

Submitted for recognition as an American National Standard

(R) LATTICED CRANE BOOM SYSTEMS—ANALYTICAL PROCEDURE

Foreword—This Document has also changed to comply with the new SAE Technical Standards Board Format. Definitions has been changed to Section 3. All other section numbers have changed.

1. **Scope**—This SAE Information Report applies to wire rope supported, latticed crane boom systems mounted on mobile construction type cranes for lift crane service.

1.1 **Purpose**—The purpose of this document 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. **References**

2.1 **Applicable Publications**—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated the latest revision of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J987—Crane Structures—Method of Test

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

2.1.2 ANSI PUBLICATION—Available from ANSI, 11 West 42nd Street, New York, NY 10036-8002.

ANSI A58.1-1982—Minimum Design Loads for Buildings and Other Structures

2.1.3 OTHER PUBLICATIONS

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

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

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3. Definitions

- 3.1 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.
- 3.2 Boom Systems**—A boom or boom and jib combination and the associated suspension system and supporting structure.
- 3.3 Buckling Ratio**—Critical buckling is the loading condition where deflection becomes mathematically unbounded. 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. In determining the buckling load of a boom, proper consideration must be given to the effects of any tapering sections of the boom or other variations in boom properties which influence buckling. (See 2.1.1 and 2.1.3.)
- 3.4 Chords**—The main load-carrying members placed at the extreme corners of the boom or jib cross section.
- 3.5 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.
- 3.6 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.
- 3.7 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.
- 3.8 Lattice Boom (or Jib)**—Constructed in the form of a truss with lacing members between the chords.
- 3.9 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.
- 3.10 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.
- 3.11 Mathematical Symbols**—Mathematical symbols not defined in this document are defined in SAE J987. Revised as suggested by Bonesteel.

- 4. 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 SAE 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:

- 4.1** 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.
- 4.2** A production boom system that has been rated by 4.1 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 4.1. If these conditions are met, no additional SAE J987 testing is required.

4.3 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.

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 rated hook load, hoist, and boom suspension live loads including hoist line to drum offset, boom deadweight loads, hoist rope, and boom suspension deadweight loads, a horizontal side load applied to the boom tip equal to 2% of the rated load, and the effects of boom foot inclination. Wind along with other in-service operating conditions combine to affect the crane operator's ability to control a load. The diversity of load shapes, sizes, and lifting heights which occurs during crane operation makes the calculation of in-service wind effect rather arbitrary for general crane rating considerations.

5.1.1 The horizontal side load (2% of rated load) provides for the normal rating conditions associated with machine operation, including wind effects, during lifting crane service with freely suspended loads.

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 rating conditions has not been provided for. While such factors may be appropriate for a specific operating condition, they are not applicable to ratings for general lift crane service. Such factors include traveling with a load, out-of-level operation, duty cycle operation, and unusual wind effects on the boom or lifted load.

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 4.2). 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**—In this document, the calculated boom chord stress is the average stress at a cross section of the chord. This corresponds to the value S_{ra} in the test standard SAE J987. It is intended that this calculation procedure be sufficiently accurate to determine the stress (S_{ra}) and deflection (Z_b), as defined in SAE J987. It is also intended that boom ratings determined by use of this calculation method shall be capable of passing SAE J987 test criteria. It is recognized that a test procedure measures all effects present at the time of testing, some of which may not be practical or even possible to predict by calculation. To account for these effects, experience has shown that the following minimum recommended strength margins are required for calculated values of stress. The specified strength margins have been derived from the statistical analysis of hundreds of test results reflecting data on cranes from many manufacturers. For additional background information concerning the determination of the specified strength margins refer to Appendix A.

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 B.

- 5.2.3 The lateral deflection of the boom tip Z_b , must be equal to or less than 2% of the boom length with the rated load and sideload as defined per 5.1. (See Equation 1.)

$$Z_b \leq 0.02L_b \quad (\text{Eq. 1})$$

where:

Z_b = Boom point deflection from plane R

L_b = Length of boom

NOTE—The sideload 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 to be out of service and the boom lowered to the ground or secured by some other means. The specified wind velocity shall be calculated based on boom strength and other considerations such as stability. Analysis of the boom for out-of-service wind loadings may be performed using the methods outlined in this document (Section 8) in conjunction with wind forces developed by the methods shown in Appendix B.

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 (8.3) when the specified wind from the frontal direction forces the boom rearward into the boom stops. There is to be no rated load or hoist-line weight considered to be acting at the boom tip. The weight of the hoist line running up the boom and the load block or ball 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 rated load acting at the boom tip. The weight of the hoist line running up the boom, the vertical parts of hoist line, and the load block or ball should 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 B.

7.2.2 In lieu of a specified exposure factor, "Exposure C" from Table B1, Appendix B, 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 as follows. Other acceptable methods, such as a nonlinear finite element analysis, can produce similar results if properly applied. In any case, the solution technique must accurately represent the physical system and include all the criteria and factors listed in 8.1 to 8.4.

The equations presented in this document 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 in 8.1 have proven to yield good correlation to test data. For typical equation solutions, see 3.1.1.2 and 3.1.3.1 which only define a simplified model of a boom and do not contain all the factors listed in 8.1.

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 the boom as a function of the distance from the boom foot (x). The general in-plane equation is shown in Equation 2:

$$-EI \frac{d^2 y}{dx^2} = Y(x) + Py + Qy \quad (\text{Eq. 2})$$

where:

- P = Boom compression due to boom point forces
- Q = Boom compression due to the intermediate suspension
- Y(x) = Moment function of x which should include the effects of:
 - a. force due to lifted load
 - b. suspension line force
 - c. boom weight distribution
 - d. boom point offset from the nominal boom centerline
 - e. forces due to load hoist line
 - f. vertical eccentricity
 - g. forces due to intermediate suspension
 - h. wind fore or aft force (out-of-service condition only)

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 shown in Equation 3:

$$-EI \frac{d^2 z}{dx^2} = Z(x) + Pz + Qz \quad (\text{Eq. 3})$$

where:

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

- a. 2% side load
- b. boom foot inclination
- 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 unsymmetrical boom point loads
- f. hoist rope offset from the C_L of drum and boom point
- g. wind side load (out-of-service condition only)

8.3 Bending Moments—The in-plane and out-of-plane bending moments are calculated from the general expressions (Equations 4 and 5):

$$M_y(x) = -EI \frac{d^2 y}{dx^2} (\text{in-plane}) \quad (\text{Eq. 4})$$

$$M_z(x) = -EI \frac{d^2 x}{dx^2} (\text{out-of-plane}) \quad (\text{Eq. 5})$$

After Equations 2 and 3 are solved for y and z , Solutions of Equations 2 and 3 are used to find critical buckling, W_{cr} and P_{cr} as referred to in 3.2.3 and in 3.1.1.2 and 3.1.3.1.

8.4 Additional Considerations

- 8.4.1 The shear deformation effects are not treated in Equations 2 and 3. If these effects are determined to be significant for the particular design being evaluated, they should be included in the analysis. This is usually accomplished by making an appropriate adjustment of I or E values. In addition, E or I should be considered as functions of x if either varies significantly along the length of the boom, such as for tapered ends with shorter boom lengths.
- 8.4.2 The Equations 2 and 3 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 are computed by summing the stresses produced by in-plane and out-of-plane moments, the axial load, and local chord bending stress induced by torsional displacements.
- 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 obtained by the method outlined in this document are to be compared to known test data to verify that the calculated values of stress (S_{ra}) and deflection (Z_b), correlate with the values measured during test. An effort shall be made to explain and resolve any notable differences. Where test results indicate that the strength margins specified in 5.2 should be modified for better correlation, in no case shall the strength margins be reduced below those corresponding values specified in SAE J987.

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. Modifications to Procedures for Boom-Jib Combinations—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 2 and 3 can be developed for the jib. They shall be solved simultaneously with Equations 2 and 3 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 Forces and Loadings—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 Stress and Deflection Criteria

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 8.1 are the same as SAE J987. The deflection Z_j must be less than 2% of the total combination length (see Equation 6):

$$Z_j \leq 0.02(L_j + L_b) \quad (\text{Eq. 6})$$

Also, the deflection of each individual boom or jib member shall not exceed 2% of the length of that member. To satisfy this criterion, 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 (see Equation 7):

$$Z_j \leq 0.02L_j + Z_b + Z'(L_j \cos \beta + \theta)(L_j \sin \beta) \quad (\text{Eq. 7})$$

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.

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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. Notes

10.1 Marginal Indicia—The change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. An (R) symbol to the left of the document title indicates a complete revision of the report.

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APPENDIX A

A.1 In this document, 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 (see Equation A1):

$$\frac{1}{n} = \frac{S_{ra}}{S_{cr}} + \frac{S_{rm} - S_{ra}}{S_y} \quad (\text{Eq. A1})$$

which can be rewritten as Equation A2:

$$\frac{S_{cr}}{S_{ra}} = n \left[\frac{S_{cr}}{S_y} \left(\frac{S_{rm}}{S_{ra}} - 1 \right) + 1 \right] = m \quad (\text{Eq. A2})$$

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_0) set equal to 1.0.

The cumulative distribution function (CDF) of the Three Parameter Weibull function is shown in Equation A3:

$$\text{CDF} = F(x) = 1 - \exp \left[- \left(\frac{x - x_0}{\theta - x_0} \right)^b \right] \quad (\text{Eq. A3})$$

where:

$x_0 = 1.0$, 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 3.1.2.2 for details and rank order tables.)

1. Plot $S_{rm}/S_{ra} - 1$ data using Weibull probability techniques after assigning each data point a (median) rank order.
2. Linear regression of data Y versus X (see Equation A4).

$$Y = \ln \left[\ln \left(\frac{1}{1 - F(x)} \right) \right] \text{ versus } X = \ln \quad (\text{Eq. A4})$$

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where:

F (x) = 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 Tables A1 and A2.

TABLE A1—CHORD TEST RESULTS

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 A2—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

Using the preceding information, the required calculated strength margins (m) can be calculated from Equation (A2). Table A3 shows required calculated strength margins (m) for various load and stress conditions described in SAE J987 based on $S_{cr}/S_y = 0.9$ and 70% reliability.

TABLE A3—REQUIRED CALCULATED STRENGTH MARGINS

Load Type	Stress Type	Reference Paragraph	Assumed S_{rm}/S_{ra}	Assumed S_{cr}/S_y	n (J987)	Req'd m
Rated	Compression	5.2.2, 7.3, 9.2	1.14	0.9	1.6	1.80
Rated	Tension	5.2.1, 7.3, 9.2	1.14	0.9	1.5	1.69
Erection	Compression	6.2.2, 9.2	1.14	0.9	1.4	1.58
Erection	Tension	6.2.1, 9.2	1.14	0.9	1.3	1.46