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Research Article

Design and analysis of assembly of Piston, Connecting rod and Crank shaft

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Abstract

The present aim of the project is to study the effect of the materials being used for the Piston, Connecting rod and Crank Shaft assembly for an engine of a four wheeler vehicle. The material selected for the piston is Cast Iron, Manganese steel for the connecting rod and High Carbon Steel for the crank shaft. The engine speed was desired to be increased. The effect of the materials used for the assembly and its behavior was required to be studied. The parts piston, connecting rod and crankshaft are designed using theoretical calculations. The designed parts are modeled and assembled in 3D modeling software Pro/Engineer. The meshing is done in Hypermesh. The Finite Element Analysis is done in Ansys. The FE Analysis involves structural and analysis of the assembly. The parts of the assembly should be rigid. And, when they are connected together, they should perform as a mechanism. This requires calculation of the forces acting on the components and the dynamic stresses. As the assembly will be working under high temperatures, thermal analysis also has to be done. From the results, it is observed that a change in the piston material will allow the engine to operate at the new high speed.

Keywords: *Engine displacement, Piston skirt, Under square, Crank web, HyperMesh, Ansys.*

1. Introduction

The assembly of the piston, connecting rod and crank shaft in an engine behaves like a mechanism during the working of the engine. The weight of the Cast Iron piston is preventing the engine to operate at a higher speed. The dimensions of the engine piston, connecting rod and crank shaft are calculated theoretically. Both structural analysis and dynamic analysis are to be done for the assembly. As the piston and the other components of the assembly work under high temperatures, thermal analysis is also done.

The piston, rings, and wrist pin

The piston makes the crankshaft to turn by utilizing the energy supplied to it by the combustion of the fuel. It is cylindrical in shape and reciprocates inside the cylinder. Pistons are provided with groves near the top and provide an air tight fit. The pistons do not allow the high pressure mixture from the combustion chambers into the crankcase. The piston has four strokes in total, two upside and two down. During the intake stroke, the piston moves down and the cylinder is filled with air fuel mixture. The upward stroke compresses the mixture and as it reaches near the top position, the ignition of the fuel causes the piston to move downwards, the third stroke. During the fourth stroke, the piston moves upward and pushes the burnt gases to the exhaust system. The piston operates under high pressure and high temperature.

The top portion of the piston is called as Crown. It's bottom is called as skirt. The diameter of the piston crown is less than the skirt. There are groves at the top for oil ring and compression rings. The oil groove is wider and deep than the compression ring. The oil ring scraps the excess oil and returns back and prevents the oil reaching the combustion chamber. Lands are the spaces between the grooves. In the design of pistons, the weight of the piston is an important factor.

The top surface of the piston called as "Crown" is provided many shapes viz. convex, concave, and flat to control the combustion. Some pistons are provided with a narrow groove above the top ring to reduce the heat reaching the top ring.

The wrist pin connects the connecting rod at the bottom of the piston, wherein the pin connects by passing through the side of the piston.

Piston stroke

The piston stroke displacement is determined by the axis of the crank throws from the axis of the crankshaft.

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Increasing the stroke increases the low-speed torque of the engine. This increases the reciprocating vibration and limits the high speed capability of the engine. If the stroke is longer than the cylinder bore diameter is called as "Under square" or long-stroke.

Materials for the Piston

Cast Iron, Aluminum Alloy and Cast Steel etc. are the common materials used for piston. These pistons have greater strength and resistance to wear. In Aluminum Alloy pistons piston slap results due to insufficient piston clearance. A vertical slot is cut to overcome the defect. To increase the life of grooves and to reduce the wear, a ferrous metal rings are inserted in the grooves of high speed engines.

Connecting rod

The connecting rod links the piston and the crankshaft. It has a hole at the upper end (small end) and is connected to the piston by the wrist pin. The lower end, also called as Big end, is attached to the crankshaft. The small end is press fit and can swivel in the piston. The Connecting rods are usually made of alloy steel, Titanium and sometimes with aluminum. They are not rigidly fixed at either end, so that the angle between the connecting rod and the piston can change as the rod moves up and down and rotates around the crankshaft. The big end is connected to the bearing journal on the crank throw. The connecting rod is under a lot of stress with every rotation. High factor of safety is provided as the failure of the connecting rod is very likely under such heavy stresses. Attention has to be paid to eliminate the stress risers in the connecting rod during production. Also, the bolts should be tightened with proper torque.

Wearing of engine is due to the sideward force exerted on the piston which results into wearing of the cylinder into an oval cross section.

For a given engine block, the sum of the length of the connecting rod plus the piston stroke is a fixed number. This is determined by the fixed distance between the crankshaft axis and the top of the cylinder block where the cylinder head fastens. Thus, for a given cylinder block longer stroke, giving greater engine displacement and power, requires a shorter connecting rod (or a piston with smaller compression height), resulting in accelerated cylinder wear.

Materials used for Connecting Rod

Steel has good strength, durability and has less cost. But, it has high density which creates excessive stresses on the crank shaft. This requires a heavier crankshaft for carrying the loads. This causes to limit the maximum RPM of the engine. It also reduces the acceleration or declaration rates of engine speed. Light alloy metals such as aluminum and titanium are used to overcome these problems.

Crankshaft

The turning motion to the wheels is provided by the crankshaft, which converts the reciprocating motion of the pistons into a rotary motion. The crankshaft is usually either alloy steel or cast iron. Crankshafts are connected to the pistons by the connecting-rods. The crank shaft has crank throws which are offset from the crank. The big end of the connecting rod is attached to it. The crank shaft is connected to a flywheel to reduce the torsion vibrations.

2. Design calculations

Pressure calculations

Specifications of the engine

Table 1 Engine specs

Type : air cooled 4-stroke SOHC
Bore x stroke (mm) = 79.5 x 80.5 mm
Displacement - 1598 Cm^3
Maximum power = 77 @5250rpm
Maximum torque = 153 @3800 rpm
Compression ratio = 9.35/1
Density of petrol = 0.00000073722 kg/mm^3
Temperature = 60^0F

Density of petrol C_8H_{18} = 737.22 kg/m^3 at 60 ^0F
= 0.00073722 kg/cm^3
= 0.00000073722 kg/mm^3

T = 60^0F = 15.55^0C = 288.855K

Mass = density x volume = 0.00000073722 x 159800 = 0.1178kg
Molecular cut for petrol 114.2285 g/mole

PV = mRT
P = (0.1178 x 8.3143 x 288.555) / (0.11422 x 0.0001598)
P = 12287695.65 $j/m^3 = N/m^2$
Gas pressure, P =12.287 N/mm^2
Mean effective pressure, $P_m = 2\pi (T_{nc} / V_d)$
= 153 x 2 x 3.14 / 1598 = 1.202

Indicated power IP = $(P_m \times l \times A \times n)/60$
= $(1.202 \times 80.5 \times 3.14 \times 79.5^2 \times 4)/(4 \times 60)$
= 128018.57 kw

Brake power BP = $(2 \pi N T) / 60$
= (2 x 3.14 x 5250 x 153) / (4 x 60) = 84073.5 kw

Mechanical efficiency, = BP / IP = 84073.5 / 128078.57
= 0.656 = 65.6%

Piston

Material: Cast Iron

Temperature at the center of piston head

$T_c = 260^0c$ to 290^0c

Temperature at the edge of piston head

Te = 185^0c to 215^0c

Maximum gas pressure p = 12.287/mm^2

Bore or outside diameter of piston = 79.5mm

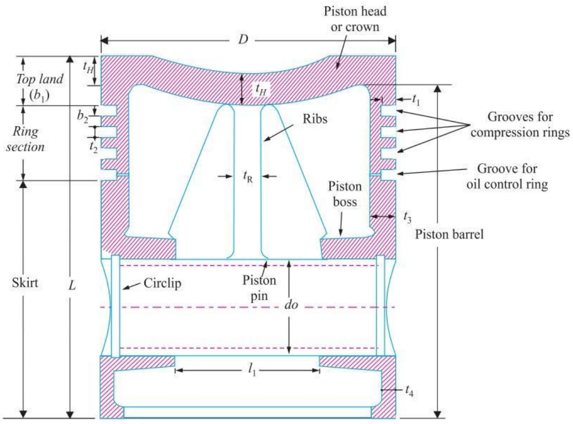

Fig.1 Piston nomenclature

1. *Thickness of piston head*

Th = Sqrt (3pD^2 / 16 x tensile stress)

Tensile stress = 50 to 90Mpa

Th = **15.57mm** (or)

Considering heat transfer

Th = h / (12.56 x k (t_c – t_g)

Heat conductivity force = 174.75w/m/^{0}c
t_c-t_e = 75^0c
H = C x HCV x m B.P (in KW)
C = constant = 0.05
HCV = 47 x 10^3KJ/kg for petrol
m = mass of fuel for brake power per second
BP = brake power
H = C x HCV x (m/BP)
= 0.05 x 47 x 10^3 x 0.11 = 258.5
Th = h / (12.56 x k (t_c – t_g)
= 258.5/ (12.56 x 174.75 x 75) = 0.00157m

Thickness of piston head, Th = = 15.57mm

2. *Piston rings*

Radial thickness t1

= D*(Sqrt (3*p_w / tensile stress))

p_w = pressure of the gas on the cylinder wall = 0.042N/mm^2
tensile stress = allowable bending (tensile stress) for cast iron rings = 110Mpa
t_1 = 2.69mm

Axial thickness t_2 = D/10n_r = 79.5/10 x 3
[n_r = no of rings = 3]
t_2 = 2.65mm

Width of the top land b1= 1.2t_h = 1.2 x 15.57 **=18.684mm**

Width of other land (i.e.) distance between ring grooves, **b_2 = t_2 = 2.6mm**

The gap between the free ends of the ring = 3.5t to 4t = **7.72mm**

3. Piston barrel

t_3 = 0.03D + b + 4.5
b = radial depth of piston ring
b = t_1 +0.4 = 7.473mm
t_3 = 0.03 x 79.5+7.43+4.5
t_3 = 14.35mm

The piston wall thickness towards the open end

t_4 = 0.35t_3

t_4= 5.0225mm

4. Piston skirt

Maximum gas load on the pisto

P = p x πD^2/4 = (12.287 x π x 79.5^2)/4

P = 60960.67N

Maximum side thrust on the cylinder

R = p/10 = 6096.067

R = bearing pressure x bearing area of the piston skirt

R = p_b x D x l

l = length of the piston skirt in mm = **45.6 mm**

Bearing pressure Pb = 1.5N/mm^2

Total length of the piston

L = length of the skirt + length of ring section + top land

Length of ring section = 5 b_2 or t_2 = 2.6mm

L = 45.6 + 2.6 + 18.65 = **66.9mm**

5. Piston pin - material heat treated alloy steel

Center of piston pin should be 0.02D to 0.04D above the center of skirt = 0.04D = 3.18mm Tensile strength = 710 to 910Mpa
Length of the pin in the connecting rod bushing, l_1 = 0.45D = 35.775mm
Load on the piston due to gas pressure = 60960.67N
p =bearing pressure x bearing area

p = p_{b1} x d_0 x l_1
l_1 = 35.775mm;
p_{b1} = 50 – 100Mpa for bronze, pb1 = 100Mpa
d_0 = 17.04mm
Inner diameter of piston pin, d_i = 0.6d_0 = 10.22mm
Maximum bending moment at the center of pin
M = P.D/8 = (60960.67 x 79.5)/8

M = 605796.658s N-mm

$Z = \pi/32\ [\{(d_0)^4 - (d_c)^4\}/d_0] = 4445.0689$

Allowable bending stress $\sigma b = M/Z = 139.02$
This is less than the allowable value 140mpa for heat treated alloy steel
The mean diameter of the piston bosses = $1.5d_0 = 1.5 \times 17.04 = 25.56$mm

Design calculations of connecting rod

1. *Dimensions of cross section of connecting rod*

Thickness of flange & web of the section = t
Width of section B= 4t
Height of section H=5t
Area of section A= 2(4t×t) +3t×t
$A=11t^2$
MI of section about x axis, $Ixx=1\backslash 12\ (4t\ (5t)^3-3t\ (3t)^3)$ $=419\backslash 12t^4$
MI of section about y axis, $I_{YY}=\ (2+1\backslash 12t\ (4t)^3+1\backslash 12\ (3t)\ t^3) = 131\backslash 12\ t^4$
$I_{XX}\backslash\ I_{YY}= 3.2$
Length of connecting rod = 2 times the stroke
L= 2×80.5 =161mm
Buckling load w_B = maximum gas force × F.O.S
W_B =60960.67× 6 =365764.02

$$W_B = \frac{\sigma_C \times A}{1+ a(L\backslash K_{XX})^2}$$

σ_C = compressive yield stress= 172 MPa

$$k_{xx}= I_{XX}\backslash A= \frac{419\backslash 12t^4}{11t^2}$$

$= 3.17t^2 = 1.78t$
f_c= maximum load
f_c= p= 39414.88611
$a= f_c\backslash\pi^2E$

$$a= \frac{39414.88611}{\pi^2 \times 80000}$$

a = 0.05

$$236489.3166 = \frac{172 \times 11t^2}{1+0.05(161/1.78t)^2}$$

$5993.856t^4-749198.1551t^2-162418497.747714=0$

On solving, **t = 23.32mm**

Width of section, B = 4t =93.28mm
Height of section, H = 5t = 116.6mm
Area A = $11t^2$ = 5982.64mm^2
Height at the big end (crank end) = H_2 = 1.1H to 1.25H
H_2 =128.26 mm
Height at the small end (piston end) = 0.9H
H_1 =104.94mm

2. *Dimensions of crank pin*

Load on the crank pin = projected area × bearing pressure, $F_L = d_c \times l_c \times p_{bc}$
$l_c = 1.25\ d_c$ to $1.5d_c$
$F_L = 1.5\ d_c^2 \times p_{bc}$
p_{bc}= allowable bearing press. at the crank pin bearing
p_{bc}= 12.5N/mm²
$F_L = (\pi D^2 / 4) \times P = 60960.67$
$60960.67 = 1.5\ d_c^2 \times 12.5$
$d_c^2 = 3251.2357 = 57.01$mm
$l_c = 1.5d_c = 85.515$mm

3. *Piston pin (gudgeon pin (or) wrist pin)*

d_o=outside dia of the piston pin
l_1=length of the piston pin in the bush of the small end of the connecting rod in mm
$l_1=0.45D=0.45\times 79.5=35.775$mm
Load on the piston due to gas pressure
$P_{max}= (\pi D^2 / 4) \times P = 62017.45$ N
Load on the piston pin due to bearing pressure (or)
Bearing load=bearing pressure bearing area
Load = $P_{b1}\times d_o\times l_1$
P_{b1}=bearing pressure at the small end of the connecting rod bushing
P_{b1}=77.28N/mm²
$60960.67=77.28\times d_o\times 35.77$
d_o = 22.05mm
$d_i=0.6\ d_o=13.23$mm
length between the supports $l_2 = (l_1 + D)/2$ = 57.635mm

Crankshaft

D = piston diameter or cylinder bore = 79.5 mm
P = maximum intensity of pressure on the piston = 12.287 N/mm²
F_p = thrust in the connecting rod will be equal to the gas load on the piston
$= \prod/4\times D^2\times p$
d_c = Diameter of crankpin = 57.01 mm [taken from the big end of connecting rod]
l_c = length of crankpin = 85.515 mm

Due to the piston gas load (F_p) acting horizontally, there will be two horizontal reactions H_1 & H_2 at bearings 1 & 2 respectively.
Considering the crankpin as simply supported beam i.e., $H_1 = H_2$
$= H_1 + H_2 = F_p = 30462.97$ N
b = distance between the bearings 1 & 2 is equal to twice the piston diameter
= 2D = 2×79.5 = 159 mm
$b_1 = b_2 = b/2 = 79.5$ mm

1. *Design of left hand crank web*

Thickness of the crank web
$t = 0.4d_s$ to $0.6d_s$ = 0.22D to 0.32D
$= 0.65d_s + 6.35$ =0.32×79.5
= 25.44 mm [from 0.32D]

Width of the crank web

$w = 1.125d_c + 12.5 = 1.125\times57.01+12.5$

$= 76.63$ mm

Maximum bending moment on the crank web

$M = H_1 (b_2 – l_c/2 – t/2)$

$= 30462.97 (79.5– 85.5/2 – 2445./2)$

$= 732025.1691$ N-mm

Section modulus

$Z = 1/6\ wt^2 = 1/6\times76.63\times25.44^2 = 8265.74\ mm^3$

Bending stress on crank web

$\Sigma_b = M/Z = 732025.1691/8265.74 = 88.56\ N/mm^2$

Compressive stress on the crank web

$\Sigma_c = H_1 /wt = 30462.97/(6376.\times25.44) = 15.62 N/mm^2$

Total stress of crank web

$\Sigma = \Sigma_b + \Sigma_c = 88.56+15.62 = 104.18 N/mm^2$

Here total stress is less than the yield strength of carbon steel ($560N/mm^2$)

d_s = diameter of the shaft in mm

$t = 0.4d_s$ to $0.6d_s$

$d_s = t/0.6 = 25.44/0.6 = 42.4$mm

3. Analysis procedure

a. 2D drawings

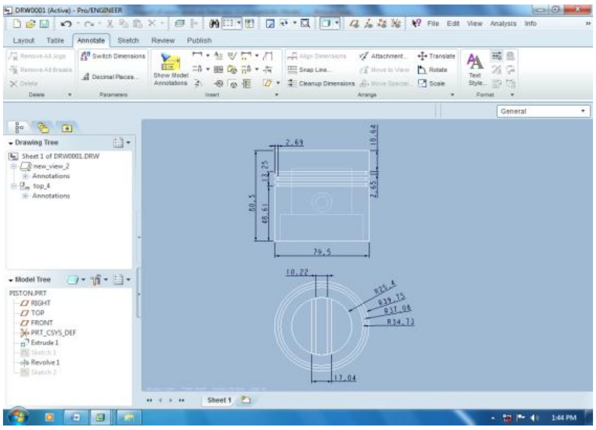

Fig.2 Piston drawing

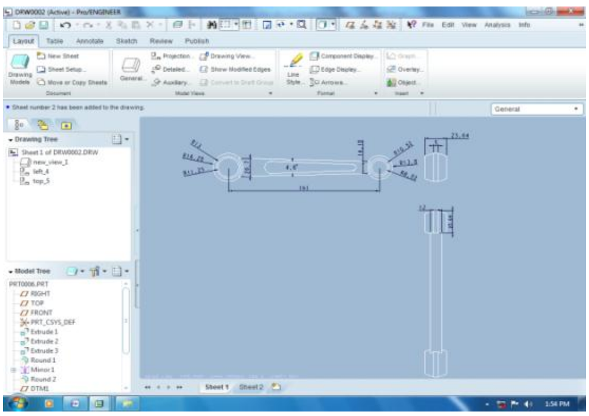

Fig.3 Connecting rod

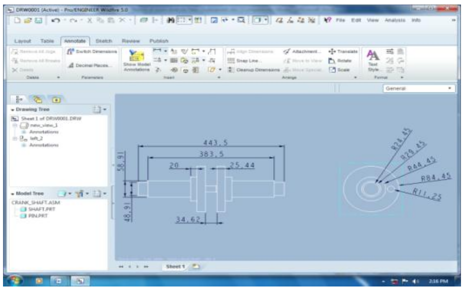

Fig.4 Crank shaft

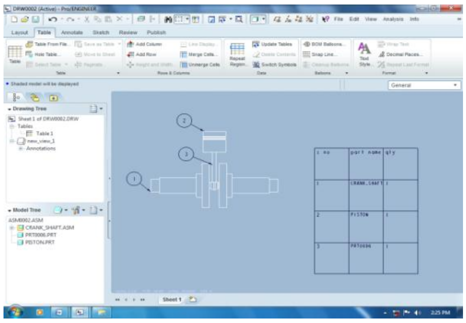

Fig.5 Assembly

b. CAD

CAD is mainly used for detailed engineering of 3D models and/or 2D drawings of physical components. It is used throughout the engineering process from conceptual design and layout of products, through strength and dynamic analysis of assemblies to definition of manufacturing methods of components.

Introduction to pro/engineer - Pro/ENGINEER Wildfire is the standard in 3D product design.

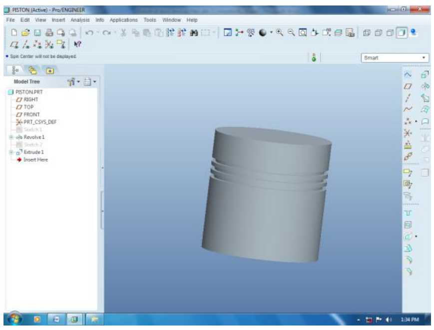

Fig.6 Model of Piston

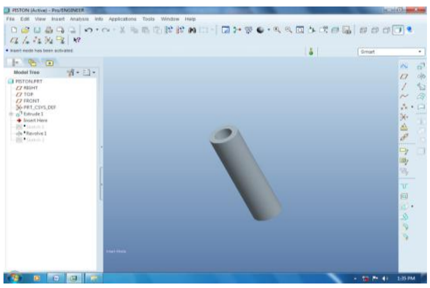

Fig.7 Model of Piston Pin

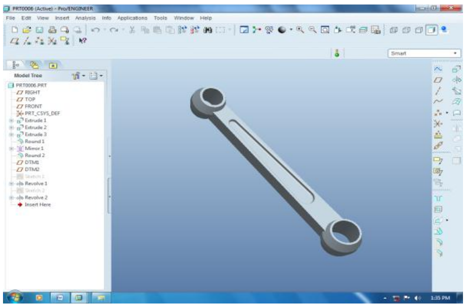

Fig.6 Model of Connecting Rod

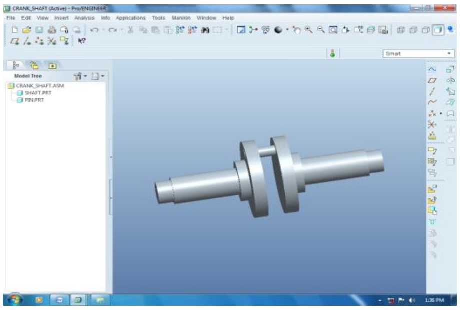

Fig.7 Model of Crank shaft

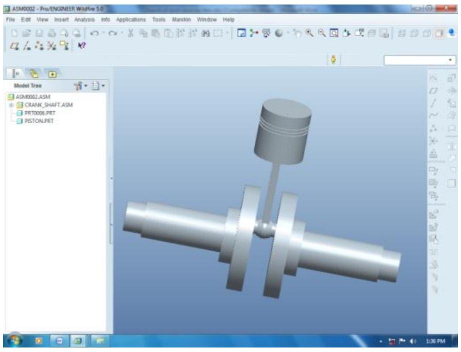

Fig.8 Model of Assembly

c. Finite Element Analysis

FEA consists of a computer model of a material or design that is stressed and analyzed for specific results. It is used in new product design and existing product refinement. 2-D modeling, and 3-D modeling are the generally two types of analysis that are used. 3-D modeling produces more accurate results than the 2 D modeling. FEA allows the programmer to do either linear or non-linear analysis. The system has a set of points called nodes whose grid is called as mesh. The mesh has the details of the material and structural properties. They define the structure's behavior under the loading conditions. Higher density of nodes is used at high stress regions like fillets, corners, etc.. The object is analyzed by the nodes through mesh which lead to the elements.

There are different types of Engineering Analysis which can be done like Structural, Vibrational, Fatigue, Heat transfer, etc. A combination of these analysis is also done where required and it is called Couple field analysis. ANSYS is general-purpose finite element analysis software package.

b.

c. Introduction to Hypermesh

Altair HyperMesh is a high-performance finite element pre-processor to prepare even the largest models, starting from import of CAD geometry to exporting an analysis run for various disciplines. Altair Engineering is the creator of the HyperWorks suite of CAE software products. It enables engineers to receive high quality meshes with maximum accuracy in the shortest time possible. Altair's connector technology automatically assembles individual parts with their Finite Element representation.

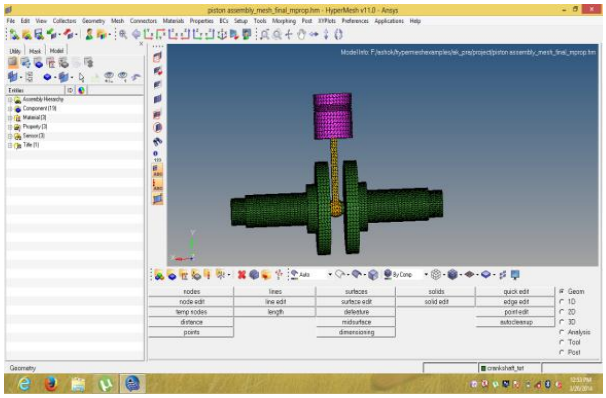

Fig.9 Meshing of the assembly

4. Analysis of the piston, connecting rod and crankshaft assembly

a. Static analysis - Element Type – Solid 20 Node 95

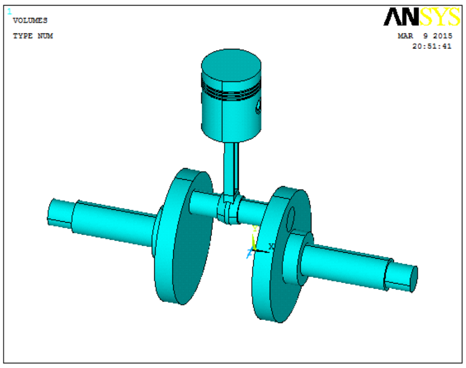

Fig.10 Model of the assembly

Table 2 Properties of the materials

Material	Young's modulus (N/mm²)	Poisson's ratio	Density (Kg / mm³)
Cast Iron	75000	0.211	0.000007
Manganese Steel	210000	0.29	0.000008
High Carbon Steel	200000	0.295	0.000007872

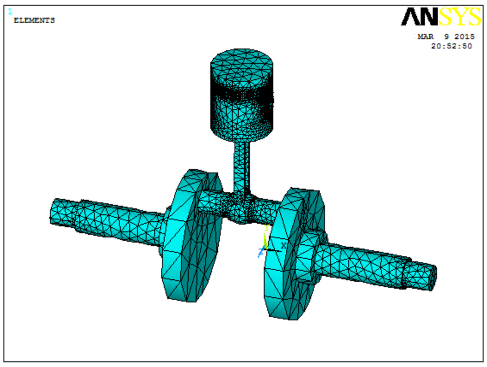

Fig.11 Meshed model

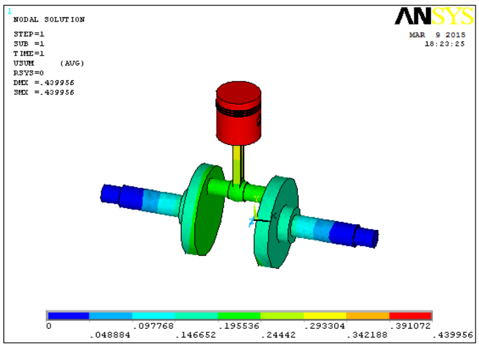

Fig.12 Displacement with Loads – Pressure on Areas – 12.26N/mm²

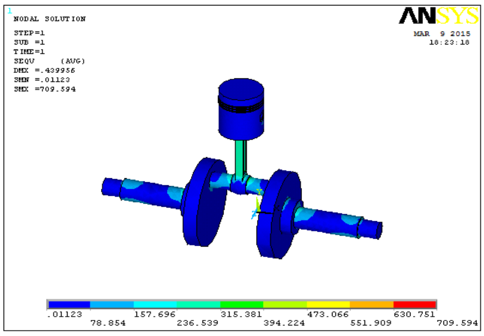

Fig.13 Von Mises Stress

b. Thermal analysis –Element Type – Solid 20Node 90

Table 3 Material's thermal properties

Material	Density (Kg / mm³)	Thermal conductivity (W/m k)	Specific heat (J/g C)
Cast Iron	0.000007	53.0	0.506
Manganese Steel	0.000008	51.9	0.472
High Carbon Steel	0.00000787	52.0	0.669

Loads : Temperature on Areas – 973K

Convection: Film Coefficient – 0.000025W/m²K

Bulk Temperature – 570K

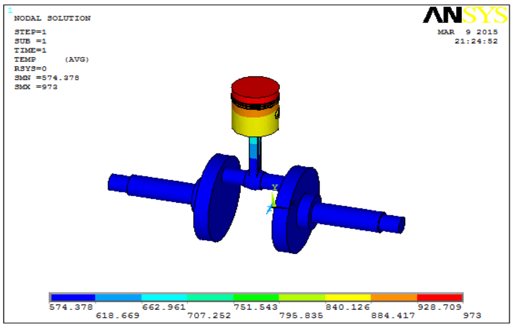

Fig.14 Nodal temperatures

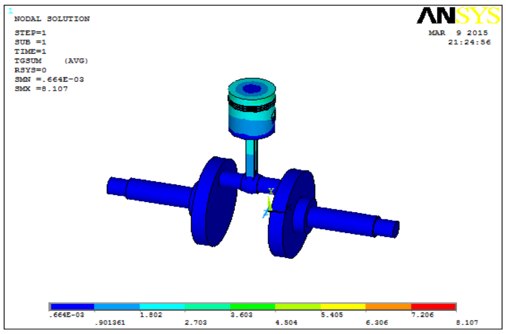

Fig.15 Thermal gradient

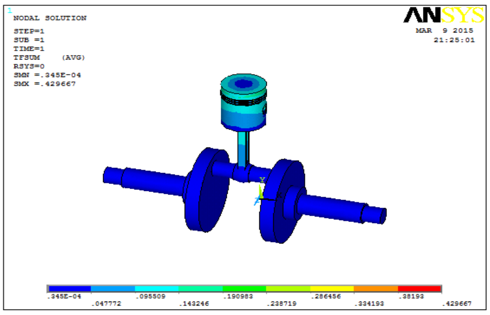

Fig.16 Thermal flux

c. Dynamic analysis-Element Type – Solid 20Node 95 Loads

Time Step – 10secs, Pressure – 12.26N/mm²

Time Step – 20secs, Pressure – 18.39N/mm²

Time Step – 30secs, Pressure – 30.65N/mm²

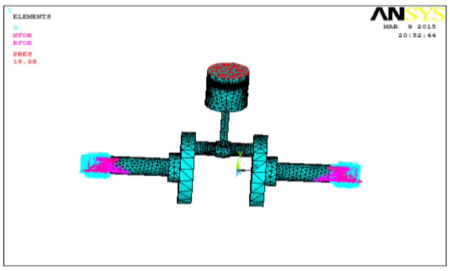

Fig.17 Loads at different time and Pressures

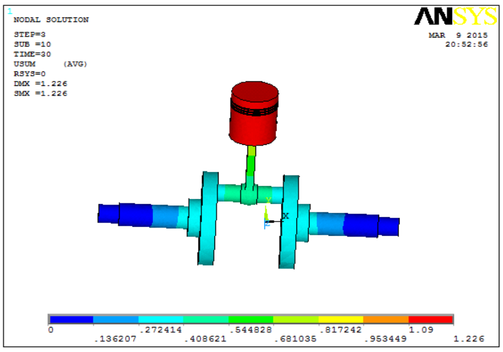

Fig.18 Displacement

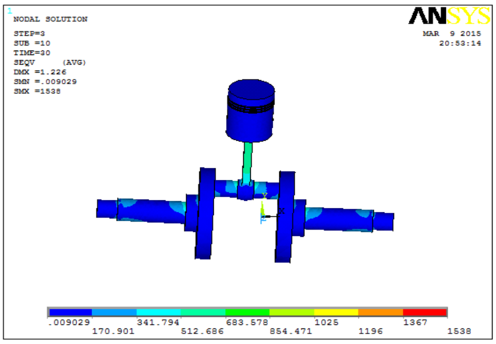

Fig.19 Stress

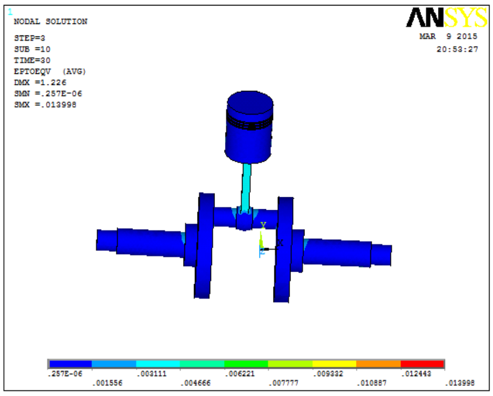

Fig.20 Strain

Results table

a. **Table 4** Static analysis

	Displacement (mm)	Von Mises Stress (N/mm²)	Strain
Piston – Cast Iron Connecting rod – Manganese Steel Crankshaft – High Carbon Steel	0.439956	709.594	0.011

b. **Table 5** Thermal analysis

	Temperature (K)	Thermal Gradient (K/mm)	Thermal Flux (W/mm²)
Piston – Cast Iron Connecting rod – Manganese Steel Crankshaft – High Carbon Steel	973	8.107	0.429667

c. **Table 6** Dynamic analysis

	Displacement (mm)	Von Mises Stress (N/mm²)	Strain
Piston – Cast Iron Connecting rod – Manganese Steel Crankshaft – High Carbon Steel	1.226	1538	0.013998

Conclusion

In this project, the main parts of the engine piston, connecting rod and crankshaft are designed using theoretical calculations for the given engine specifications. The designed parts are modeled and assembled in 3D modeling software Pro/Engineer. The materials used are Cast iron for piston, Manganese steel for the Connecting rod and High Carbon steel for crankshaft. To use the same piston assembly for higher speed engines, the material of the piston has to be changed.

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