Design and Analysis of Ceramic Matrix Composites Piston

S.Sivabalan[1],Sathishkumar G[2], R.Sridhar[3], R.Pugazhenthi[4]

[3,4]Associate professor, Department of Mechanical Engineering

[1,2] Assistant Professor, Department of Mechanical Engineering,

Vels Institute of Science Technology & Advanced Studies-Chennai

**Email:gsk032sathish@gmail.com, sivamech1990@gmail.com,*

srisampangy@gmail.com

Abstract

The aspect of the project is to analyze the piston and to check whether the induced stresses are within the permissible limit. This includes modeling, meshing, and analyzing the model. The model is created using the package pro/E, which is the most efficient modeling package. The model is translated to the finite element analysis (FEA) package analysis through the IGES translator. The translated model is parametrically meshed. Boundary condition and loading are applied. Then it is analyzed using static analysis module. The results of the analysis such as strain, stress, thermal stress, heat flux, temperature gradient and stress intensity factor are obtained and the area of maximum stress is acknowledged. The future studies can be continued, for various volume proportion of matrix and reinforcement material as well as by changing the reinforcement material.

1. Introduction

1.1. Piston

Piston of an internal combustion engine is cylindrical one that moves up and down in the cylinder of a vertical engine or reciprocates to and for in a horizontal engine cylinder. Due to this movement the cylinder volume is changed during the cycle of operation's.

Piston crown (or) head is the top of the piston. The high pressure produced during the compression process will act on the head of the piston. Piston rings one provided in the grooves on the piston furnace. These rings help in presenting the leakage of the combustion products from the combustion chamber to the crank case. If there is any leakage then it will affect the lubricating oil and there fore deteriorates the lubricating oil property. The piston pin connected the piston with the connecting rod. Rib's are provide below the piston head. The piston crown's must be able to withstand the forces exert on them by the compression products and also to transfer the heat form the piston crown's to compression chamber walls. A flat top piston has the crown Shape flat in nature that is parallel to the cylinder head. A domed (or) pop up piston has the crowns shape flat in nature that is parallel to the cylinder head. A domed (or) pop up piston has a head that is curved upwards so in order to accommodate this kind of piston there will be a hemi spherical shaped type cylinder head.

Hemi spherical shaped piston. Torpidly shaped piston offers the maximum turbulence that helps in improving the combustion. The piston's used in single acting engines one open at one end and these types of piston's are called as trunk piston. These types of piston's are seen in automobile engines and in many stationary engines. Piston of light duty engines are made by die casting process and piston of heavy-duty engines are made by forging process.

The material for the piston commonly used in the cast iron. Cast iron is used because it can with high temperature of the compression. Steel piston's are used in some automotive

engine's aluminium alloy piston's are used at present in automotive and other engines, particularly in engine of higher output and those operating at high speeds. But their strength is poor at high temperatures. In some piston's coasting is given on the head piston to increase its durability ceramic stainless steel is some of the coated materials.
The Piston Must Possess The Following Qualities

- Rigidity to withstand high pressure
- Lightness to reduce the weight
- Good heat conductivity to reduce the risk of detonation
- Silence in operation
- Covertly formed skirt to give uniform bearing
- The piston receives the most produced by combination and transmits the power to the connecting rod.
- If reciprocates to cause different stokes.
- If acts as bearing to the small end of the connecting rod and bear's thrust.

2. Materials and Methods

2.1. Ceramic Matrix Composites

Ceramic materials in general have a very attractive package of properties: high strength and high stiffness at very high temperatures, chemical inertness, low density, and so on. This attractive package is marred by one deadly flaw, namely, an utter lack of toughness. They are prone to catastrophic failures in the presence of flaws (surface or internal). They are extremely susceptible to thermal shock and are easily damaged during fabrication and/or service. It is therefore understandable that an overriding consideration in ceramic matrix composites (CMCs) is to toughen the ceramics by incorporating fibers in them and thus exploits the attractive high-temperature strength and environmental resistance of ceramic materials without risking a catastrophic failure. It is worth pointing out at the very outset that there are certain basic differences between CMCs and other composites.

2.2. Applications of Ceramic Matrix Composite

Ceramic matrix composites find applications in many areas. A convenient classification of the applications of CMCs is aerospace and non-aerospace. Materials-related drivers for applications of CMCs in the aerospace field are:

- High specific stiffness and strength leading to a weight reduction, and, consequently, decreased fuel consumption.
- Reduction in fabrication and maintenance cost.
- Higher operating temperatures leading to a greater thermal efficiency.
- Longer service life.
- Signature reduction.

2.3. Material Properties

Table 1.Materials Properties

No	Name of the matériel	Young's Modulus ' E'N/mm^2	Density ' ρ'kg/mm^3	Poissions ratio 1/M	Thermal conductivity' K' W/ mm-K
1	CastIron	100000	7.15×10^{-6}	0.3	80.2×10^{-3}
2	Al Alloy	675000	2.7×10^{-6}	0.3	38×10^{-3}
3	MMC (Al alloy + SiC)	622000	2.78×10^{-6}	0.268	55.5×10^{-3}
4	CMC (Al_2O_3 – ZrO_2) + SiC	313200	4.14×10^{-6}	0.232	37.12×10^{-3}

2.4. Cause of Failure

Propagation of Cracks during operation in the reciprocating components can be subjected to useful modifications that would give a remarkable rise in the quality of the components. The present model has a high Factor of Safety, which is unnecessary. Since the component has increased, masses it would be better that we choose a parametric solid model and analyze it using FEA techniques. The stress limits are kept under control.

Theoretical Calculation

Model Rx-100

Diameter of the piston d = 50mm = 0.05mm

Stroke length l = 50mm = 0.05mm

Compression ratio $r_e = 6.7 : 1$

$r_e = 6.7$

Initial pressure $P_1 = 1$ bar

n = 1.3

Air fuel ratio = 14 : 1

Initial temp T_1 = 31^0 C = 304 K

Factor of safety N = 6

$P_2/P_1 = (re)^n$

$P_2 = lx\ (6.7)^{1.30}$

$= 11.85$ bar

$T_2/T_1 = P_2/P_1 \times v_2/v_1$

$= 304\ (11.85/1 \times 1/6.7)$

$T_2 = 537.7^0$ K

Ma/mp = A.F ratio $\rightarrow m_a/m_f = 14$ ($\therefore m_a = 1$kg)

$= m_f = 1/14$

Q_{2-3} kg of air $= C_f \times m_f$

$= 40500 \times 1/14$

Q_{2-3} = 2892.86 KJ/kg

Mass of charge / kg of air (m) $= m_a + m_f$

$= 1 + 1/14$

$m = 16/14$ kg

$Q_{2-3} = m\, c_a(T_f - T_2)$

$2892.86 = 16/14 \times 0.718 \times (T_3 - 537.7)$

$T_3 = 4063.12$ K

$P_3 = P_2(T_3 / T_2)$

$= 11.85\ (4063.12/537.7)$

$P_3 = 89.5$ bar

Thrust force F $= \prod/4 \times d^2 \times p_3$

$= \prod/4 \times (0.05)^2 \times (89.5 \times 10^5)$

$= 17573.28$ N

Design thrust force $[F_T]$ = N x F

$= 6 \times 17573.28$

$[F_T] = 105439.68$N

Note (T_3, p_3 and $[F_T]$ were obtained in the sparking area.
Due to heat convection the max temp, occur on the top of the piston is 1230^0C

Max temperature $T_m = 1230 + 273 = 1503$ k

$P_m = P_2(T_m/T_2)$

$= 11.85\ (1503/537.7)$

Max pressure P_m $= 33.12$ bar

Thrust force F $= \prod/4 \times d^2 \times p_m$

$= \prod/4 \times (0.05)^2 \times 33.12 \times 10^5$

$= 6503.8$ N

Design thrust force $[F_T]$ = F.O.S x Thrust force

$= 6 \times 6503.8$

$[F_T] = 39022.8$ N

Table 2. Variation of Temperature, Design Thrust Force

Sl.No.	Max Temperature ^{0}C	Design thrust force $[F_T]$ in N
1	550	21370.68
2	700	25258.4
3	850	29157
4	1000	33045.6
5	1230	39022.8

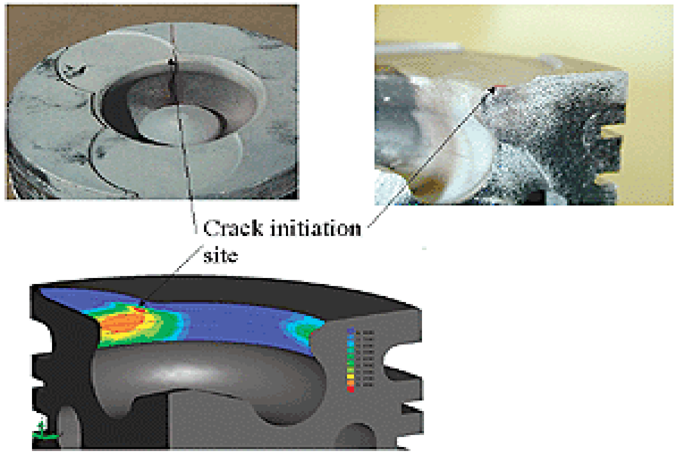

Figure 1. Crack initiation in pistons

2.5. Analysis on Composite Materials

MMC material is selected as piston material for analysis. MMC contain aluminium alloys as matrix and SIC as reinforcement particles (80% A1 alloy and 20% SIC)Secondly CMC is selected as piston material for analysis. CMC contain of Al_20_3-Zro_2 as matrix and SIC as reinforcement particles. (Cram Tec grade 950). The composition are as 80% Al_20_3-Zro_2 and 20% SIC.The material properties of the composite materials are obtained by using rule of mixture.

Table 3. Material Properties of the Composite Materials

Sl.No.	Name of the Material	Young's Modules(E) in N/mm^2	Mass density in kg/mm^3	Poisson ratio	Thermal Conductivity (K) in W/mmk
1	CMC	313200	4.17 e-6	0.232	37.12 e-3

3. Result and discussion

- The piston model created in Pro/E was teken for the analysis.
- The Piston model is Translated from Pro/E to IGES
- From the preferences menu the type of analysis the selected as structural
- The element type is selected a as plan 55 in solid-w/rotate 72.
- The model is meshed using this element
- The material properties for Aluminium alloy are defined as follows.

Young's Modulus (E)	-	313200 N/mm_2
Mass density value	-	4.14 e-6 kg/mm^3
Poisson ratio	-	0.232
Thermal conductivity (K)	-	37.12 e-3 w/mmk

- Confiined the gudgeon – pin area using boundary conditions
- Thrust force are applied on the top surface area of the piston

- The SOLVE command is used to solve the problem
- The 1st principle stress and strain are plotted using the General postprocessor
- The results are solve in the data base and the seven is cleared
- Repeated the above same for various loads and the obtained the results are stored in corresponding files.
- The switch element type in the preprocessor menu is used to change the element analysis into thermal analysis
- The element type is selected as plane 55 in solid – Tet 10 node 87.
- The model is meshed and properties of Aluminium alloy are applied for further work
- Convection loads are applied on the top and outer are of the piston
- Then the problem is solved using SOLVE command
- The temperature distribution, thermal flux and thermal gradient are plotted using the General postprocessor
- The results are solved in the database and the screen is cleared.
- For various convection temperatures the above parameters are found out.
- The switch element type command in the pre processor menu his used to change element type from thermal to structural
- The previously thermal applied loads are deleted.
- The structural pressure load is applied on the top surface of the piston and the problem is solved.
- Using General post processor the displacement, principles stress values due to both thermal and structural loads are plotted.
- The obtained results are stored in appropriate files.

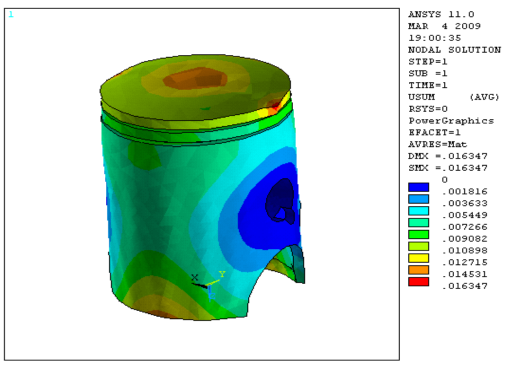

Figure 2. Strain (CMC)

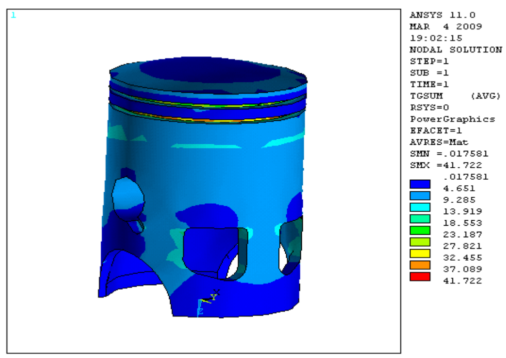

Figure 3. Thermal Gradient (CMC)

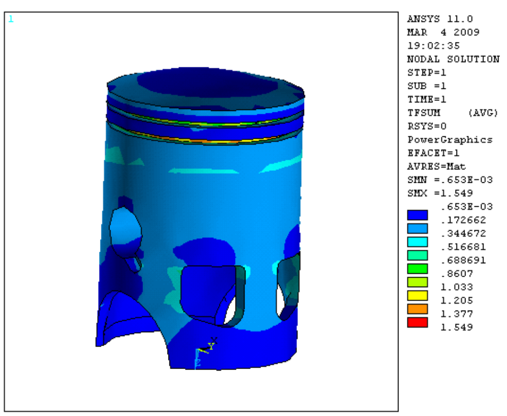

Figure 4. Thermal Stress (CMC)

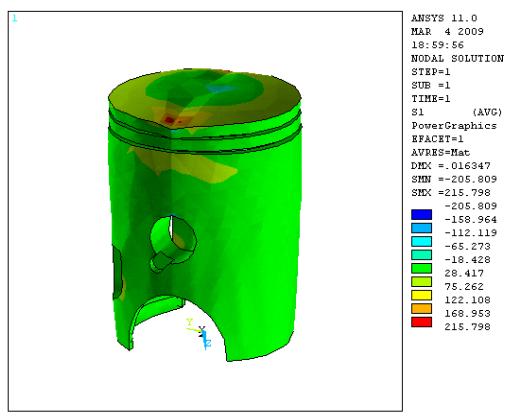

Figure 5. Stress (CMC)

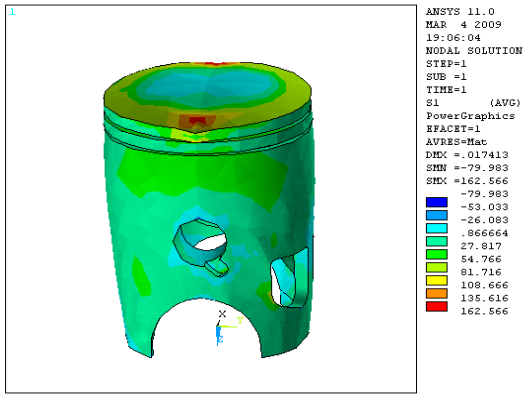

Figure 6. Principle Stress (CMC)

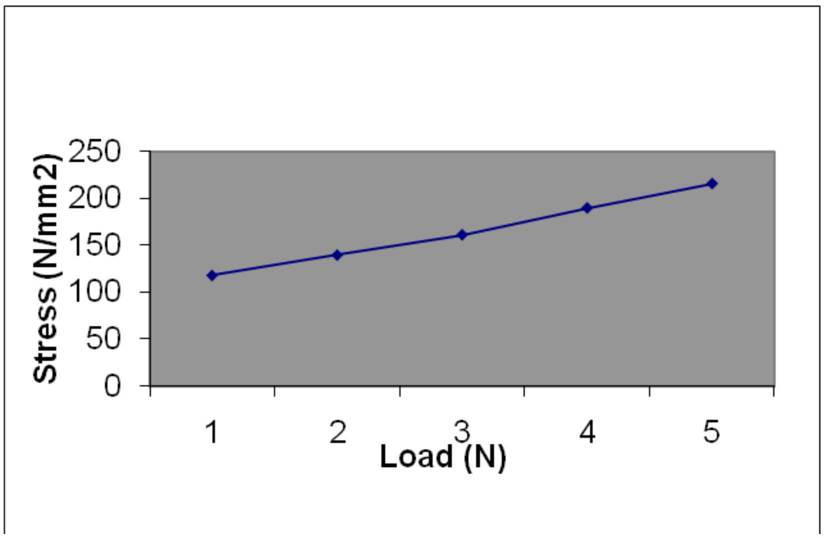

Figure 7. Stress VS Load

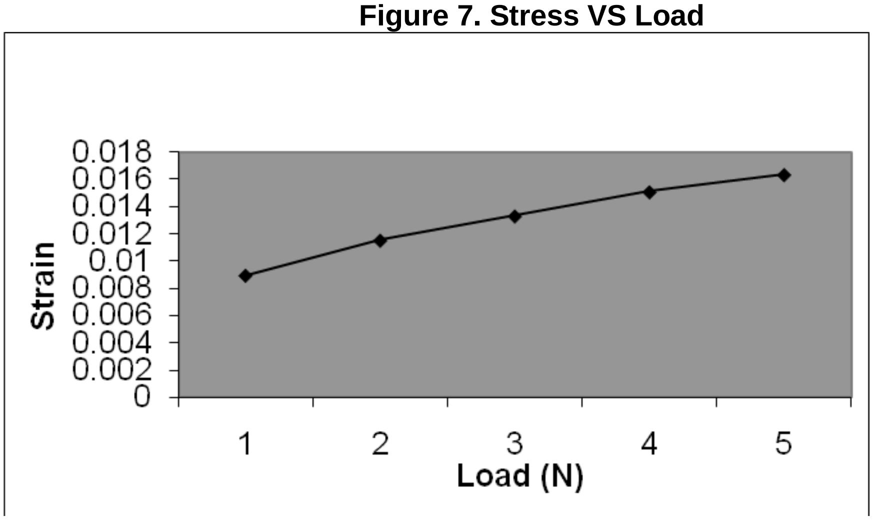

Figure 8. Stress VS Load

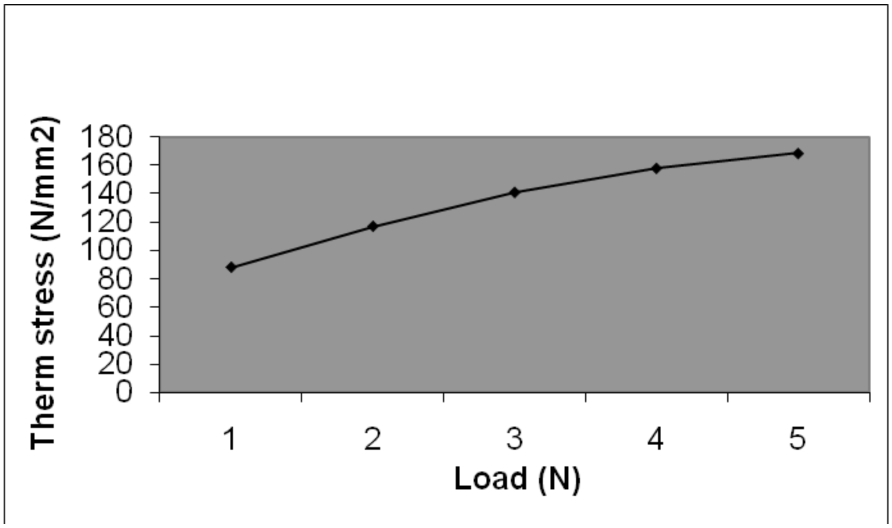

Figure 9. Thermal stress VS Load

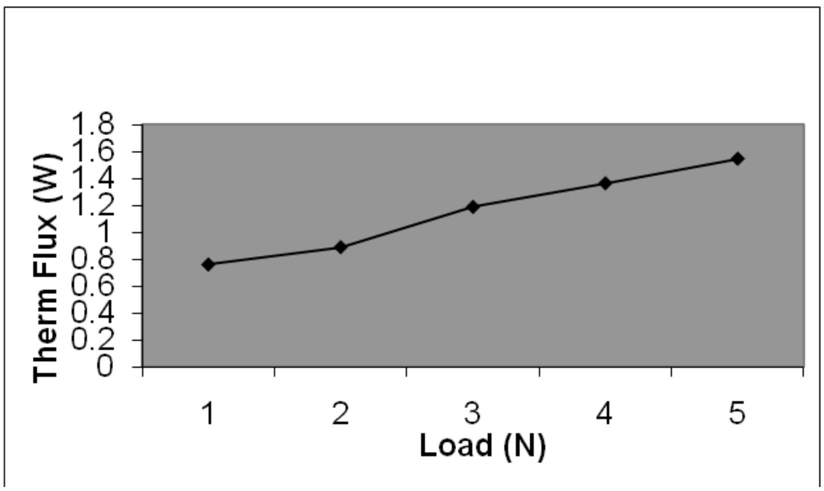

Figure 10.Thermal Flux VS Load

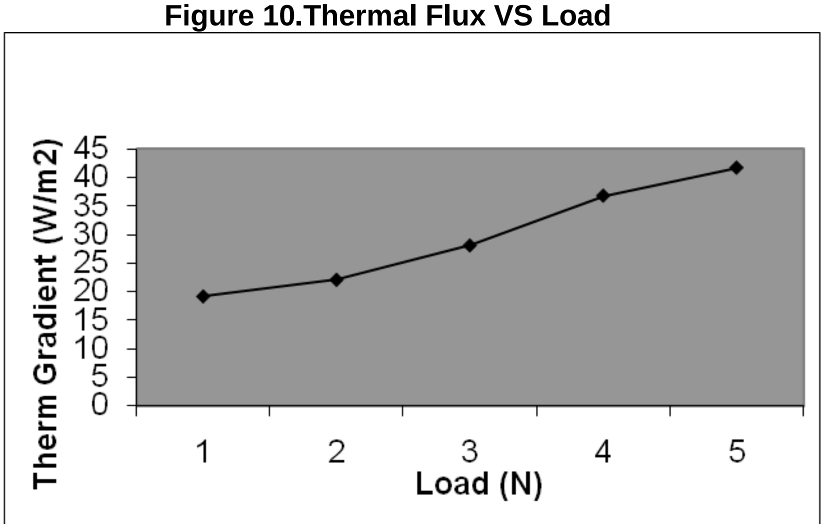

Figure 11.Thermal Gradient VS Load

Table 4.Stress strain and thermal analysis CMC

Sl. No.	Design thrust force [Fr] in 'N'	Temp.^{0}C	Stress-Strain analysis		Thermal Analysis		
			Stress ^{t} N/mm^2	Strain	Thermal Stress N/mm^2	Thermal Flux (W)	Thermal gradient (W/m^2)
1	21370.68	550	118.184	0.008952	88.123	0.7625	19.257
2	25258.4	700	139.808	0.011526	117.12	0.8919	22.157
3	29157.90	850	161.393	0.013306	141.112	1.191	28.154
4	33045.6	1000	189.912	0.01508	158.156	1.367	36.839
5	39022.8	1230	216.798	0.01634	162.66	1.549	41.722

The graph shows that on increasing of the load, the stress also increased gradually. The line is slanting one.The graph 2 shows that on increasing of the load, the stress also increased gradually. The line is slightly inclined one.The graph 3 shows that on increasing of the strain, the stress also increased gradually. The line is a inclined one.The graph 4 shows that on increasing of the load, the thermal stress also increased gradually. The line is slightly curved.The graph 5 shows that on increasing of the load, the thermal flux also increased gradually. The line is slightly curved.

4. Conclusion

Thus, we have arrived at the final phase of the project. An existing design of piston was modeled and analyzed for available boundary conditions with petrol as the working fuel. The piston model was analyzed for newly proposed composite materials, Ceramic material composite (CMC) and Metal matrix composite (MMC). From the results, it is found that the maximum deflection of the piston for composite materials is very low compared to that of the existing material.For CMC, it is found to 216.798 N/mm2 for piston and deflection is found to be .01634 mm.. For MMC, it is found to be 168.056 N/mm^2. For piston and deflection is found to be 0.008149 mm.

References

[1] Thin-Lin Horng, "Analytical Solution of Vibration Analysis on Fixed-Free Single-Walled Carbon Nanotube-Based Mass Sensor", Journal of Surface Engineered Materials and Advanced Technology, 2012; 2(1): PP 47-52.

[2] J S Wu And H-M Chou, "Free Vibration Analysis Of A Cantilever Beam Carrying Any Number Of Elastically Mounted Point Masses With The Analytical-And-Numerical-Combined Method", Journal of Sound and Vibration, 1998, 213(2): PP 317-332.

[3] TarsicioBeleandez, Cristian Neipp, "Numerical and Experimental Analysis of a Cantilever Beam: a Laboratory Project to Introduce Geometric Nonlinearity in Mechanics of Materials", Int. J. Engng Ed., 2003;19(6): PP 885 -892.

[4] J. J. Wu and A. R. Whittaker, “The Natural Frequencies and Mode Shapes Of A Uniform Cantilever Beam With Multiple Two-DOF Spring Mass Systems”, Journal of Sound **and** Vibration, 1999; 227 (2): PP 361-381.

[5] S.S Queini, A.H Nayfeh, single mode control of a cantilever beam under principal parametric excitation, journal of sound and vibration 224 (1999) 3347.

[6] M.MKannel, Y.A.Amer, response of parametrically excited one degree of freedom system with nonlinear damping and stiffness, PhysicaScripta 66 (2002) 410-416.

[7] C.Chin, A.H.Nayfeh, W. Lacarbonara, two-to-one internal resonance in parametrically excited buckled beam, AIAA , 1997; 97 : 1081.

[8] Haxton RS, Barr ADS. The auto parametric vibration absorber, ASME J.Eng Industry 1972; 94:119-25.

[9] Brian J. Schwarz & Mark H. Richardson," EXPERIMENTAL MODAL ANALYSIS", CSI Reliability Week, Orlando, FL, Oct-1999.

[10] D. Ravi Prasad and D.R. Seshu "A STUDY OF DYNAMIC CHAARECTERISTIC OF STRUCTURAL MATERIALS USING MODAL ANALYSIS" Asian journal of civil engineering.

[11] D.Y. Zheng. Free Vibration Analysis of a Cracked Beam By finite Element Method. Journal of Sound and Vibration, 2004: 457-475.

[12] Huszar, Zsolt. Vibration of cracked reinforced and prestressed concrete beams Architecture and Civil Engineering, Vol. 6, 2008: 155- 164

[13] G.M.Owolabi, S23wamidas, SeshadrI Crack detection in beams using changes in frequencies and amplitudes of frequency response functions. Journal of Sound and Vibration, 265(2004) 1-22

[14] M.Behzad, Ebrahimi, A.Meghdari. A continuous vibration theory for beams with a vertical edge crack. Mechanical Engineering, Vol. 17, 2010: 194-204.

[15] E. I. Shifrin. “Natural Frequencies of a Beam with an Arbitrary Number of Cracks.” Journal of Sound and Vibration, 222(3), 1999: 409–423

[16] Duryodhan, N. S. et al,Life Determination by Fatigue Analysis and Modal of Intermediate Steering Shaft and Its Optimization, International Journal of Science Technology & Engineering (IJSTE), Volume 2, Issue 1, July (2015)

[17] Duryodhan, N. S. et al, Modelling Of Intermediate Steering Shaft of Fiesta Car and Its Static Structural Analysis, International Conference on Quality Upgradation in Engineering, Science and Technology (ICQUEST-2015),(2015).

[18] Kumer, S. et al, Design and Stress Analysis of Steering Rack Using CAE Tool, International Journal of Advances in Engineering Sciences, Volume 4, Issue 3, April (2014).

[19] Kumer, S. et al, Design and Optimization of Steering Rack using CAE Tool, International Journal of Enhanced Research in Science Technology & Engineering, Volume 3, Issue 6, pp.106-110, June (2014).

[20] Venkatesh, J.; Murthy, P. B., Design and Structural Analysis of High Speed Helical Gear Using ANSYS, International Journal of Engineering Research and Applications, Volume 4, Issue 3(Version 2), pp.01-05, March (2014).

[21] Dhuri, C. et al, Selection, Modification And Analysis of Steering Mechanism For An All-Terrain Vehicle, International Journal on Theoretical and Applied Research in Mechanical Engineering (IJTARME), Volume 4, Issue 2, (2013).

[22] Lohith, K. et al, Development of Four Wheel Steering System for A Car, International Journal of Application or Innovation in Engineering & Management (IJAIEM), Volume 12, Issue 1, April (2013).

[23] Sarkar, G. T. et al, Stress Analysis of Helical Gear by Finite Element Method, International Journal of Mechanical Engineering and Robotic Research (IJMERR), Volume 2, October (2013). [24] Singh, T.; Parvez, M., Comparative Study of Stress Analysis of Helical Gear Using AGMA Standards and FEM, International Journal of Engineering Sciences & Research Technology (IJESRT), July (2013).