Stress Analysis of a Boom of Pick-n-Carry Mobile Crane

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Abstract: ***High strength and light weight boom structure is the main challenge for manufacturers to design a telescopic boom for mobile cranes. Crane booms work in fully retracted positions and fully extended positions. Normally the crane booms perform better in case when the boom is retracted but when the boom is extended than the load carrying capacity of boom decreases. As the distance between the nearer point on crane and load point increases the load carrying capacity decreases. Crane boom works at greater heights when the crane boom achieves maximum achievable boom angle [1]. In the present work the stress analysis of crane boom and its parts is done using the manual calculations using SAE J1078 standard [2]. The crane boom should have light weight and high strength so in this present work the different crane boom sections will be compared.***

Keywords: Boom, Strength

1. Introduction

Mobile cranes are very commonly used in construction industry as these cranes can move freely at the job location. A telescopic mobile crane is used to pick and carry heavy loads. These cranes can also travel on public roadways. Boom structure is integral part of mobile cranes. It has usually two or more boom sections that can be extended and retracted to perform at greater heights. Mobile crane's lifting capacity is generally limited by either structural strength or tipping moment [1]. The main causes of crane accidents are structural failure or instability of mobile cranes [4]. The major problems encountered with heavy duty mobile cranes to provide a telescopic boom with the required and desired strength in different extended positions of booms without having the boom unduly heavy relative to size and weight of outermost section of boom [1]. The problem becomes more complicated when the boom design consist of four pate sections. In old designs of cranes the boom section used were four plate sections. The main section is required to be strongest and the largest in comparison to the succeeding extensions of the boom. The main problem is to design the main section to be as strong as possible and also to decrease the overall weight of the boom of mobile crane.

2. Calculations

2.1 Purpose

The purpose of manual calculations is to establish the method for analysis to determine the competence of telescopic mobile crane booms [2].

2.2 Basis for Analysis

The boom shall be deemed competent when the solution to interaction equations yields a value less than or equal to one. The areas considered in this analysis are axial loading, torsional loading, bidirectional bending and panel buckling [2]. The most important are Compressive stress calculations in this analysis. The manual calculations are done using SAE J1078 and AISC Specifications.

2.3 Methodology/Approach

Boom plays important role in lifting operations. It is very important to predict whether the crane boom design is safe for various working conditions. In the present work calculations are made for the stress analysis of crane boom and its sections. Hydra crane's 44' boom is taken for analysis purpose and this boom is having 12 tonne lifting capacity. The data collected from boom design i.e. Weights, CG location, lengths and cross sectional geometry data of boom sections, cylinders and other assembly parts. The calculations are done for stress analysis of boom in four different working conditions of crane boom as following:

1) When the boom is fully Extended and at 0 degree boom angle.
2) When the boom is fully Extended and at maximum achievable angle i.e. 55 degrees
3) When the boom is fully Retracted and at 0 degree boom angle.
4) When the boom is fully Retracted and at maximum achievable angle i.e. 55 degrees

Forces and moments are calculated for above four cases. Stresses induced on different parts of boom are analyzed in above four cases. The crane boom design in fully retracted position and fully extended position is shown below.

2..4 Assumptions

1. Wind force is supposed to be negligible on head section.
2. Torque is created on head due to side load.
3. The fleet angle of winch rope is supposed to be negligible.
4. Wind forces are distributed along the length of the side of the section with its response at the centre.
5. The axial stresses generated by friction forces due to section reaction points from one to next are very small in comparison to other stresses, and the section carrying the cylinder bear the axial loads.

2.5 Calculation Procedure for stress analysis

Step-1 Data collection

a) Description of geometry and loading (boom length, working radius, boom angle, rated load etc).
b) Identify Boom arrangement.
   i. Shear and moment diagrams are generated.
   ii. Forces and moment equations are solved.
c) Identify crane boom sections for the purpose of analysis.
   i. Material properties are determined.
   ii. Section properties are determined.

Step-2 The section properties considering the Compressive, Actual and the Allowable stresses are calculated.
Step-3 To find the solution of interaction equations for the compressive stresses.
Step-4 Actual and Allowable shear stress in the webs are calculated.
Step-5 Tensile stresses are calculated.

2.5.1 Data Collection

Data is collected from the existing boom design made in Solid works. Boom distances and section properties are determined from the design. All the parameters required for stress analysis calculations are determined from existing design of boom.

W1 = Weight of Fly Jib =80.198112kg = 196.7154 lb
W2 = Weight of 2nd Extension = 264.7109 kg = 583.7872 lb
W3 = Weight of 1st Extension = 401.292 kg = 884.9999 lb
W4 = Weight of Mother Boom = 711.29kg = 1568.662 lb
W5 = Weight of Extension Cylinder = 147 k g = 324.1903 lb
W6 = Weight of Lug 1 = 43 kg = 94.83118 lb
W7 = Weight of Lug 2 = 30.5 kg = 67.26398 lb
W8 = Weight of Lug 3 = 25.6 kg = 56.45763 lb
W9 = Weight of Hook Block = 149 kg = 328.6011 lb

Table 1: Boom distances

Boom Distances	Boom (Fully Extended) Boom length=13093mm	Boom (Fully Retracted) Boom length = 7801mm
Fly Jib		
Load pt. to 2nd ext. end pt. hor. (L1)	389.45mm(15.33268 in)	389.45 mm(15.33267in)
Load pt. to boom center line, ver. (L2)	103.35mm(4.068898 in)	103.35 mm(4.068897in)
Pulley center to 2nd ext. end pt., hor. (L3)	169.45mm (6.67126 in)	169.45 mm(6.671259 in)
Pulley outer to 2nd ext. end pt. ver. (L4)	185.65mm(7.309055 in)	185.65 mm(7.309055 in)
Pin point to flyjib head (L5)	191.38mm(7.534646 in)	191.38 mm(7.534645 in)
C.G. to flyjib center line, hor. (L6)	1.12mm (0.044094 in)	1.12 mm (0.044094in)
Pin point to flyjib center line, ver. (L7)	117.5mm (4.625984 in)	117.5 mm (4.625984 in)
2nd Extension		
Bottom pad to end pt. (L8)	2803.6mm(110.378 in)	111.88 mm(4.404724in)
Bottom pad to top pad, hor. (L9)	971.4mm(38.24409 in)	3663.12mm(144.2173in)
Bottom pad to C.G. (L10)	854.43mm(33.63898 in)	3719.22mm(146.4259in)
1st Extension		
Bottom pad on 2nd ext. to bottom pad on 1st ext.	2925mm (115.1575 in)	3719.22mm(146.4259in)
Bottom pad to top pad, hor. (L12)	1953.6mm(76.91339 in)	4392 mm(172.913386in)
Bottom pad to C.G. (L13)	520.73mm(20.50118 in)	3394.22mm(133.6307in)
Bottom pad on 2nd ext. to top pad on 1st ext. (L14)	1792mm (70.55118 in)	4717 mm(185.708661in)
Bottom pad to ext. cyl. Point on 1st extension (L15)	985.05mm(38.7815 in)	3585.05mm(141.1437in)
Mother Boom		
Top pad to lift cyl. (L16)	3377mm(132.9528 in)	777 mm(30.5905512 in)
Bottom pad to lift cyl. (L17)	5169mm (203.5039 in)	5169 mm(203.50397 in)
Lift cyl. to boom pivot pt. (L18)	1806mm (71.10236 in)	1806.00mm(71.10236in)
Boom pivot pt. to C.G. (L19)	3167.72mm(124.713in)	3167.72mm(124.7133in)
Boom pivot pt. to boom center line (L20)	457.65mm(18.01772 in)	457.65mm(18.017716in)
Boom pivot pt. to extension cyl. pt. (L21)	389.9mm(15.35039in)	389.9 mm(15.350393in)
Boom pivot pt. to lift cyl. Pt. on chassis, hor. (L22)	3019.98mm (118.8969)	3019.98mm(118.8969in)
Boom pivot pt. to lift cyl. Pt. on boom, ver. (L23)	386.65mm(15.22244 in)	386.65mm(15.22244in)
Boom pivot pt. to lift cyl. Pt. on chassis, ver. (L24)	1572.5mm(61.90945in)	1572.5mm(61.90945in)
Boom pivot pt. to lug1, hor. (L25)	4505mm (177.3622 in)	4505 mm(177.3622in)
Boom pivot pt. to lug2, hor. (L26)	4805mm (189.1732 in)	4805.00mm(189.1733in)
Boom pivot pt. to lug3, hor. (L27)	5205mm(204.9213 in)	5205.00mm(204.9212in)
Boom pivot pt. to lug1, ver. (L28)	156.65mm(6.167323 in)	156.65 mm(6.167322in)
Boom pivot pt. to lug2, ver. (L29)	156.65mm(6.167323 in)	156.65 mm(6.16732in)
Boom pivot pt. to lug3, ver. (L30)	156.65mm(6.167323 in)	156.65mm(6.167322in)
Breadth of Mother Boom (L31)	325mm(12.79528)	325mm (12.79528in)

Table 2: Cylinder data

Extension Cylinder Data	*Lift Cylinder Data*
Bore = 100mm	Bore = 125mm
Stroke = 2100mm	Stroke = 1600mm
Closed Center Length = 2500mm	Closed Center Length = 1980mm
Width = 147 Kg	Number of Cylinders = 2

2.5.2 Material properties of crane boom

The material of boom of mobile crane is Mild steel having IS: 2062 grade having Ultimate tensile strength = 410Mpa, Yield strength = 250N/mm² = 36.2594344325 ksi, Poisson's ratio = 0.29,
Mass density = 7.85kg/m²

Table 3: Section Properties of 44' Crane Boom

Boom Sections	*Mother Boom*	*1st Extension*	*2nd Extension*	*Fly Jib*
B(mm)	325	275	185	90
H(mm)	450	380	298	231
TTop(Tt)	8	8	8	4
TBottom(Tb)	10	8	8	4
TSide(Ts)	8	8	8	4
Length (Ls)	7100	5000	3900	4080
Ix(mm^4)	39196.337	21655.059	9215.0811	1666.9225
Zx(mm^3)	1742.06	1139.74	618.462	144.322
Iy(mm^4)	22517.404	13155.701	4380.5343	378.69947
Zy(mm^3)	1385.7	956.78	473.57	84.155
Area(mm^2)	127.62	102.24	74.72	25.04
Volume(mm^3)	90610.2	51120	29140.8	10216.32

2.5.3 External load applied in four cases

Lifting crane rated loads must not exceed 85% of the tipping load at specified radius in case of rubber tire mounted machines. The external load applied in all cases is taken from the load chart of mobile crane (Figure 2).

Table 4: Load lifted in four working conditions of crane boom

External load	*Case-1 Boom*	*Case-2 Boom*	*Case-3 Boom*	*Case-4 Boom*
P (Kg)	3420	7623	2100	4230

2.5.4 Forces and moments in Boom sections [3]

a) Maximum load calculation

Where

$Pz = P1 \times SA$

$Px = Fll \times P1$

$M1 = (Py \times Li1) + (Pz \times Li2) - P \times Li4 \div N$

$M2 = Px \times Li1$

$T = Px \times Li2$

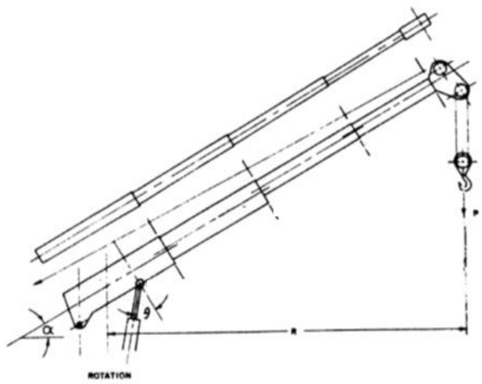

Figure 1: Loading diagram – Boom Assembly [3]

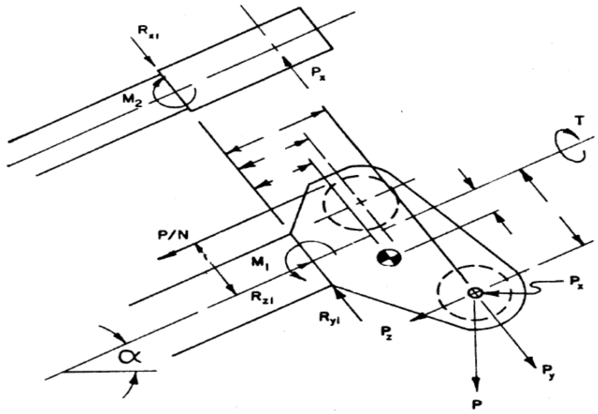

Figure 2: Load moment diagram – Head section [3]

b) Forces and moment in flyjib [3]

Moments

$$Mx1 = (Py \times Li1) + (Pz \times Li2) - (P1 \div N) \times Li4 + Py \times Li5 + w1 \times CA \times Li6$$

$$My1 = Px \times Li1 + Px \times Li5 + 0.5 \times gi \times d1 \times (Li5 \wedge 2)$$

Axial Force

$Rz1 = (P1 \div N) + Pz + (w1 \times SA)$

$Par1 = (P1 \div N) + Pz + (w1 \times SA)$

$Pal1 = w2 \times SA$

Vertical reactions

$Ry1 = PY + w1 \times CA$

$Rx1 = PX + gi \times d1 \times Li5$

$Vyr1 = Py + w1 \times CA$

$Vyl1 = Ry + w1 \times CA$

$Vxr1 = Px + gi \times d1 \times Li5$

$Vxl1 = 0$

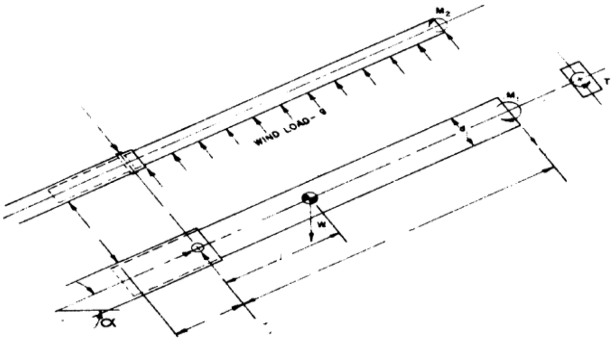

Figure 3: Load moment diagram – Flyjib [3]

c) Forces and moments in 2nd Extension [3]

Moments

$$Mx2 = Mx1 + Ry1 \times Li8 + \left(0.5 \times w2 \times CA \times \left((Li8 \wedge 2) \div (Li8 + Li9)\right)\right)$$

$$My2 = My1 + Rx1 \times Li8 + \left(0.5 \times gi \times d2 \times (Li8 \wedge 2)\right)$$

Axial Force

$Rz2 = Rz1 + w2 \times SA$

$Par2 = Rz1 + \left((w2 \times SA \times Li8) \div (Li8 + Li9)\right)$

Vertical Reactions

$$Ry3 = (Mx2 \div Li9) - ((0.5 \times w2 \times CA \times Li9) \div (Li9 + Li8))$$
$$Ry2 = Ry1 + Ry3 + w2 \times CA$$
$$Rx3 = My2 \div Li9$$
$$Rx2 = Rx1 + Rx3 + gi \times d2 \times Li8$$

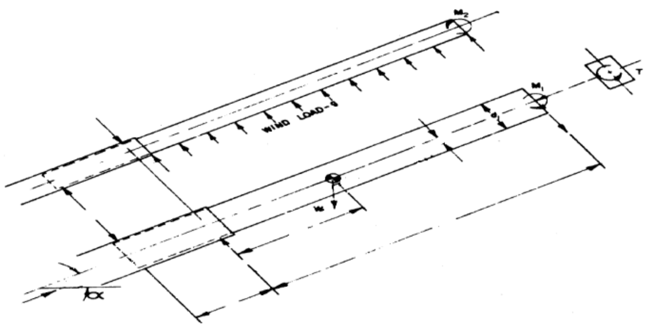

Figure 4: Load moment diagram 2nd Extension [3]

$$Vyr2 = Ry1 + ((w2 \times CA \times Li8) \div (Li8 + Li9))$$
$$Vyl2 = Ry3 + ((w2 \times CA \times Li9) \div (Li9 + Li8))$$
$$Vxr2 = Rx1 + gi \times d2 \times Li8$$
$$Vxl2 = Rx3$$

d) Forces and moments in 1st extension [3]

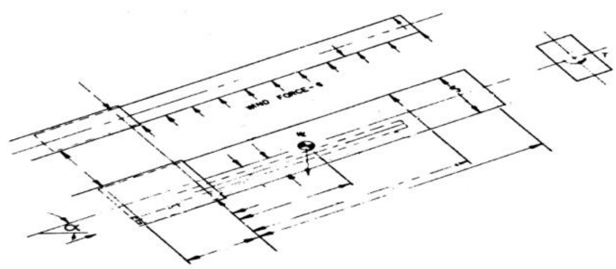

Figure 5: Load moment diagram 1st Extension [3]

Moments
$$Mx3 = Ry2 \times Li11 - Ry3 \times Li14 - w3 \times CA \times Li12 - w6 \times CA \times Li15$$
$$My3 = Rx2 \times Li11 - Rx3 \times Li14 + (0.5 \times gi \times d3 \times (Li11 \wedge 2))$$
$$Rz3 = Rz2 + w3 \times SA$$
$$Par3 = Rz2 + ((w3 \times SA \times Li11) \div (Li11 + Li12))$$
$$Pal3 = ((w3 \times SA \times Li12) \div (Li11 + Li12))$$
Vertical reactions
$$Ry5 = (Mx3 \div Li12) - ((0.5 \times w3 \times CA \times Li12) \div (Li11 + Li12))$$
$$Ry4 = Ry2 - Ry3 + Ry5 + w3 \times CA + w6 \times CA$$
$$Rx5 = (My3 \div Li12)$$
$$Rx4 = Rx2 - Rx3 + Rx5 + gi \times d3 \times Li11$$
$$Vyr3 = Ry2 - Ry3 + ((w3 \times CA \times Li11) \div (Li11 + Li12)) + w6 \times CA$$
$$Vyl3 = Ry5 + ((w3 \times CA \times Li12) \div (Li11 + Li12))$$
$$Vxr3 = Rx2 - Rx3 + gi \times d3 \times Li11$$
$$Vxl3 = Rx5$$

e) Forces and moments in mother boom [3]

Moments
$$Mx4 = (Ry4 \times Li16) - (Ry5 \times Li17) + ((0.5 \times w4 \times CA \times (Li16 \wedge 2)) \div (Li16 + Li17)) + w7 \times Li25 + w8 \times Li26 + w9 \times Li27 + w5 \times Li27 + w5 \times Li21$$
$$My4 = (Rx4 \times Li16) - (Rx5 \times Li17) + (0.5 \times gi \times d4 \times (Li16 \wedge 2))$$
Axial load on cylinder
$$Rz4 = Rz3 + (w4 + w5 + w7 + w8 + w9) \times SA$$
Axial load on section
$$Par4 = (w4 \times Li16) \div (Li16 + Li18)$$
$$Pal4 = Par3$$
Derrick cylinder reaction
$$Rd = (Ry4 \times (Li16 + Li18) - Ry5 \times (Li17 + Li18) + w4 \times (Li19 \times CA - Li20 \times SA) + (w5 \times Li21 \times CA - Rz4 \times Li20) \div ((Li18 - ((Li20 - (d4 \div 2)) \div OT)) \times CT)$$
Pivot Pin loading
$$Rx6 = Rx4 - Rx5 + gi \times d4 \times (Li16 + Li18)$$
$$Rzr6 = (Rd \times ST \div 2) + (Rx4 \times (Li16 + Li18) \div Li31) - (Rx5 \times (Li17 + Li18) \div Li31) - (Rz4 \div 2) + (w4 \times SA \div 2) + ((0.5 \times gi \times d4 \times ((Li16 + Li18) \wedge 2) \div li31) + ((w7 + w8 + w9) \times SA \div 2)$$

$$RZL6 = (Rd \times ST \div 2) - (Rx4 \times (Li16 + Li18) \div Li31) + (Rx5 \times (Li17 + Li18) \div Li31) - (Rz4 \div 2) + (w4 \times SA \div 2) - ((0.5 \times gi \times d4 \times ((Li16 + Li18) \wedge 2) \div Li31) + ((w7 + w8 + w9) \times SA \div 2)$$

$$Ryr6 = 0.5 \times (Rd \times CT + Ry5 - Ry4 - (w4 + w5 + w7 + w8 + w9) \times CA) - (Px \times (Li2 - Li20) \div Li31) + (gi \times d4 \times (Li16 + Li18) \times Li20 \div Li31)$$

$$Ryl6 = 0.5 \times (Rd \times CT + Ry5 - Ry4 - (w4 + w5 + w7 + w8 + w9) \times CA) + (Px \times (Li2 - Li20) \div Li31) - ((gi \times d4 \times (Li16 + Li18) \times Li20) \div Li31)$$

Vertical shear force

$$Vyr4 = Ry4 - Ry5 + ((w4 \times CA \times Li16) \div (Li16 + Li18))$$

$$Vyl4 = Ry4 - Ry5 + ((w4 \times CA \times Li16) \div (Li16 + Li18))$$

$$Vyl4 = Ryr6 + Ryl6 + ((w4 \times CA \times Li16) \div (Li16 + Li18)) + (w5 + w7 + w8 + w9) \times CA$$

Lateral shear force

$$Vxr4 = Rx4 - Rx5 + gi \times d4 \times Li16$$

$$Vxl4 = Rx4 - gi \times d4 \times \times Li18$$

Extension cylinder reaction

$$Recy = (w1 + w2 + w3 + w6 + P) \times SA$$

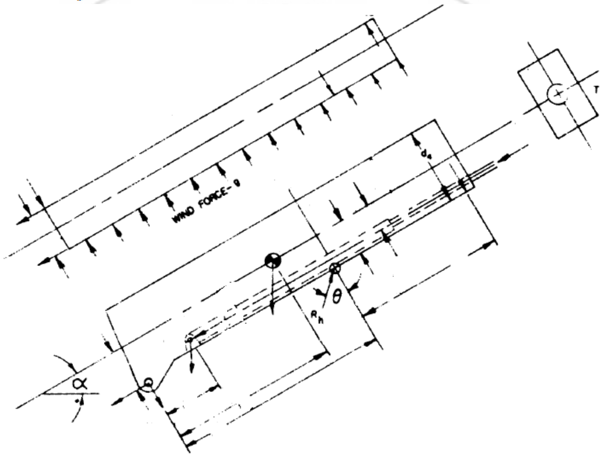

Figure 6: Mother Boom [3]

f) Calculations for forces and moments

Table 5: Maximum load calculation in four working conditions of boom

Max. load calculation	*Case-1 Boom retracted at α=0*	*Case-2 Boom retracted at α=55*	*Case-3 Boom extended at α=0*	*Case-4 Boom extended at α=55*
P1	7542.386912	16811.58346	4631.290209	9328.741707
Py	7542.386912	371.9858096	4631.290209	206.414794
Pz	0	-16807.46754	0	-9326.457782
Px	452.5432147	1008.695008	277.8774125	559.7245024
M1	107312.6607	-81256.63568	65893.73905	-45089.27836
M2	6938.699014	15465.99491	4260.604658	8582.075097
T	1841.352017	4104.276733	1130.654747	2277.461706

Table 6: Forces and Moments on Flyjib in four working conditions of boom

Forces & Moments in Fly Jib	*Case-1 Boom retracted at α=0*	*Case-2 Boom retracted at α=55*	*Case-3 Boom extended at α=0*	*Case-4 Boom extended at α=55*
Mx1	154106.0881	-100840.3028	94630.43061	-55956.17152
My1	10348.45181	23066.1544	6354.312523	12799.40092
Rz1	2514.128971	-11380.4301	1543.763403	-6393.700926
Par1	2514.128971	-11380.4301	1543.763403	-6393.700926
Pal1	0	-583.64426	0	-583.64426
Ry1	7719.253927	375.8993029	4828.00561	210.3282873
Rx1	452.5432206	1008.695013	277.8774184	559.7245083
Vyr1	7719.253927	375.8993029	4828.00561	210.3282873
Vyl1	7896.120941	379.8127962	5024.721012	214.2417806
Vxr1	452.5432206	1008.695013	277.8774184	559.7245083
Vxl1	0	0	0	0

Table 7: Forces and Moments on 2nd extension in four working conditions of boom

Forces & Moments in 2nd Extension	*Case-1 Boom retracted at α=0°*	*Case-2 Boom retracted at α=55°*	*Case-3 Boom extended at α=0°*	*Case-4 Boom extended at α=55°*
Mx2	188145.379	-99183.72686	651463.7831	-46729.45479
My2	12341.77999	27509.17796	37025.85919	36960.10858
Rz2	2514.128971	-11964.07436	1543.763403	-6977.345186
Par2	2514.128971	-11397.72761	1543.763403	-6703.163914
Pal2	0	-566.3467448	0	-274.181272
Ry3	1021.353535	-694.0051988	16959.2515	-1224.907855
Ry2	9324.394649	-305.1885791	22371.04429	-1001.662251
Rx3	85.57765285	190.7480836	968.1457931	966.4265574
Rx2	538.1208778	1199.443101	1246.023322	1526.151109
Vyr2	7736.555678	376.2821345	5261.570045	217.1773762
Vyl2	1587.838971	-681.4707137	17109.47424	-1218.839627
Vxr2	452.543225	1008.695018	277.877529	559.7245515
Vxl2	85.57765285	190.7480836	968.1457931	966.4265574

Table 8: Forces and Moments on 1st extension in four working conditions of boom

Forces & Moments in 1st Extension	*Case-1 Boom retracted at α=0°*	*Case-2 Boom retracted at α=55°*	*Case-3 Boom extended at α=0°*	*Case-4 Boom extended at α=55°*
Mx3	-236779.145	-17316.44824	1307951.838	28784.93906
My3	-9007.106321	152948.0703	75185.08548	86526.85779
Rz3	2514.128971	-12848.85755	1543.763403	-7862.128377
Par3	2514.128971	-12349.96065	1543.763403	-7841.970732
Pal2	0	-566.3467448	0	-274.181272
Ry5	-1781.362965	-105.6660519	16828.32043	8308.15707
Ry4	7501.509191	304.8310505	23219.94426	8553.083157
Rx5	-52.09027791	884.5357435	977.5292646	24974.79759
Rx4	-61.51303245	1044.541862	2235.05866	1166.037355
Vyr3	8458.84854	399.4554291	6037.232056	244.4799542
Vyl3	-957.3393497	-94.62437859	17182.71221	8308.603203
Vxr3	452.5432413	1008.695189	277.8776762	559.7247415
Vxl3	-52.09027791	884.5357435	977.5292646	24974.79759

Table 9: Forces and Moments on Mother boom in four positions of boom

Forces & Moments in Mother Boom	*Case-1 Boom retracted at α=0°*	*Case-2 Boom retracted at α=55°*	*Case-3 Boom extended at α=0°*	*Case-4 Boom extended at α=55°*
MX4	622711.8133	58484.59092	-201343.3013	-524573.7277
MY4	8718.859774	-148053.3942	98226.16802	-4927441.742
RZ4	2514.128971	-14864.93786	1543.763403	-10762.9921
PAR4	471.8739654	471.8739654	1022.066741	1598.691336
PAL4	2514.128971	-12349.96065	1543.763403	-7841.970732
Rd	-20926.87593	7006.081268	-4308.992559	-5657.970635
Rx6	-9.422600613	160.0062728	1257.529705	-23808.75992
Rzr6	-628.0130257	-4095.315699	13892.86666	-489031.9266
Rzl6	-1886.115945	17268.28419	-15436.63006	497218.1659
Ryr6	5041.759233	3054.470077	-1965.600278	-1335.467486
Ryl6	4055.075347	855.2041597	-2571.459408	-2498.579113
Vyr4	9754.746121	420.9381426	7413.690575	280.2999403
Vyl4	10016.62047	3930.026115	-2738.479954	-3788.761907
Vxr4	147.090947	-853.7935171	-1266.912751	-199.6107923
Vxl4	-61.51314008	1044.541755	2235.058553	1166.037247
Recy	0	-9361.192813	0	-5969.02351

2.6 Equations used for stress analysis:

2.6.1 Calculation of section properties based on compressive stresses

$$Btf = B \div Tt$$

$$Btw = H \div Ts$$

$$Bta = 184 \div Sqrt(Fost \times Fyi)$$

$$Fa = Par \div (As \times 1000)$$

$$Fbx = Mx \div (Zx \times 1000)$$

$$Fby = My \div (Zy \times 1000)$$

$$Ff = Fa + Fbx$$

$$Fw = Fa + Fby$$

If ($Btf \leq Bta$) and ($Btw \leq Bta$) Then the plates in compression are fully effective at yield [10].

$Btxr = 184 \div Sqrt(Abs(Ff))$

$Btyr = 184 \div Sqrt(Abs(Fw))$

If (BTF ≤ BTXR) and (BTW ≤ BTYR) Then the plates in compression are fully effective at actual stress [10].

$Btq = Ts \div Tb$

If Btq ≤ 95 ÷ Sqr (FYi) Then Qs = 1

$Sigr = 0.5 \times Fyi$

$Rx = Sqrt(Ix \div As)$

$Ry = Sqrt(Iy \div As)$

$Cc = Sqrt(((Pi) \wedge 2) \times E \div (Qs \times Qa \times (Fyi - Sigr)))$

$Klx = k \times Ls \div Rx$

$Kly = k \times Ls \div Ry$

If Klx < Kly then Kl = Kly

If Kl > Cc then, Elastic range

$Faa = 12 \times (Pi \wedge 2) \times E \div (23 \times (Kl \wedge 2))$

If Kl < Cc

$$Faa = Qs \times Qa \times \left(1 - Sigr \times ((Kl) \wedge 2) \div (Fyi \times (Cc \wedge 2))\right) \times Fyi \div (5 \div 3) + (3 \div 8) \times (Kl \div Cc) - (1 \div 8) \times ((Kl \div Cc) \wedge 3))$$

2.6.2 Inelastic lateral Buckling

If M1 > M2 then Mxmin = M1

And Mxmax = Mx

$Bm = B - Ts$

$Hm = H - ((Tt + Tb) \div 2)$

$$J = 4 \times (Bm \wedge 2) \times (Hm \wedge 2) \div ((2 \times Hm \div Ts) + (B \div Tb) + (B \div Tt))$$

2.6.3 Inelastic Lateral buckling check

$$Cb = 1.75 + 1.05 \times (Mxmin \div Mxmax) + 0.3 \times ((Mxmin \div Mxmax) \wedge 2)$$

Where 1 ≤ Cb ≤ 1.3

$Kle = Sqrt(5.1 \times Kt \times Ls \times Zx \div Sqrt(J \times Iy)) \div Sqrt(Cb)$

If Kle < (102000 ÷ FYi) than

$Fbxa = Fost \times Fyi$

$Fbya = Fost \times Fyi$

2.6.4 Solution to interaction equations for compressive stresses

$Xa = Abs(Fa \div Faa)$, $Xb = Abs(Fbx \div Fbxa)$,

$Xc = Abx(Fby \div Fbya)$

$Fex = 12 \times (Pi \wedge 2) \times E \div (23 \times (Klx \wedge 2))$

$Fey = 12 \times (Pi \wedge 2) \times E \div (23 \times (Kly \wedge 2))$

If Xa ≤ 0.15 than Xd = Xa + Xb + Xc

If Xd ≤ 1 than the design will be safe against buckling

And if Xd > 1, Than Xd = (Fa ÷ (FOST x Fyi)) + Xb + Xc

And

$$Xd1 = Xa + Cmx \times Fbx \div ((1 - (Fa \div Fex)) \times (Fbxa) + Cmy \times Fby \div ((1 - (Fa \div Fey)) \times Fbya)$$

If Xd and Xd1 equal to or less than one than the design will be safe

2.6.5 Actual and allowable shear stresses in webs

$$Fs = (Vyr \div (2 \times B \times Ts) + T \div (2 \times As \times Ts)) \div 1000$$

If H ÷ T ≤ 380 ÷Sqrt (Fyi) than Fsa = 0.4 X Fyi

And if Fsa = 0.4 ≤ Fyi than stiffeners are not required

If Abs (Fs) ≤ Abs (Fsa) than the design will be safe against shear

2.6.6 Tensile stresses

$Ft = (-Fa + Fbx + Fby)$

$Fta = (Fost \times Fyi)$

If Ft ≤ Fta, than the design will be safe against tensile failure

2.7 Calculations for stress analysis

2.7.1 Case – 1 When the boom is fully retracted and at an angle = 0°

Table 10: Calculation of section properties based on Compressive stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btf	22.5	23.125	34.375	40.625
Btw	57.75	37.25	47.5	56.25
Bta	37.52760125	37.52760125	37.52760125	37.52760125
Fa	0.647769747	0.217079155	0.158647833	0.023854741
Fbx	17.49799981	4.985189659	-3.404386091	5.857673294
Fby	2.015089483	0.427064602	-0.154267742	0.261896522
Ff	18.14576956	5.202268814	-3.245738257	5.881528035
Fw	2.662859231	0.644143757	0.004380091	0.285751263
Btxr	43.19466672	80.67174073	102.1318211	75.87046351
Btyr	112.7570535	229.259015	278.201253	344.2102065

Table 11: Calculation for determination of allowable stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btq	1	1	1	0.8
Qs	1	1	1	1
Qa	1	1	1	1
Sigr	18.21210326	18.21210326	18.21210326	18.21210326
Rx	3.212231386	4.372173945	5.729818869	6.899691211
Ry	1.531074066	3.014471493	4.465939585	5.22957065
Cc	126.4389349	126.4389349	126.4389349	126.4389349
Klx	100.0114263	81.27634792	68.71086092	81.02610697
Kly	209.8264543	117.8827969	88.15631737	106.9026801
Kl	209.8264543	117.8827969	88.15631737	106.9026801
Faa	3.450282756	10.75387107	14.62058838	12.26578541

Table 12: Inelastic lateral buckling check

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Mxmax	107312.6607	107312.6607	-236779.145	622711.8133
Mxmin	154106.0881	188145.379	107312.6607	107312.6607
Bm	3.385826772	6.968503937	10.51181102	12.48031496
Hm	8.937007874	11.41732283	14.64566929	17.36220472
J	23.10704846	213.2229929	586.1236399	14.4505726
Cb	1.3	1.3	1.3	1.939857148
Kle	22.59101563	15.3019954	12.89915202	1024.190401
Fbxa	24.0399763	24.0399763	24.0399763	24.0399763
Fbya	24.0399763	24.0399763	24.0399763	24.0399763

Table 13: Solution to interaction equations for the Compressive Stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Xa	0.18774396	0.020186141	0.010850988	0.00194482
Xb	0.727870926	0.207370823	0.141613538	0.243663855
Xc	0.08382244	0.017764768	0.006417134	0.010894209
Fex	15.18713766	22.9957093	32.17543233	23.13796849
Fey	3.450282756	10.93136281	19.54646796	1.358038263
Xd	0.999437326	0.245321731	0.15888166	0.256502883

Table 14: Calculation of Actual and Allowable shear stress in the webs

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Fs	8.423187941	1.938650714	1.424902372	13.29223421
H/Ts	57.75	37.25	47.5	56.25
Fsa	14.56968261	14.56968261	14.56968261	14.56968261

Table 15: Calculation of tensile stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Ft	18.86531955	5.195175106	-3.717301666	6.095715074
Fta	24.0399763	24.0399763	24.0399763	24.0399763

2.7.2 Case – 2 When the boom is fully retracted and at an angle = 55°

Table 16: Calculation of section properties based on Compressive stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btf	22.5	23.125	34.375	40.625
Btw	57.75	37.25	47.5	56.25
Bta	37.52760125	37.52760125	37.52760125	37.52760125
Fa	-2.93218781	-0.984121781	-0.77931344	0.023854741
Fbx	-11.4499279	-2.628019312	-0.248974104	0.550147948
Fby	4.491528395	0.951904517	2.619593083	-4.447217864
Ff	-14.3821157	-3.612141093	-1.028287544	0.574002689
Fw	1.559340583	-0.032217263	1.840279643	-4.423363123
Btxr	48.51839586	96.81339948	181.4514886	242.8627227
Btyr	147.3490473	1025.117154	135.6362931	87.48659752

Table 17: Calculation for determination of allowable stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btq	1	1	1	0.8
Qs	1	1	1	1
Qa	1	1	1	1

Sigr	18.21210326	18.21210326	18.21210326	18.21210326
Rx	3.212231386	4.372173945	5.729818869	6.899691211
Ry	1.531074066	3.014471493	4.465939585	5.22957065
Cc	126.4389349	126.4389349	126.4389349	126.4389349
Klx	100.0114263	81.27634792	68.71086092	81.02610697
Kly	209.8264543	117.8827969	88.15631737	106.9026801
Kl	209.8264543	117.8827969	88.15631737	106.9026801
Faa	3.450282756	10.75387107	14.62058838	12.26578541

Table 18: Inelastic lateral buckling check

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Mxmax	-100840.303	-99183.72686	-17316.44824	58484.59092
Mxmin	-81256.6357	-81256.63568	-81256.63568	-81256.63568
Bm	3.385826772	6.968503937	10.51181102	12.48031496
Hm	8.937007874	11.41732283	14.64566929	17.36220472
J	23.10704846	213.2229929	586.1236399	1024.190401
Cb	1.3	1.3	1.3	1
Kle	22.59101563	15.3019954	12.89915202	16.47618776
Fbxa	24.0399763	24.0399763	24.0399763	24.0399763
Fbya	24.0399763	24.0399763	24.0399763	24.0399763

Table 19: Solution to interaction equations for the Compressive Stresses.

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Xa	0.84983986	0.091513258	0.039869783	0.00194482
Xb	0.476286988	0.109318715	0.01035667	0.022884713
Xc	0.186835808	0.039596733	0.108968206	0.184992606
Fex	15.18713766	22.9957093	32.17543233	23.13796849
Fey	3.450282756	10.93136281	19.54646796	13.29223421
Xd	Xd = 0.663123 Xd1 =0.669321	0.240428706	0.159194659	0.209822138

Table 20: Calculation of Actual and Allowable shear stress in the webs

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Fs	3.694306965	0.644589912	0.469717905	0.381606865
H/Ts	57.75	37.25	47.5	56.25
Fsa	14.56968261	14.56968261	14.56968261	14.56968261

Table 21: Calculation of tensile stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Ft	-4.0262117	-0.691993014	3.149932419	-3.920924657
Fta	24.0399763	24.0399763	24.0399763	24.0399763

2.7.3 Case – 3 When the boom is fully extended and at an angle = 0°

Table 22: Calculation of section properties based on Compressive stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btf	22.5	23.125	34.375	40.625
Btw	57.75	37.25	47.5	56.25
Bta	37.52760125	37.52760125	37.52760125	37.61277208
Fa	0.397753353	0.133294218	0.097415336	0.051668749
Fbx	10.744827	17.26149498	18.80559643	-1.86861933
Fby	1.237335649	1.281211771	1.287720267	2.950511007
Ff	11.14258036	17.3947892	18.90301177	-1.816950581
Fw	1.635089003	1.41450599	1.385135603	3.002179756
Btxr	55.12199605	44.11723016	42.32064915	136.504279
Btyr	143.8954707	154.7089461	156.3405649	106.1938771

Table 23: Calculation for determination of allowable stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btq	1	1	1	0.8
Qs	1	1	1	1
Qa	1	1	1	1
Sigr	18.21210326	18.21210326	18.21210326	18.12971722
Rx	3.212231386	4.372173945	5.729818869	6.899691211
Ry	1.531074066	3.014471493	4.465939585	5.22957065
Cc	126.4389349	126.4389349	126.4389349	126.4389349

Klx	100.0114263	81.27634792	68.71086092	81.02610697
Kly	209.8264543	117.8827969	88.15631737	106.9026801
Kl	209.8264543	117.8827969	88.15631737	106.9026801
Faa	3.450282756	12.92512958	14.62058838	12.2423439

Table 24: Inelastic lateral buckling check

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Mxmax	94630.43061	651463.7831	1307951.838	-198647.3593
Mxmin	65893.73905	65893.73905	65893.73905	65893.73905
Bm	3.385826772	6.968503937	10.51181102	12.48031496
Hm	8.937007874	11.41732283	14.64566929	17.36220472
J	23.10704846	213.2229929	586.1236399	1024.190401
Cb	1.3	1.3	1.3	1.3
Kle	22.59101563	15.3019954	12.89915202	14.4505726
Fbxa	24.0399763	24.0399763	24.0399763	24.0399763
Fbya	24.0399763	24.0399763	24.0399763	24.0399763

Table 25: Solution to interaction equations for the Compressive Stresses

Parameters	*Flyjib*	*2nd extension*	*3rd extension*	*Mother boom*
Xa	0.049756429	0.010312795	0.006662888	0.004220495
Xb	0.446956639	0.718032945	0.782263518	0.073594439
Xc	0.05146992	0.053295051	0.053565788	0.123291256
Fex	15.18713766	30.79273489	32.17543233	23.13796849
Fey	3.450282756	14.63779841	19.54646796	13.29223421
Xd	0.548182987	0.781640792	0.842492193	0.20110619

Table 26: Calculation of Actual and Allowable shear stress in the webs

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Fs	5.251086953	1.301788484	0.998486465	0.998248754
H/Ts	57.75	37.25	47.5	56.25
Fsa	14.56968261	14.56968261	14.56968261	14.56968261

Table 27: Calculation of tensile stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Ft	11.5844093	18.40941253	19.99590136	1.030222927
Fta	24.0399763	24.0399763	24.0399763	24.0399763

2.7.4 Case – 4 When the boom is fully extended and at an angle = 55°

In this case the side thickness is taken as 16mm and total breadth of mother boom is taken 341mm. Because the strength required for mother boom is high when the boom has to work at 55 degree angle and boom is in extended position.

Table 28: Calculation of section properties based on Compressive stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btf	22.5	23.125	34.375	42.625
Btw	57.75	37.25	47.5	28.125
Bta	37.52760125	37.52760125	37.52760125	37.52760125
Fa	-1.64734828	-	-	0.051668756
Fbx	-6.35355222	-	0.410112361	-3.76680393
Fby	2.492347518	1.278936593	1.481974619	-
Ff	-8.0009005	-	-	-
Fw	0.84499924	0.703790157	0.992129202	-
Btxr	65.05016286	136.6211111	651.6263213	95.4619965
Btyr	200.1657019	219.329086	184.7284162	32.34760603

Table 29: Calculation for determination of allowable stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Btq	1	1	1	1.6
Qs	1	1	1	1
Qa	1	1	1	1
Sigr	18.21210326	18.21210326	18.21210326	18.21210326
Rx	3.212231386	4.372173945	5.729818869	6.314209581
Ry	1.531074066	3.014471493	4.465939585	5.743301605
Cc	126.4389349	126.4389349	126.4389349	126.4389349
Klx	100.0114263	70.23659581	68.71086092	88.53920842
Kly	209.8264543	101.8707972	88.15631737	97.34037259
Kl	209.8264543	101.8707972	88.15631737	97.34037259
Faa	3.450282756	12.92512958	14.62058838	13.50143141

Table 30: Inelastic lateral buckling check

Parameter	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Mxmax	-55956.1715	-46749.53354	28523.80769	-524573.7277
Mxmin	-45089.2784	-45089.27836	-45089.27836	-45089.27836
Bm	-55956.1715	6.968503937	10.51181102	12.79527559
Hm	3.385826772	11.41732283	14.64566929	17.36220472
J	23.10704846	213.2229929	586.1236399	1497.231279
Cb	1.3	1.3	1	1.3
Kle	22.59101563	14.22485027	14.70729614	12.83437332
Fbxa	24.0399763	24.0399763	24.0399763	24.0399763
Fbya	24.0399763	24.0399763	24.0399763	24.0399763

Table 31: Solution to interaction equations for the Compressive Stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Xa	0.477453123	0.044498311	0.03350381	0.003826909
Xb	0.236758298	0.051526587	0.017059599	-0.15668917
Xc	0.103675124	0.05320041	0.06164626	-1.348063316
Fex	15.18713766	30.79273489	32.17543233	19.37777468
Fey	3.450282756	14.63779841	19.54646796	16.03205385
Xd	0.817886545	0.149225308	0.112209669	-1.500925576

Table 32: Calculation of Actual and Allowable shear stress in the webs

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Fs	2.051452949	0.359306127	0.2637354	0.074997356
H/Ts	57.75	37.25	47.5	28.125
Fsa	14.56968261	14.56968261	14.56968261	14.56968261

Table 33: Calculation of tensile stresses

Parameters	*Flyjib*	*2nd extension*	*1st extension*	*Mother boom*
Ft	-2.21385643	0.6153851	2.381932396	-36.22588286
Fta	24.0399763	24.0399763	24.0399763	24.0399763

3. Result

The manual calculations are done so as to check whether the boom design is safe or not against the extreme loading conditions and calculations are done for four different working conditions. When the boom is fully retracted that is safe against stresses when it is working at 0° boom angle and also when it is working at maximum boom angle i.e.55°. But when the boom is fully extended and it working in extreme loading conditions then it is found from manual calculations that the boom is safe against stresses when working at boom angle 0° but it not safe when working at 55°. It is found that the plates in compression are not fully effective at yield and not even fully effective at actual stress. When boom is working at 55° then the stiffeners are required for the mother so as to increase the strength of boom. When boom is working at 55° and manual calculations are done using stiffeners than results found are satisfactory.

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