating using this recommended practice must pass the SAE J987 test procedures in which the strength margin n=1.60 is calculated by the interaction formula using S_{ra} and S_{rm}. The maximum stress S_{rm} cannot be readily calculated, but study of test data shows that for 70% of occurrences, $S_{rm}/S_{ra}<1.14$ when both open and closed section data are included in the analysis (see Table B2). The following minimum recommended strength margins for calculated values of S_{ra} are based on the values in Table B3 (Appendix B) with criteria of 8.4.6 being met.

5.2.1 Tensile stresses in any boom chord or lacing member shall not exceed the member yield stress divided by 1.69.

5.2.2 Compression stress in any boom chord or lacing member shall not exceed the member critical stress (S_{cr}) divided by 1.80. S_{cr} shall be taken as defined in SAE J987, Appendix A.

5.2.3 The deflection criterion is that the lateral deflection Z_b must be equal to or less than 2% of the boom length with the rated load and side load as defined per 4.1.

$$Z_b \leq 0.02\ L_b \text{ (see 9.2.2 for nomenclature)} \quad (4\text{-}1)$$

Note: The side load and boom foot inclination must be used in the calculation to determine Z_b.

5.3 Overall Boom Buckling: Buckling competence with the rated loads is determined by ratios W_{cr}/RL where W_{cr} is the hook load, which would produce critical buckling of the boom and RL is the rated load and P_{cr}/P where P_{cr} is the boom compression, which would cause critical buckling and P is the boom compression with rated load.

5.3.1 The ratio W_{cr}/RL shall be greater than or equal to 1.50 in either plane.

5.3.2 The ratio P_{cr}/P shall be greater than or equal to 1.30 in either plane.

6. ERECTION LOAD CALCULATIONS FOR BOOM:

6.1 Forces and Loadings: The forces considered to act on the boom structure during erection shall include boom deadweight loads, hoist rope and boom suspension deadweight loads, and boom suspension forces.

6.2 Stress Criteria:

6.2.1 Tensile stresses in any boom chord or lacing member shall not exceed the member yield stress divided by 1.46.

6.2.2 Compression stresses in any boom chord or lacing member shall not exceed the member critical stress (S_{cr}) divided by 1.58. S_{cr} shall be taken as defined in SAE J987.

6.3 Overall Boom Buckling: Buckling competence with erection load is determined by the ratio P_{cr}/P.

6.3.1 The ratio P_{cr}/P shall be greater than or equal to 1.30 in either plane.

7. OUT OF SERVICE WIND CALCULATION:

The manufacturer shall specify the wind velocity at which the machine should be considered out of service and the boom lowered to the ground or some other less hazardous position. The specified wind is calculated based on boom strength and other considerations such as stability.

7.1 Out of Service Criteria for Boom Strength:

7.1.1 At the maximum rated boom angle, the boom shall have an adequate strength margin when the specified wind from the front forces the boom rearward into the boom stops. There is to be no load, hoist line, or hook weight acting at the boom tip. The weight of the hoist line running up the boom may be considered.

7.1.2 At any boom angle the specified wind forces acting on the boom, from any direction, shall not exceed adequate strength margins (7.3). There is to be no load, hoist line, or hook weight acting at the boom tip. The weight of the hoist line running up the boom may be considered.

7.2 Wind Loading Criteria:

7.2.1 The wind loadings considered to act on the boom shall be calculated as specified in Appendix A.

7.2.2 In lieu of a specified exposure factor, "Exposure C" from Table A1, Appendix A, should be used.

7.3 Stress Criteria: The limiting stress criteria are to be the same as for rated loads per Section 5.

8. MATHEMATICAL METHODS:

A classical mathematical method that can yield good comparison to test data if properly applied is presented below. There are other acceptable methods.

The equations presented in this recommended practice are based on a beam-column analytical model of the boom in which the main chords act together to resist axial compressive loads and bending as extreme fibers in a built-up cross section. The lacing members serve to transmit shear, brace the main chords, and provide cross-sectional stability. The flexural properties (EI) of the boom cross section are based on the moment of inertia (I) of the chord areas with respect to the centroid of the boom, and the material modulus of elasticity (E).

The solutions of the differential equations below have proven to yield good correlation to test data. For typical equation solutions, see references 3 and 4 which only define a simplified model of a boom and do not contain all the factors listed below.

The mathematical analysis of the beam column shall consider both the in-plane and out-of-plane cases.

8.1 In-Plane Analysis: The in-plane case refers to the calculation of deflections (y) in the vertical plane through the centerline of boom as a function of the distance from the boom foot (x). The general in-plane equation is:

$$-EI \frac{d^2y}{dx^2} = Y(x) + Py + Qy \qquad (1)$$

Where: P = Boom compression due to the boom point forces
Q = Boom compression due to the intermediate suspension
Y(x) = Moment function of x, which should include the effects of:
a. boom weight distribution
b. boom point offset from the nominal boom C_L
c. wind force fore or aft (if applicable)
d. vertical eccentricity
e. suspension line force at its application point
f. force due to lifted load
g. forces due to hoist line at its application point
h. forces due to intermediate suspension at its application point

8.2 Out-of-Plane Analysis: The out-of-plane case refers to the calculation of deflections (z) in the transverse plane through the centerline of the boom as a function of the distance from the boom foot (x). The general out-of-plane equation is:

$$-EI \frac{d^2z}{dx^2} = Z(x) + Pz + Qz \qquad (2)$$

Where: Z(x) = Moment function of x, which should include effects of:

a. wind side load (if applicable)
b. hoist rope offset from the C_L of drum and boom point
c. horizontal force from the suspension line due to boom tip deflection
d. horizontal force from the intermediate suspension due to midpoint connection deflection
e. horizontal eccentricity due to manufacturing tolerances, unsymmetrical boom point loads and/or unequal pendant loads
f. side load
g. boom foot inclination

8.3 Bending Moments: The in-plane and out-of-plane bending moments are calculated from the general expressions:

$$M_y(x) = -EI \frac{d^2y}{dx^2} \text{ (in-plane)} \qquad (3)$$

$$M_z(x) = -EI \frac{d^2z}{dx^2} \text{ (out-of-plane)} \qquad (4)$$

after equations 1 and 2 are solved for y and z. Solutions of equations (1) and (2) are used to find critical buckling, W_{cr} and P_{cr} as referred to in 4.3 and in references 3 and 4.

8.4 Additional Considerations:

8.4.1 The shear effects are not considered in equations (1) and (2) but should be for more detailed analysis. E or I should be considered as functions of x if either vary significantly along the length of the boom.

8.4.2 The equations (1) and (2) shall account for changes in axial load due to intermediate suspension or other axial force changes.

8.4.3 The mast or gantry, for suspension connection, may be considered to be rigid if side deflection does not significantly influence the results.

8.4.4 The stresses in the chord members should be computed by summing the stresses produced by in-plane and out-of-plane moments, the axial load, and bending stress created by torsion.

8.4.5 The stresses in the lacing members can be calculated by considering the total shear force produced by bending and torsion.

8.4.6 The calculation results are to be compared to known test data to verify that the calculated values of S_{ra} are approximately equal to the tested values of S_{ra} (see 4.2) and that the calculated and the test deflections are approximately equal.

8.4.7 Additional appropriate calculations are to be performed to verify the structural competence at local areas not covered by the analytical methods presented here. For example, design details near load input points should be evaluated for unsupported bending, local torsion, plate buckling or other stress concentration problems. Stress levels should consider the various stress classes and limits of SAE J987.

9. <u>MODIFICATIONS TO PROCEDURES FOR BOOM-JIB COMBINATIONS</u>:

If a jib is mounted at the boom point, the solution for both the boom and jib with the load applied to the jib can be evaluated. A second pair of differential equations similar to equations (1) and (2) can be developed for the jib. They shall be solved simultaneously with equations (1) and (2) by applying the necessary boundary conditions for both the in-plane and out-of-plane cases. Additionally, the analysis shall account for the effects of torsion on the main boom resulting from jib offset.

9.1 <u>Forces and Loadings</u>: The forces considered to act on the boom are those of 5.1, 6.1, 7.2, and in addition, the deadweight effects of the jib and associated parts and the forces from the jib and the jib suspension. The rated load should now be considered to act on the jib point with horizontal side load applied to the load equal to 2% of the rated load.

9.2 <u>Stress and Deflection Criteria</u>:

9.2.1 The stress criteria given in 5.2, 6.2, and 7.3 should apply for the boom-jib combination.

9.2.2 The lateral deflection criterion for the rated load and side load of 9.1 are the same as SAE J987. The deflection Z_j must be less than 2% of the total combination length:

$$Z_j \leq 0.02\ (L_j + L_b) \qquad (5)$$

Also, the deflection of each individual boom or jib member shall not exceed 2% of the length of that member. To satisfy this criteria, the deflection of an individual member does not include the deflection, rotation, or slope of the member on which it is mounted. For a single jib mounted on a boom, the following relationship is given:

$$Z_j \leq 0.02\ L_j + Z_b + Z'\ (L_j \cos \beta) + \theta\ (L_j \sin \beta) \qquad (6)$$

9.2.2 (Continued):

Where: R = plane perpendicular to boom foot pin C_L
Z_j = jib point deflection from plane R
Z_b = boom point deflection from plane R
L_j = length of jib
L_b = length of boom
β = jib offset angle from C_L boom
Z' = boom tip slope (out of plane)
θ = boom point rotation about x axis (radians)

9.3 Overall Boom System Buckling: For the buckling of the boom, the jib, or the overall system, the criteria of 5.3 apply to rated conditions and the criteria of 6.3 apply to erection conditions.

9.4 Multiple Jibs: A jib mounted on the point of another jib shall be treated by appropriate modifications to the procedures described for a single jib.

10. REFERENCES:

1. ANSI A58.1-1972, "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures."

2. SAE J987 "Crane Structures - Method of Test", 1967.

3. Timoshenko and Gere, "Theory of Elastic Stability," Second Ed., McGraw-Hill, New York, 1961.

4. E. J. Vroonland, "Analysis of Pendant-Supported Latticed-Crane Booms," Sept. 1971, SAE Paper 710697.

5. C. Lipson and N. J. Sheth, "Statistical Design and Analysis of Engineering Experiments," McGraw-Hill, Inc., 1973.

APPENDIX A

Wind Loadings

Wind loadings should be calculated using data from reference 1, 6.9, relating to trussed towers. Wind pressure (q) is given by

$$q = k\ V^2 \left(\frac{H}{H_r}\right)^b \qquad \text{(A1)}$$

Where:
- q = wind velocity pressure at height H; lb/ft^2 (kN/m^2)
- V = wind velocity at reference height; mph (kM/h)
- H_r = reference height; 30 ft (10 m)
- k = constant, depending on exposure; lb-h^2/ft^2-mile^2 (kN-h^2/m^2-km^2)
- b = dimensionless constant

Constants and exposure descriptions are given in Table A1, where the data from reference 1 has been tabulated.

TABLE A1 - Constants and Exposure Descriptions

Exposure	k	b	Exposure Direction
A	1.1×10^{-3} (0.219)	0.467	Center of large cities and very rough hilly terrain
B	2.0×10^{-3} (0.398)	0.340	Suburban areas, towns, city outskirts, wooded areas and rolling terrain
C	3.3×10^{-3} (0.657)	0.229	Flat open country, open flat coastal belts, and grassland

Net pressure coefficients for various shapes of boom parts are given in Table A2.

TABLE A2 - Net Pressure Coefficients C_f for Rectangular and Triangular Section Booms

Member Shape	ϕ[a]	Rectangular Booms C_f	Triangular Booms C_f
Flat (angles)	0.000 - 0.45	4.13 - 5.18 ϕ	3.71 - 4.47 ϕ
	0.45 - 0.70	1.8	1.7
	0.70 - 1.0	1.33 + 0.67 ϕ	1.00 + ϕ
Rounded (tubes)	0.000 - 0.45	2.75 - 3.45 ϕ	2.47 - 2.98 ϕ

[a] ϕ = ratio of the solid area to the total area of one side of the boom.

The net force/unit length (f) at height H on the boom is then:

$$f = C_f\ Aq \quad \text{lb/ft (kN/M)} \tag{A2}$$

Where: A = area of the near side of boom/unit length accounting for chords, diagonals, and flat plates; ft^2/ft (m^2/m). The shadow effects are accounted for in C_f.

The effects of wind on the boom system and lifted load may be calculated for ratings during in-service conditions. The wind velocity pressure (q) should be calculated from equation (A1) using the constants for the appropriate Exposure Description from Table A1.

Net pressure coefficients (C_f) for the boom should be calculated from Table A2. Net pressure coefficients for the load can be selected from Table A3, and the net force (F) acting on the load can then be calculated from equation (A3):

$$F = C_f\ A_L\ q \quad \text{lb (kN)} \tag{A3}$$

Where: F = horizontal force acting on centroid of load area; lb (kN)
A_L = area of largest load side; ft^2 (m^2)

Note that the height of the lifted load will affect the boom system calculations as well as the stability ratings.

TABLE A3 - Net Pressure Coefficient for Signs (Loads) When Above Ground Level, C_f

a/b[a]	6	10	16	20	40	60	80
C	1.2	1.3	1.42	1.52	1.75	1.84	2.0

[a]a = greater dimension of load
b = smaller dimension of load

APPENDIX B

In this recommended practice, the calculated chord stress would be the average stress (S_{ra}) in the chord at that point. In a test method such as SAE J987, more than one gage is applied and more than one stress value is recorded. The average stress (S_{ra}) and the maximum stress (S_{rm}) can be determined from these data. The strength margin (n) is then determined by the interaction formula:

$$\frac{1}{n} = \frac{S_{ra}}{S_{cr}} + \frac{S_{rm} - S_{ra}}{S_y} \qquad \text{(B1)}$$

which can be rewritten as:

$$\frac{S_{cr}}{S_{ra}} = n\left[\frac{S_{cr}}{S_y}\left(\frac{S_{rm}}{S_{ra}} - 1\right) + 1\right] = m \qquad \text{(B2)}$$

The required calculated strength margin (m) will be greater than n as a function of S_{cr}/S_y and S_{rm}/S_{ra} where S_y is the stress at the material yield point.

By analyzing test data using an appropriate statistical distribution method, the correlation of the ratio S_{rm}/S_{ra} may be evaluated. Since the ratio S_{rm}/S_{ra} can never be less than 1.0, an appropriate statistical distribution method would be a Three Parameter Weibull with the third parameter (X_o) set equal to 1.0.

The cumulative distribution function (CDF) of the Three Parameter Weibull function (Reference 5) is:

$$CDF = F(x) = 1 - \exp\left[-\left(\frac{x - x_o}{\theta - x_o}\right)^b\right] \qquad \text{(B3)}$$

Where: x_o = 1.0, which is the minimum expected value of x
θ = characteristic value, or the scale parameter
b = Weibull slope, or shape parameter
x = S_{rm}/S_{ra} = any assigned value for which is desired to calculate CDF value
CDF = Cumulative Distribution Function. Fraction of data having a value of less than x input to equation

The determination of b and θ may be accomplished in either of two ways: (See Reference 5 for details and rank order tables.)

1. Plot $\left(\frac{S_{rm}}{S_{ra}} - 1\right)$ data using Weibull probability techniques after assigning each data point a (median) rank order.

2. Linear regression of data $\underline{Y}$ versus $\underline{X}$.

$$Y = \ln \left[\ln \left(\frac{1}{1 - F(x)} \right) \right] \text{ versus}$$

$$X = \ln (x-1), \text{ where}$$

$$F(x) = \text{rank order of point x input}$$

Because of the large amount of test data (S_{rm}/S_{ra}) studied, the linear regression method was selected. Open type (for example, angles) and closed type (for example, tubular) chord members were studied independently. Results are tabulated in Table B1 and B2.

TABLE B1

Type Chord Section	Open	Closed	All
No. of Data	564	505	1069
Slope: b	1.415	1.007	1.152
Scale: θ	1.136	1.099	1.119
Coefficient of Correlation (R^2)	0.98	0.94	0.96

TABLE B2 - Values of S_{rm}/S_{ra} for Various CDF Values

CDF %	Open	Closed	All
70	1.15	1.12	1.14
85	1.21	1.19	1.21
95	1.29	1.29	1.31