To Design a New Cross Section for Connecting Rod with a Target of 10% Weight Reduction

Priyanka Inderchandji Mutha[1]

[1]*Student, Dept. of Mechanical Engineering, Govt. College of Engineering, Aurangabad*

Abstract - The connecting rod is an intermediate member between the piston and the Crankshaft. Its function is to transmit the push and pull forces from the piston pin to the crank pin, converting the reciprocating motion of the piston into rotary motion of the crank. Traditionally, I cross-section has been used to design the connecting rod. This paper describes design and analysis of alternate cross sections evaluated to achieve weight reduction for cost benefits.

Alternate designs were modelled in Creo2.0 and were analyzed using ANSYS 18.2. Through concept selection study, the C section was selected and further was further optimized for a minimum weight considering FOS of 2 using Response Surface Methodology (RSM) in Minitab 17.

***Key Words*: Connecting rod, Static Analysis, I section, C section, Fatigue Analysis, CREO 2.0^R, ANSYS 18.2^R, MINITAB 17^R and Finite Element Analysis, Response Surface Methodology (RSM).**

1. INTRODUCTION

In a reciprocating piston engine, the connecting rod connects the piston to the crank or crankshaft. The major stresses induced in the connecting rod are combination of axial and bending stresses in operation. The axial stresses are produced due to cylinder gas pressure (compressive only) and the inertia force arising in account of reciprocating action (both tensile and compressive), whereas bending stresses are caused due to the centrifugal effects.

The connecting rods are made traditionally with I cross section. This is due to the rigidity provided by the I-section which proves to be good in taking bending moment and provide effective fatigue life. But a trade-off can been seen between the stress carrying capacity v/s weight of connecting rod due to the use of I-Section. Different cross section like H Section, Circular Section, Hollow circular section etc. are presently been used in Industry as an alternative to the I section, where weight of component is critical factor for design.

The objective of this study is to design and optimize a new cross section of connecting rod for its weight. To achieve this three cross sections, T Section, C section and hollow C section were designed. Bending stresses and fatigue life were calculated using theoretical calculations. The equivalent stress and principal stresses were evaluated using ANSYS. Designed concepts were compared using a decision matrix to select the one best concept. The selected C cross-section design was further optimized for weight reduction using Response Surface Methodology. An overall 14% weight reduction is achieved in C cross-section design as compared to the original I section design.

1.1 THEORETICAL CALCULATION OF FORCES ACTING ON CONNECTING ROD

Bajaj Pulsar 220 CC Engine connecting rod was considered for the study purpose. A reversed engineered model of connecting rod was created using CREO 2.0.

a. Pressure calculation:

Below engine specifications were considered:

Engine type air cooled 4-stroke
Bore × Stroke (mm) = 67 x 62.4
Displacement = 220 CC
Maximum Power = 21.05 @ 8500 (Ps @ RPM)
Maximum Torque = 19.12 @ 7000 (Nm @ RPM)
Compression Ratio = 9.5/1
Density of petrol at 288.855 K = 737.22*10-9 kg/mm^3
Molecular weight M = 114.228 g/mole
Ideal gas constant R = 8.3143 J/mol.k

From gas equation,
$PV=m*R_{specific}*T$
Where, P = Pressure
V = Volume
m = Mass
$R_{specific}$ = Specific gas constant
T = Temperature
But,
Mass of air = Density * Volume
Density for Grey Cast Iron = 737.22 E-9 kg/mm^3
m =737.22E-9*220E3
m = 0.16 kg
$R_{specific}$ = R/M
$R_{specific}$ = 8.3143/0.114228
$R_{specific}$ = 72.79
$P = m* R_{specific}* T/V$
P = 0.16*72.79*288.85/200E3
P = 15.5 MPa
P ~ 16 MPA.

b. Design calculations for connecting rod:

For an I section, in general

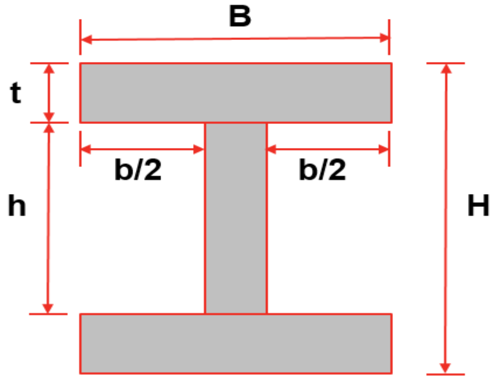


Figure 1: Standard Dimensions of I Section

Where,
Thickness of flange and web of the section = t = 1.16 mm
Total width of the section B = 10 mm
Total height of the section H = 18 mm
Flange width of the section b = 8 mm
Flange height of the section h = 15.7 mm
Moment of inertia about X axis I_{xx} = 2.28007E-09 mm^4
Moment of inertia about Y axis I_{yy}= 8.30133E-10 mm^4
Therefore I_{xx} / I_{yy} = 2.75

Length of the connecting rod (L) = 2 times the stroke
L = 108.4 mm
Total Force acting F = Fp-Fi
Where Fp = force acting on piston
Fi = force due to inertia of reciprocating parts
Fp = $(\pi d^2/4)$ * gas pressure
Fp = **54646.47** N

Fi = Mass * Acceleration = m* ω^2*r (cos θ + cos2θ/n)
r = crank radius
r = stroke of piston / 2
r = 62.4 /2 = 31.2 mm
m = mass of connecting rod
m = 194 gm
θ = Crank angle from the dead center
θ = 0 considering that connecting rod is at the TDC position
n = length of connecting rod / crank radius
n = 108.4/31.2 = ~ 4
g = acceleration due to gravity, 9.81 m/sec
v = crank velocity m/s
ω = $2\pi n/60$
ω = 2π*8500/60 = 890.118 rad/sec
v = r* ω = 31.2*e-3*890.118 = 0.03 m/s

On substituting.
Fi = 4009.31 N
Therefore,
F = 54646.47 – 4009.31
F = 50637.16 N

F_{in} = force due to inertia of connecting rod
F_{in} = (Mass * Acceleration)/2 = (m* ω^2*r)/2
F_{in} = 4009.31/2 = 2004.65 N

M = Max Bending moment
M = m* ω^2* r* L/ (9 * √3)
M = 33.34 Nm

Z = Section modulus
Z = $(BH^2/6) - (bh^3/6H)$
Z = 2.5 E-07 m^3

σ_{max} = Max bending stress
σ_{max} = M/Z
σ_{max} = 131.63 MPa

N = Fatigue life
N = $10^{-c/b} * S^{1/b}$
b = -1/3 log $(0.8*S_{ut}/S_e)$
c = log $((0.8*S_{ut})^2/S_e)$
S_{ut} = Ultimate tensile strength of cast iron = 450 MPa
S_e = Yield strength of cast iron = 280 MPa
N = 2.1 E+09 cycles

1.2 Design and Analysis

After considering multiple cross-sections, three new cross sections for connecting rod were selected for the study, those were - T section, C section and hollow C section. Figures below shows the different designs.

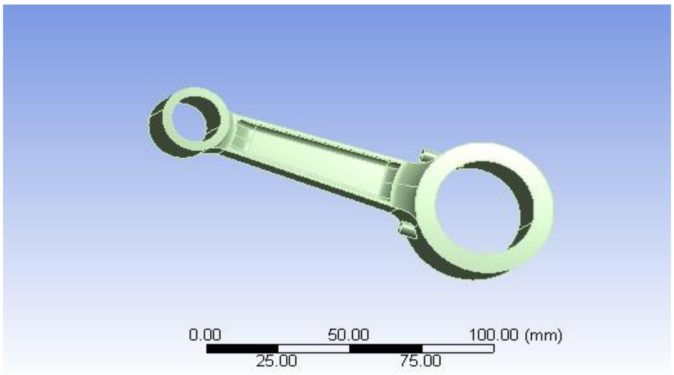


Figure 2 : Original Connecting Rod with I section

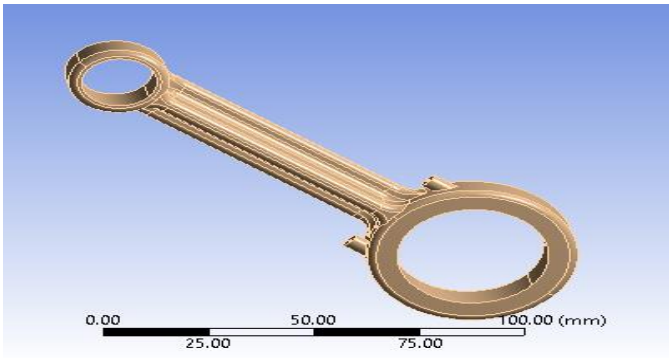


Figure 3 : Connecting Rod with T section

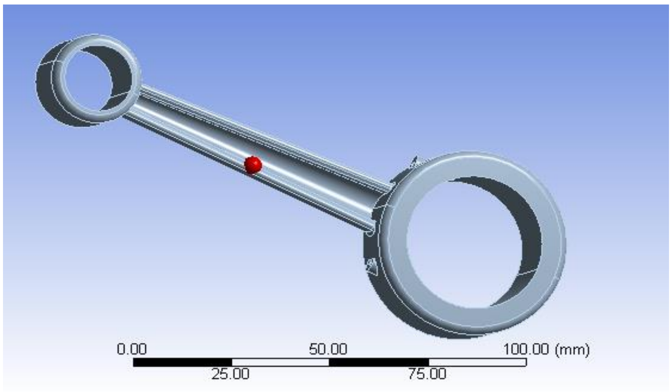


Figure 4 : Connecting Rod with C section

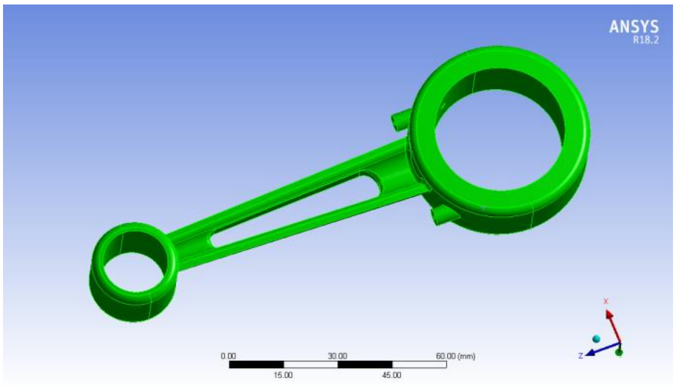


Figure 5 : Connecting Rod with hollow C section

Figure 2 shows the original I section design of connecting rod, while Figure 3, 4, 5 shows connecting rod with T, C and hollow C section respectively.

The modelled designs of Creo 2.0 were imported into ANSYS 18.2 Workbench and were subjected to the boundary conditions to analyse equivalent stress and principal stresses.

The bigger end of connecting rod was considered as fixed. The smaller end was applied with the gas pressure of 16 MPa. Boundary conditions are shown in Figure 6. Table 1 summarises the weight and stress components for each of the design.

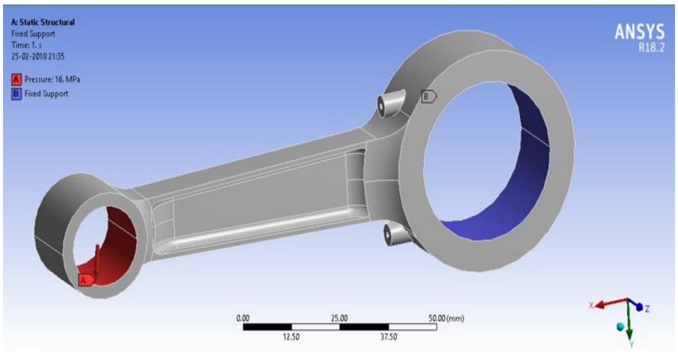


Figure 6 : Boundary Conditions in ANSYS

Table 1: Weight and Stress components for different sections

Sr. No.	Name	Weight (gm)	Eq. Stress (MPa)	Max P (MPa)	Min P (MPa)
1	I section	194	72.1	62.92	16.36
2	T Section	217	84.26	75.16	16.39
3	C Section	176	80.19	70.94	16.21
4	Hollow C Section	164	83.91	73.99	18.13

Figure 7, 8, 9 below shows the equivalent stress (72.1 MPa), max. & min. principal stress (62.92 and 16.36 MPa) for the original I section.

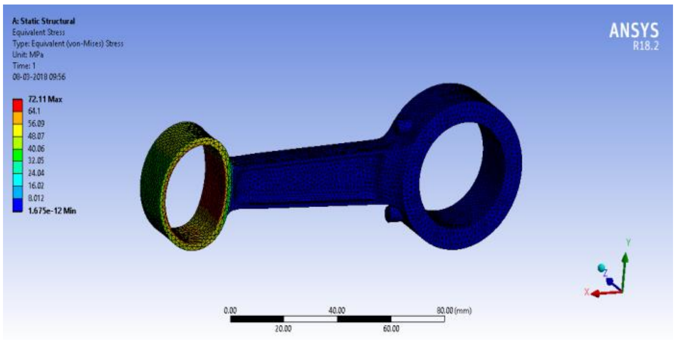


Figure 7: Eq. Stress plot for Original I section

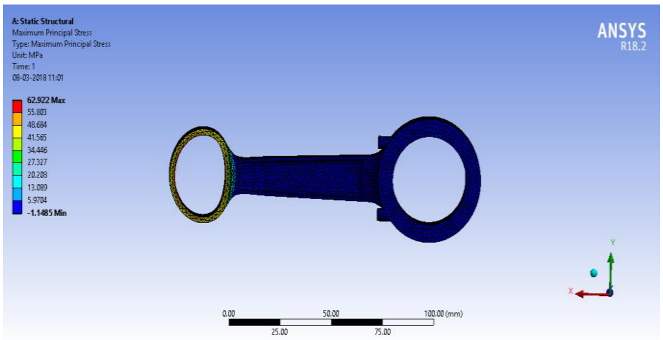


Figure 8: Max Principal Stress plot for Original I section

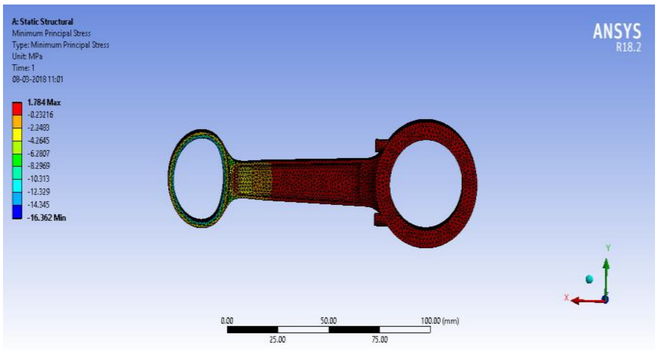


Figure 9: Min Principal Stress plot for Original I section

Figure 10, 11, 12 below shows the equivalent stress (84.26 MPa), max. & min. principal stress (75.16 and 16.39 MPa) for the T section. There is 20 % increase in equivalent stress from I section to T section along with the increase in weight of 12 %.

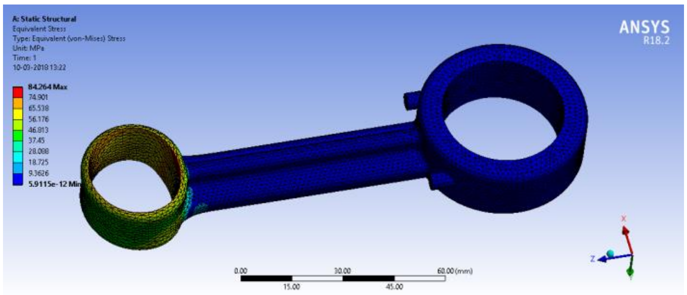


Figure 10: Eq. Stress plot for T section

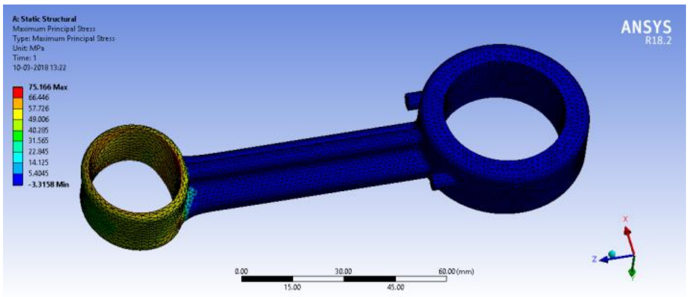


Figure 11: Max Principal Stress plot for T section

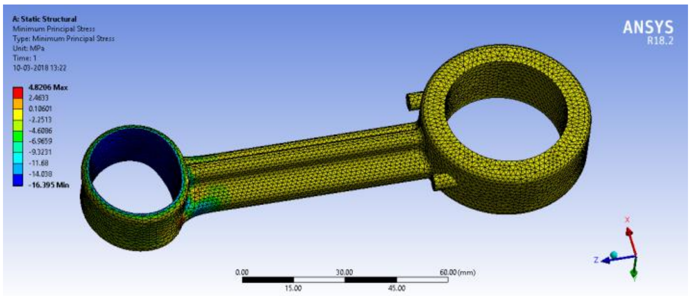


Figure 12: Min Principal Stress plot for T section

Figure 13, 14, 15 below shows the equivalent stress (80.19 MPa), max. & min. principal stress (70.41 and 16.21 MPa) for the C section. There is 11 % increase in equivalent stress from I section to C section with a weight reduction of 9 %.

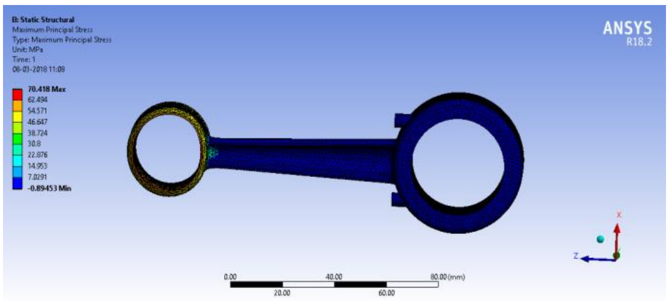


Figure 13: Eq. Stress plot for C section

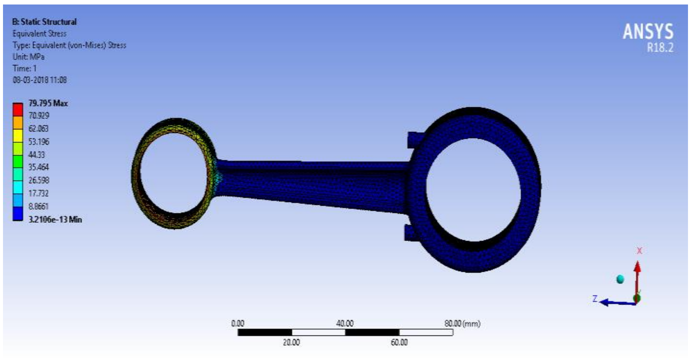


Figure 14: Max Principal Stress plot for C section

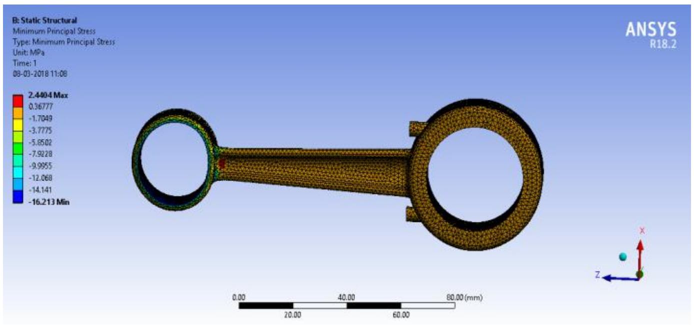


Figure 15: Min Principal Stress plot for C section

Figure 16, 17, 18 below shows the equivalent stress (83.91 MPa), max. & min. principal stress (73.99 and 18.13 MPa) for the hollow C section. There is 17 % increase in equivalent stress from I section to hollow C section with a weight reduction of 15 %.

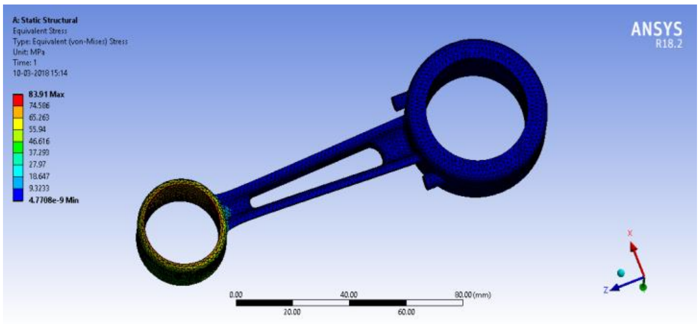


Figure 16: Eq. Stress plot for Hollow C section

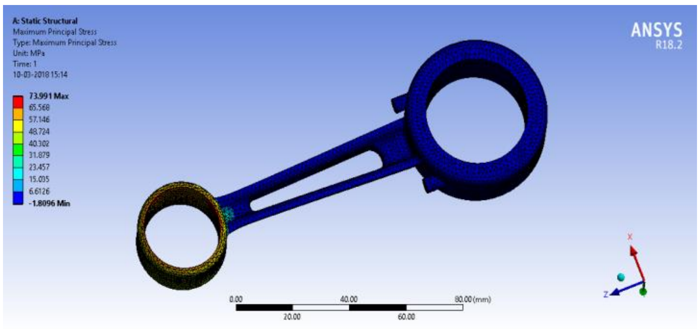


Figure 17: Max Principal Stress plot for Hollow C section

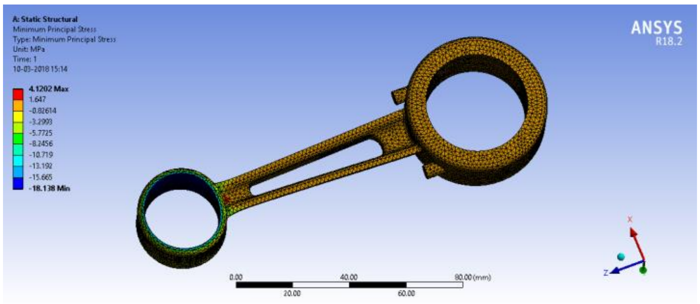
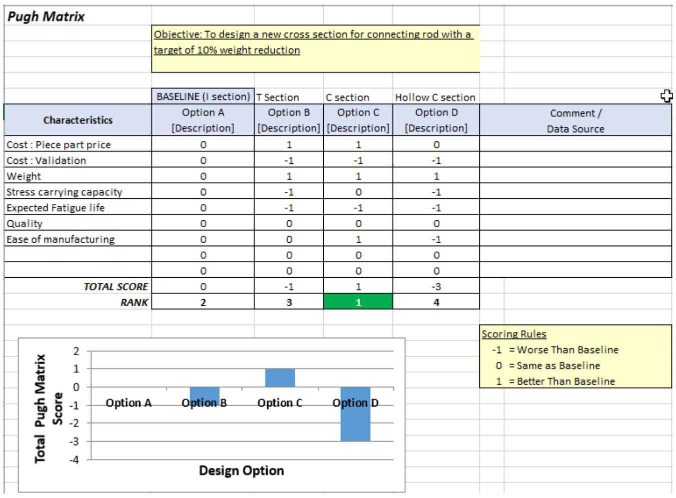


Figure 18: Min Principal Stress plot for Hollow C section

Decision Matrix:

To select best concept out of the three concepts a decision matrix was formulated. The concepts were rated against original I section with characteristics chosen as shown in Figure 19. Based on the output of decision matrix, C section was selected for further optimisation of weight.



Pugh Matrix

Objective: To design a new cross section for connecting rod with a target of 10% weight reduction

Characteristics	BASELINE (I section) Option A [Description]	T Section Option B [Description]	C section Option C [Description]	Hollow C section Option D [Description]	Comment / Data Source
Cost : Piece part price	0	1	1	0	
Cost : Validation	0	-1	-1	-1	
Weight	0	1	1	1	
Stress carrying capacity	0	-1	0	-1	
Expected Fatigue life	0	-1	-1	-1	
Quality	0	0	0	0	
Ease of manufacturing	0	0	1	-1	
	0	0	0	0	
	0	0	0	0	
TOTAL SCORE	0	-1	1	-3	
RANK	2	3	1	4	

Scoring Rules
-1 = Worse Than Baseline
0 = Same as Baseline
1 = Better Than Baseline

Figure 19: Decision Matrix

2. OPTIMIZATION OF C SECTION

2.1 Response surface optimization

To evaluate further possibility of op optimization of C section to gain more weight reduction and still being within the stress limits of the material, a DOE was performed with two factor i.e. "r_1" (inner radius of section C at small end) and "t" (thickness of C section).

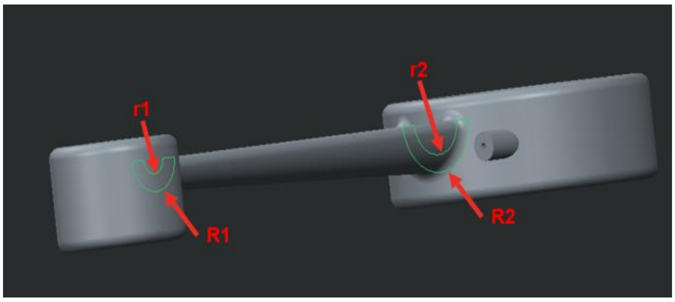


Figure 20: C section details

Where From r_1 and t, other section details are determined as below:

R_1 = Outer radius of section C at small end = $r_1 + t$

r_2 = Inner radius of section C at big end = R_1 (Constraint)

R_2 = Outer radius of section C at big end = $r_2 + t$

For the DOE, three levels for each of the two factor were considered as below. One level above and below base design r_1 = 2.5 mm and t =3 mm was considered.

Table 2: DOE factors and levels

Factors	Levels		
r_1	2	2.5	3
t	2.5	3	3.5

Using above Table 2, 9 unique concepts were designed in Creo 2.0 and were imported into ANSYS 18.2 Workbench.

Table 3: DOE concepts details

	r1 mm	R1 mm	r2 mm	R2 mm	r mm	R mm	t mm	mass gm
C1	2	4.5	4.5	7	4.02	6.43	2.5	164.65
C2	2.5	5	5	7.5	4.53	7.03	2.5	166.76
C3	3	5.5	5.5	8	5.03	7.53	2.5	168.88
C4	2	5	5	8	4.44	7.44	3	170.82
C5	2.5	5.5	5.5	8.5	4.94	7.94	3	173.36
C6	3	6	6	9	5.44	8.44	3	175.91
C7	2	5.5	5.5	9	4.84	8.34	3.5	177.84
C8	2.5	6	6	9.5	5.34	8.84	3.5	180.81
C9	3	6.5	6.5	10	5.88	9.34	3.5	183.81

All concepts were then subjected to the same boundary conditions and were analysed for equivalent stress and principal stresses.

Concept C5 is same as the baseline C section which was analysed earlier.

Table 4: ANSYS results for DOE concepts

	Eq. Stress (MPa)	Max P (MPa)	Min P (MPa)
C1	79.92	70.55	16.35
C2	70.5	70.06	16.23
C3	78.99	69.55	16.32
C4	80.27	70.84	16.31
C5	79.65	70.25	16.33
C6	78.66	69.62	16.28
C7	79.98	70.72	16.32
C8	79.01	69.81	16.3
C9	79.3	70.00	16.28

The bending stress and fatigue life were also calculated using theoretical calculations for the 9 concepts:

Table 5: Bending Stress and Fatigue life for DOE concepts

	Bending stress (MPa)	FOS	Fatigue life N (no of cycles)
C1	314.39	1.43	8.21E+08
C2	249.43	1.80	8.70E+08
C3	212.41	2.12	9.25E+08
C4	204.30	2.20	7.94E+08
C5	175.20	2.57	8.51E+08
C6	152.09	2.96	9.18E+08
C7	148.72	3.03	8.04E+08
C8	129.86	3.47	8.97E+08
C9	115.10	3.91	8.77E+08

A response surface method explores the relationships between several explanatory variables and one or more response variables. It maps the design space created using the DOE study data to find an optimal solution for response variable.

A response surface optimizer was ran using Minitab 17 by targeting FOS as 2, minimizing weight and maximizing fatigue life. Bending stress was not considered as an independent parameter to be optimized as FOS is function of bending stress and yield limit.

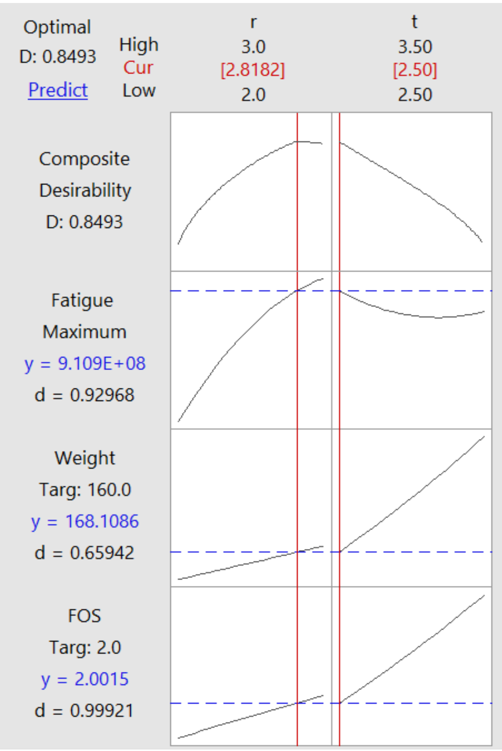


Figure 21: Response Surface Optimizer Results

The response surface optimizer for a targeted FOS of 2 suggests that r = 2.8 mm and t = 2.5 mm should give the minimum weight with maximum fatigue life.

2.2 Proof of concept

The suggested optimized design from Minitab optimizer was then modelled in Creo2.0 for a proof of concept. The modelled design weighs 168 grams which is close to the values given by the optimizer results. The Bending stress and fatigue life were calculated using theoretical formulae for the optimized C section. Also, the model was analyzed using ANSYS workbench for equivalent stress and principal stresses.

Table 6: Baseline and optimized C section results

		Stress			Life
	Mass (gms)	σ_{max} (MPa)	FOS	Eq. Stress (MPa)	Fatigue life N (no of cycles)
Base C Section (C5)	173.00	175.20	2.57	79.65	8.51E+08
Optimized C Section	168.00	226.08	1.99	78.62	9.45E+08

Comparing the Response Surface optimizer results from Figure 21 and the results for optimized C section from Table 6, there is a close co-relation between values.

Compared to original I section (194 grams), the optimized C section (173 grams) weighs 14% less.

3. CONCLUSIONS

The main objective of this study was to explore a new cross section of connecting rod with a reduced weight as compared to traditional I section. Following are the results:

An optimized C section was obtained with overall 14% weight reduction using response surface optimization methodology.

As compared to traditional I section, the Equivalent stress in new C section was increased by 10% considering FOS as 2.

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