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Performance Evaluation of Stress Concentration Factor for Shoulder Fillet on Round Bar under Bending Loading

Hiren Prajapati, Bhavesh Patel,

Abstract: ***In industries, many unexpected failures of machine components occurs due to lack of proper design, sudden changes that happen during working conditions and pre-existing geometrical irregularities. The geometric discontinuities cannot be avoided as they fulfill functional requirements. The shaft or round bar with shoulder fillet is one of the machine components working under different loading conditions. In the present work, shoulder filleted shaft/round bar working under bending loading conditions is taken for study and the stress concentration factor was evaluated. Finite element analysis (FEA) is performed for a total of seven different geometries with different D/d ratios and analyzed them using ANSYS 19.0 workbench software. Based on the equivalent (Von Mises) stresses obtained from the FEA, stress concentration factor (SCF) for the shoulder filleted shaft is calculated and compared with the theoretical results obtained from derived modified Pilkey's equations, Roark's equations, and S. M. Tipton equations. The outcome of results shows that for lower D/d ratios both results were identical in nature but for higher D/d ratios, the results found deviated. The SCFs are decreased with increasing D/d ratios. The results of SCFs are presented in the form of graphs for comparison purpose as well as one can refer it for his/her applications.***

Keywords: Bending loading; finite element analysis; stress concentration factor; shoulder fillet; equivalent (Von Mises) stress.

I. INTRODUCTION

Round bars (Shafts), flat bars and flat plates are most important as they are widely used in the different mechanical and other related industries for making of different types of machinery and their parts. Among these, round bars are used for making various types of shafts, spindles, and axles. All these elements are widely used for motion and power transmission purpose in the various mechanical devices and systems. These elements are continuous in length and sometimes steps are provided as per needs. So the design of these elements is very crucial especially shafts under different loading conditions i.e. axial tension, bending and torsional loading. To perform specific functions, different types of geometrical discontinuities are provided on the shafts. For example shoulder fillets are provided on the shaft to couple the bearings and pulleys, to align the shaft, keyways are

provided on the shafts, etc. Due to these discontinuities, strength of the shafts may reduce; therefore sometimes these discontinuities are called as stress risers. To evade abrupt change in cross-section of the shafts, steps with shoulder fillets are provided for the gradual reduction in diameter to keep the stress lines uniform and to avoid higher stress concentration [1]. In the design of any shaft, to achieve appropriate and effective design, the study of the effects of geometrical discontinuities is very important. These geometric discontinuities will cause significant stress concentrations. Fillets are widely used in mechanical parts to provide smooth move-in regions where there is an abrupt change in cross-section like in shoulders [2].

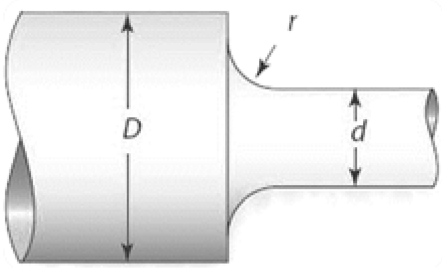

Fig. 1 Geometry of round bar [2]

Figure 1 shows a shaft with a shoulder fillet. Maximum stress is accrued in the shaft where an abrupt change in the cross-section is presented in figure 1. This accrued stress is known as stress concentration (SC) and it can be measured using factor known as stress concentration factor (SCF). SCF is the ratio of the maximum stress (σ_{max}) to the nominal stress (σ_0) as presented in Equation (1).

$$k_t = \frac{\sigma_{max}}{\sigma_0} \qquad (1)$$

Where k_t = Stress concentration factor

In the number of machine elements design textbooks, the stress concentration factors (SCFs) for the shaft with shoulder fillet radius are fully explained and sets of stress concentration factor (SCF) graphs were presented by Norton, Shigley and Robert [1, 3].

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* Correspondence Author
Hiren Prajapati*, Faculty of Engineering and Technology, Ganpat University, Ganpat Vidyanagar, India.
Email: hirs.mech1985@gmail.com
Bhavesh Patel, Faculty of Engineering and Technology, Ganpat University, Ganpat Vidyanagar, India.
Email: bpp01@ganpatuniversity.ac.in

SCF is higher for larger D/d ratio and smaller fillet radius (r) which can be clearly observed from figure 2. Due to mechanical restrictions like space limits or the presence of neighboring parts, it is often challenging to take higher fillet radius [3].

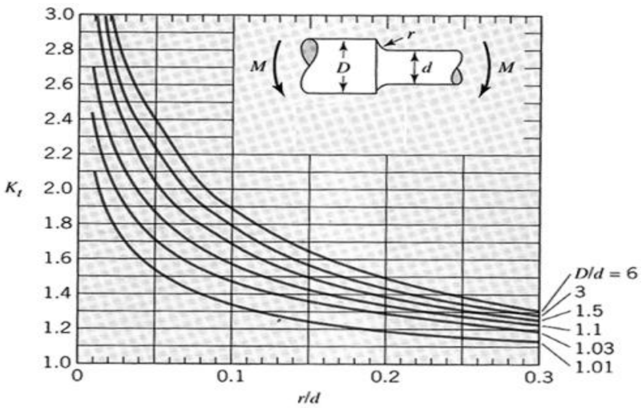

Fig. 2 Variation of stress concentration factor with r/d for a filleted shaft under bending loading [3]

Augusto et al. presented a number of methods for finding the SCF i.e. analytical methods, experimental methods, and computational methods [4]. In the present work, SCF is derived using analytical method and results are confirmed by computational method (Finite Elements Methods - FEM). As described by Bhavesh Patel et al. [5], the number of researchers has carried out various techniques to determine the stress concentration factor for bending loading, torsional loading, and axial tension loading conditions. For bending loading Pilkey's et al., Young et al. and Tipton et al. have given number of equations for different range of r/d and D/d ratios. All these equations are matched with the results presented by Peterson's in the form of curves and provided wide range of h/r, r/d and D/d ratios. Numerous equations were modified and presented by Bhavesh Patel et al. [5] for bending loading for range from $0.1 \leq h/r \leq 2.0$ to $2.0 \leq h/r \leq 20$ and the results compared and validated through Finite Element Analysis.

II. METHODOLOGY

The number of equations presented by Pilkey [6], Young et al. [7] and S M. Tipton et al. [8] are altered in the form of fillet radius by Bhavesh Patel et al. [5] for bending loading conditions through mathematical formulation for the same range of h/r ($0.1 \leq h/r \leq 2.0$ to $2.0 \leq h/r \leq 20$) as mentioned in the Petersons SCF handbook [6]. Also in the paper [5], a range of SCFs were given for various modified equations of fillet radius. To obtain the fillet radius based on modified equations, it is essential to put the SCF from the range of SCF given by them and it gives an optimum value of SCF. Here, in the present work, effort is made to validate the results of SCFs which are given by Bhavesh Patel et al. [5] using computational method (Finite Element Analysis). Equivalent (von Mises) stresses have been calculated from the FEA results.

III. FINITE ELEMENT ANALYSIS

The Finite element analysis (FEA) is widely used for the complex geometries where traditional analysis methods are not able to solve the problems as FEA divides the complex geometries into smaller parts (elements). Finite element analysis of shoulder filleted shaft subjected to bending loading is carried out using ANSYS 19.0. Total seven different 3D models of shoulder filleted shaft with different D/d ratios are modeled in Solid works 16.0. EN31 was modeled as a linear elastic material in ANSYS as round bar material. Table 1 shows the material properties of EN31.

Table 1 Material properties of EN31

Property	Value	Unit
Density	7600	Kg/m^3
Isotropic properties		
Young's modulus	207	MPa
Poisson's ratio	0.3	--
Bulk modulus	172.5	GPa
Shear modulus	80	GPa
Tensile Yield strength	460	MPa
Tensile Ultimate strength	560	MPa

The shoulder filleted shaft has meshed with rectangular elements. The average value of the mesh size is 0.01 mm (fine size), resulting in 105460 nodes and 24461 elements. The meshed shoulder shaft with dimensions of D = 40 mm, d = 33.33 mm (D/d = 1.20) and fillet radius as 3.34 mm is shown in figure 3. For bending loading as shown in figure 4, the model is fixed from the end of larger diameter and load is applied to the smaller end in the perpendicular direction.

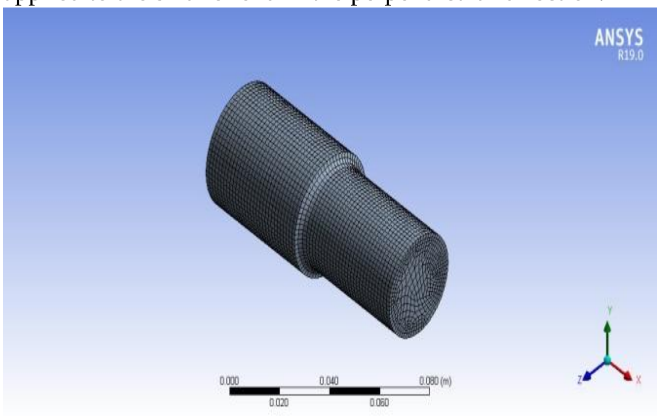

Fig. 3 Meshed model of shoulder shaft

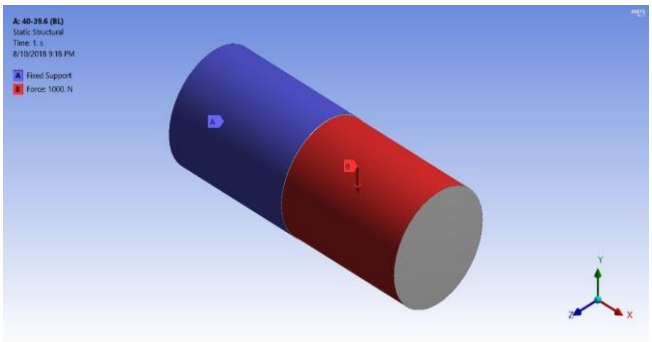

Fig. 4 Loading and boundary conditions

The results of the finite element analysis are presented and compared for shoulder filleted shaft. Total seven different models are prepared, analyze and simulated.

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Figure 5 to figure 11 shows various FEA results of a shaft with shoulder fillet under bending loading. Here, for analysis purpose, the applied load is considered constant as 1000 N for all iterations with different D/d ratios.

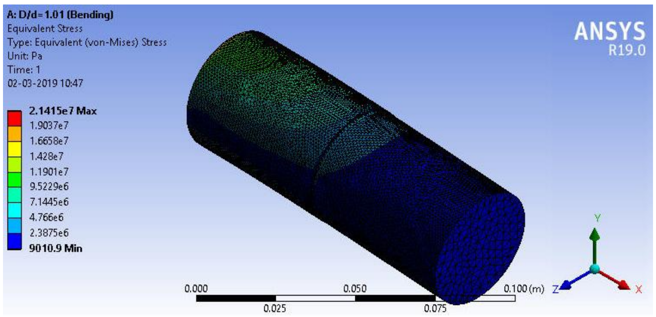

Fig. 5 Equivalent (von Mises) stress for D/d = 1.01 (D = 40 mm and d = 39.6 mm)

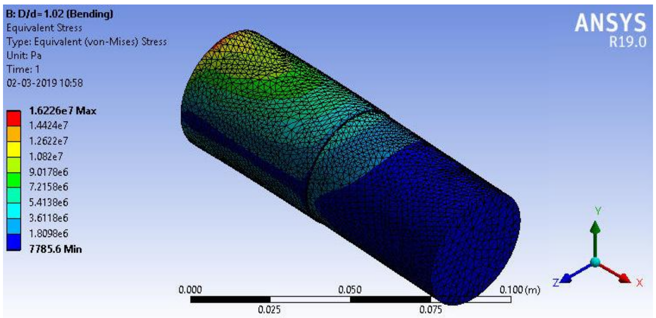

Fig. 6 Equivalent (von Mises) stress for D/d = 1.02 (D = 40 mm and d = 39.21 mm)

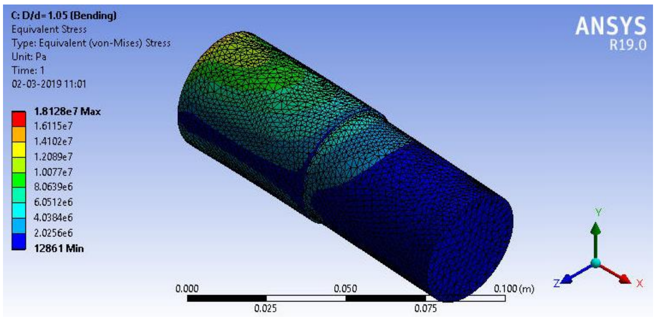

Fig. 7 Equivalent (von Mises) stress for D/d = 1.05 (D = 40 mm and d = 38.095 mm)

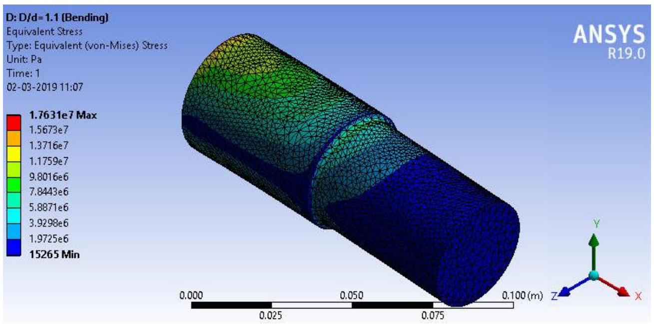

Fig. 8 Equivalent (von Mises) stress for D/d = 1.1 (D = 40 mm and d = 36.36 mm)

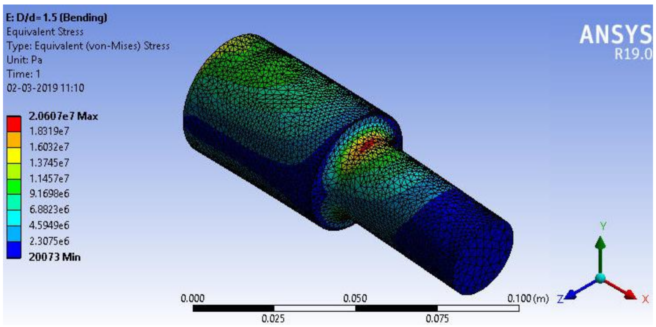

Fig. 9 Equivalent (von Mises) stress for D/d = 1.5 (D = 40 mm and d = 26.67 mm)

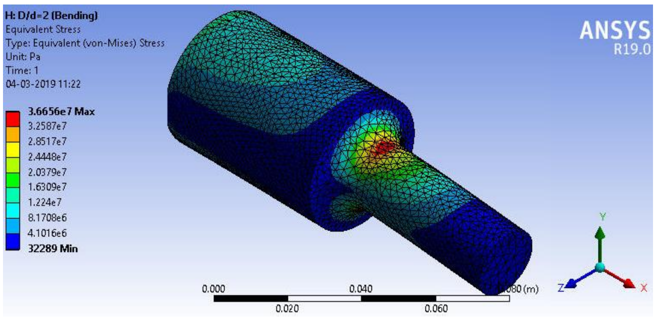

Fig. 10 Equivalent (von Mises) stress for D/d = 2 (D = 40 mm and d = 20 mm)

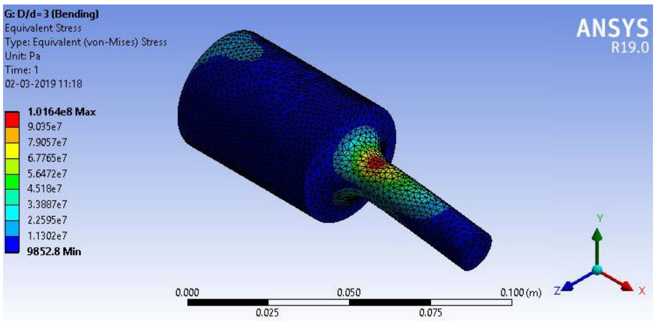

Fig. 11 Equivalent (von Mises) stress for D/d = 3 (D = 40 mm and d = 13.33 mm)

From the above FEA results, equivalent von Mises stresses of shoulder filleted shaft are identified and utilized them for determination of stress concentration factors (SCFs). All the results of FEA for SCFs are tabulated in the Table 2, Table 3 and Table 4; and its comparison are made with SCFs obtained from modified equations presented by Bhavesh Patel et al. [5].

Table 2 Comparison of SCFs obtained from FEA and theoretical SCFs obtained from the modified Pilkey's equation [5] under bending loading

D (mm)	d (mm)	D/d	Fillet height h (mm)	Fillet radius r (mm)	Load P (N)	M.I (mm^4)	Nominal stress (MPa)	Equivalent (von Mises) stress (MPa)	SCF (K_t) based on equivalent stress	Theoretical SCF (K_t)
40	39.6	1.01	0.20	0.20	1000	120651	9.02604	21.415	2.3726	2
40	39.21	1.02	0.40	0.40	1000	115968	9.29806	16.226	1.7451	1.974
40	38.09	1.05	0.95	0.95	1000	103329	10.1386	18.128	1.7880	1.91
40	36.36	1.10	1.82	1.82	1000	85752	11.6603	17.631	1.5120	1.814
40	26.67	1.50	6.67	6.67	1000	24822	29.547	20.607	0.6974	1.409
40	20	2.00	10.00	10.00	1000	7850	70.0637	36.656	0.5232	1.229
40	13.33	3.00	13.34	13.34	1000	1549	236.642	101.64	0.4295	1.114

Table 3 Comparison of SCFs obtained from FEA results and theoretical SCFs obtained from the modified Roark's equation [5] under bending loading

D (mm)	d (mm)	D/d	Fillet height h (mm)	Fillet radius r (mm)	Load P (N)	M.I (mm^4)	Nominal stress (MPa)	Equivalent (von Mises) stress (MPa)	SCF (K_t) based on equivalent stress	Theoretical SCF (K_t)
40	39.6	1.01	0.20	0.20	1000	120651	9.02604	21.415	2.3726	1.965
40	39.21	1.02	0.40	0.40	1000	115968	9.29806	16.226	1.7451	1.942
40	38.09	1.05	0.95	0.95	1000	103329	10.1386	18.128	1.7880	1.879
40	36.36	1.10	1.82	1.82	1000	85752	11.6603	17.631	1.5120	1.785
40	26.67	1.50	6.67	6.67	1000	24822	29.547	20.607	0.6974	1.386
40	20	2.00	10.00	10.00	1000	7850	70.0637	36.656	0.5232	1.212
40	13.33	3.00	13.34	13.34	1000	1549	236.642	101.64	0.4295	1.101

Table 4 Comparison of SCFs obtained from FEA results and theoretical SCFs obtained from the modified S.M. Tipton's equation [5] under bending loading

D (mm)	d (mm)	D/d	Fillet height h (mm)	Fillet radius r (mm)	Load P (N)	M.I (mm^4)	Nominal stress (MPa)	Equivalent (von Mises) stress (MPa)	SCF (K_t) based on equivalent Stress	Theoretical SCF (K_t)
40	39.6	1.01	0.20	0.20	1000	120651	9.02604	21.415	2.3726	1.968
40	39.21	1.02	0.40	0.40	1000	115968	9.29806	16.226	1.7451	1.942
40	38.09	1.05	0.95	0.95	1000	103329	10.1386	18.128	1.7880	1.867
40	36.36	1.10	1.82	1.82	1000	85752	11.6603	17.631	1.5120	1.756
40	26.67	1.50	6.67	6.67	1000	24822	29.547	20.607	0.6974	1.305
40	20	2.00	10.00	10.00	1000	7850	70.0637	36.656	0.5232	1.105
40	13.33	3.00	13.34	13.34	1000	1549	236.642	101.64	0.4295	0.961

IV. RESULTS AND DISCUSSION

There are no such techniques exist by which one can select suitable fillet radius for shoulder shafts which will give minimum stress concentration factor for a given geometry. Therefore, an effort is made to develop a criterion for selection of fillet radius for shoulder filleted shaft which will give least SCF. Modified equations for the SCFs with different D/d ratios, r/d and h/r range presented by Bhavesh Patel et al. [5] for bending loading condition are studied and their results of SCFs are compared with results obtained from FEA. ANSYS workbench 19.0 is used for FEA. Figure 12 to 14 shows the comparison of SCF obtained from FEA results and theoretical results as presented in the tabulated form in Table 2 to 4 for the modified Pilkey's, Roark's and S M Tipton equations.

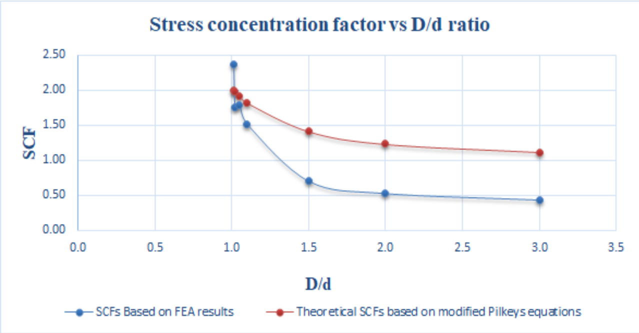

Fig. 12 D/d vs. SCF (From the results of modified Pilkey's equation)

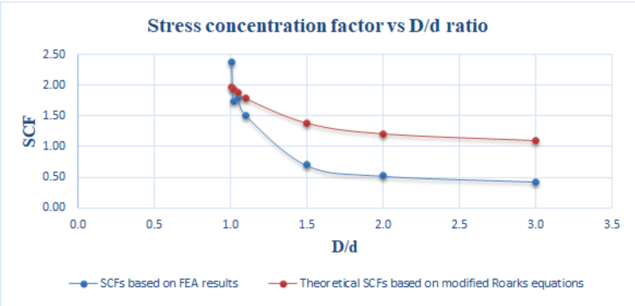

Fig. 13 D/d vs. SCF (From the results of modified Roark's equation)

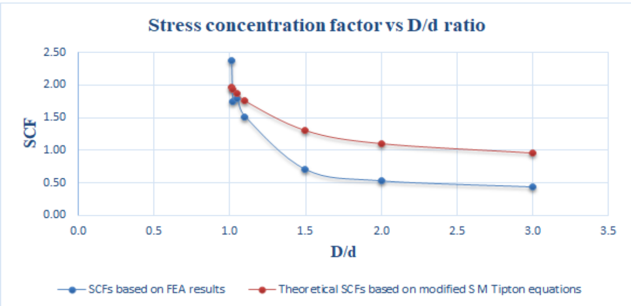

Fig. 14 D/d vs. SCF (From the results of modified S. M. Tipton equation)

V.CONCLUSIONS

Following conclusions are made based on the comparison between the results of SCF obtained from modified equations developed by Bhavesh Patel [5] and SCFs obtained from FEA for shoulder filleted shaft (round bar) under bending loading condition.

- From the figure 12 to 14, it is observed that for lower D/d ratios (D/d = 1.01, 1.02, 1.05, 1.1), theoretical results of SCFs are very nearer to the FEA results of the SCFs.
- It is also observed that for higher D/d ratios (D/d = 1.5, 2 and 3) there are much variations in the results of theoretical SCFs (based on modified Pilkey's, Roark's and S. M. Tipton equations) and SCFs obtained from FEA. These may possible if D/d ratio increased, in theoretical results of SCFs follow the same pattern of iterations but FEA iterations may not follow the same pattern.
- Also, it is perceived that the SCFs obtained by FEA and SCFs based on modified equations is decreased with increasing the D/d ratios.
- Obtained results are graphically presented and it can be utilized by design engineers based on desired D/d ratio for designing the round bar or shaft working under bending loading.

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DISCLOSURE STATEMENT

The authors declare that there is no conflict of interest.

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AUTHORS FROFILE

Hiren Prajapati did his graduation in Mechanical Engineering from GEC Modasa, and post-graduation (M. Tech.) with specialization in Advanced Manufacturing Techniques (AMT) from U V Patel College of Engineering, Ganpat University. He is presently working as an Assistant Professor in the Mechanical Engineering Department of Government Engineering College Modasa, Gujarat, India. He has guided ten M. Tech students in their dissertation work. At present, he is doing Ph. D in the area of Machine Design (Stress concentration factor) from Ganpat University. There are total of 14 research papers published/presented in National and International conferences and International referred Journals. He is an author of the book titled "Manufacturing Processes – II" of V-Sem. Mechanical Engineering and "Dynamics of Machinery (DOM)" of VI- Sem. Mechanical Engineering published by Books India Publication for GTU students.

Dr. Bhavesh P. Patel completed his graduation in Mechanical Engineering from S. V. National Institute of Technology, Surat, Gujarat, India in the year 2002 and post-graduation (ME) with specialization in CAD/CAM from L. D. College of Engineering, Ahmedabad, Gujarat, India in the year 2006 with a good academic record. He has completed his Ph. D. from JJT University, Jhunjhunu, Rajasthan in January 2013. He has industrial experience more than six years and eleven years' experience in the field of academic. He is presently working as an Associate Professor in Mechanical Engineering Department of U. V. Patel College of Engineering, Ganpat University, Kherva, Dist. Mehsana, Gujarat, India. Also, he is a Ph. D course coordinator of Faculty of Engineering and Technology, Ganpat University. He has guided 14 M. Tech. students in their dissertation. There are 21 research papers published in various International Journals in the field of design and dynamics and 29 research papers presented in National and International conferences and published in their proceedings. He is the author of a book titled "Manufacturing Processes –II" of V-Sem. Mechanical Engineering and "Dynamics of Machinery (DOM)" of VI- Sem. Mechanical Engineering published by Books India Publication for GTU students.