Fatigue Analysis of Motor Cycle Alloy Wheel

Navuri Karteek, B. Satya Krishna, B. Kiran Babu and Beulah Mani Paleti

Abstract**: *Wheels in the motor cycle play major role to carry the load. Generally spokes are subjected to fatigue loads. So it is necessary to study the response of the wheel under fatigue loads. In the present work different shapes of the wheel spokes are modeled and analyzed their response for fatigue loads by using finite element simulation software ANSYS workbench. The shape of the spokes used for the alloy wheels are curved, inclined, Y shape, Triangle shape, V Shape and H shape with constant volume. The material parametric study is also performed on the different cases of the spokes. The materials used are Structural steel, Aluminum alloy, Carbon steel and magnesium Alloy. The results show that the carbon steel shown better results when compared to remaining materials in view of life, damage and factor of safety. V curved with pad shape possess high life, high factor of safety and low damage factor compared with the remaining models.***

Index Terms: safety factor, Life, Damage, Fatigue Analysis, Young's Modulus (E), Density (ρ), Poisson's Ratio (μ), Tensile Strength (σ_{yt}), Structural Steel (SS), Aluminum(Al), Magnesium (Mg), Carbon Steel (CS).

I. INTRODUCTION

Alloy is a special material which combination of more than one metal. To increase the required physical and mechanical properties other metals will be added in different proportions. In Automobile applications, now a day's most of the wheels are replaced by alloys wheels due to their good properties. These have high strength to weight ratio compared to metals. These exhibits good cosmetic appearance and opposes the chances of corrosions. They have good heat conduction capabilities compared to pure metals. Generally magnesium and aluminum alloys are used to fabricate the wheels. Fatigue loads are crucial in designing the structure. Failure under fatigue loads occur at the value less than the yield strength of the material due to the repeated loads or cyclic loads. It is fact most of the mechanical parts are failed due to the fatigue loads only. Initially Fatigue failure is recognized in the early 1800's in Europe. With increase of machines, more number of fatigue failures was noted. Before going to design a structural component, knowing fatigue life is a greater importance as a result of the using high-strength materials and desire for higher performance from these materials. Fatigue life of a particular component is calculated by a S-N curve of particular used material.

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For calculating the mean stress effect there are four curves, i.e., Soderberg, Goodman, Gerber and Morrow. For ductile materials Soderberg empirical curve and for brittle materials Goodman empirical formulae are used. Soderberg Empirical formula is widely used due to the use of yield strength of the material. The remaining empirical formulae used ultimate strength of the material. S-N Curves are generally generated from the practical experiments. Alternating stress vs. number of cycles (S-N) curve consists of a stress values related to a number of cycles. With increasing the number of cycles the value of alternating stress decreases and keeps constant at endurance limit. So, in fatigue analysis for defining the fatigue life of the component endurance limit is used. Alternating stress can be defined for a mean stress or Stress-Ratio. The Stress-Ratio of the curve indicates the multiple S-N curves for the particular material with ratio -1(fully reversed), 0(zero based), -0.5 and 0.5. The mean stress and stress ratio characteristics are listed in the table 1 and 2.

$$\text{Mean stress} = (\sigma_{max} + \sigma_{min})/2.$$

Table 1. Mean Stress

σ_{max}	σ_{min}	Mean Stress	
1	-1	0	Fully Reversed
1	0	0.5	Zero Based

$$\text{Stress Ratio} = \sigma_{min}/\ \sigma_{max}$$

Table 2. Stress Ratio

σ_{max}	σ_{min}	Stress Ratio	
1	-1	-1	Fully Reversed
1	0	0	Zero Based
1	0.5	0.5	
1	-0.5	-0.5	

Xiu-Yang Fang [1] performed fatigue test experimentally on wheel rim under various temperature conditions. The effects of the temperature on the failure mechanism were noted. Huanyu Zhao [2] performed fatigue analysis on the crawler chain link of the excavator. The results show that fatigue crack initiates on the surface and the S_N curve of the material of the part is estimated and calculate the fatigue life of the crawler chain link of the excavator. Vahid Mortezavi [3] presented a novel approach to identify the material damage by a damping parameters using impulse excitation technique. P. Corigliano [4] performed study on the S355 butt welded specimens. The values of fatigue life by static tensile test and of the Energy Approach method were compared with the traditional fatigue life value.The obtained values are nearer to the experimental values of fatigue life.

BimalBastin [5] designed a wheel and analysed in Finite element analysis software Abacus with aluminium alloy, steel alloy, magnesium alloy and forged steel. Compared the Stresses and deflections for different materials and conclude that steel alloy has better stiffness and more feasible to use than that of aluminium alloy. SK. Johnshaw [6] analysed a magnesium alloy air craft wheel hub with radial load conditions and noted von-Misses stress, fatigue life and deformations are increases and the safety factor decreases with increasing of fatigue load. Worawat Puangchaum [7] presented a technique study on design and optimization of alloy wheels under the fatigue load condition. The results show that the rim width significantly displayed higher sensitivity than the thickness of the allow wheel. Gamachisa Mitiku Tadesse [8] conducted FEM analysis on four wheeler rim and by using aluminium alloy weight of the wheel is reduced. 60% of the weight is reduced by using aluminium alloy and with life times of the wheel is improved. Eswara kumar A. [9] conducted fatigue analysis on the pressure vessels with varying stiffeners. The results shows that rectangular stiffener design having good fatigue properties and concluded this design recommended for fatigue load applications. Eswara Kumar A. [10] conducted static analysis and modal analysis on the 2 wheeler rim with various spoke designs. The results shows curved spoke design has enough to withstand the stresses produced in it and having natural frequency. Anil kumar [11] performs fatigue analysis on the aluminium alloy wheel under different RPM's in FEA software. The results obtained from the fatigue analysis are compared with traditional techniques of experimental methods.

II. PROBLEM STATEMENT

To study the life, damage and safety factor of the various motorcycle alloy wheel designs subjected to fatigue loads by changing the number of spokes with Structural steel, Aluminum Alloy and Carbon Steel. The different types of models considered are V Shape, Curved, Inclined, Y shape, Triangular, H Shape, V shape with pad and V curved shape with pad. The basic dimensions are taken from the paper.

III. METHODOLOGY

Motor cycle alloy wheel with different spoke shapes are analyzed in the finite element analysis software ANSYS Workbench. Static structural module with fatigue tool is used for the analysis which is shown in the below Figure 1.

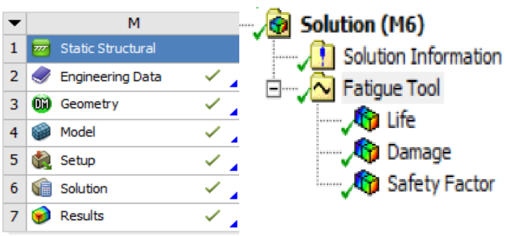


Figure 1. Schematic view of the fatigue analysis in ANSYS Workbench

There are two methods to find the life of the given structure.

1) Stress life Analysis (High cycle fatigue)
2) Strain Life Analysis (Low Cycle Fatigue).

Stress life analysis is chosen, if working stress of the given structure is less than the elastic limit of the material. And Strain life analysis is chosen, if working stress of the given structure is more than the elastic limit of the material indicates structure is going to failure within short time.

In this case, the working stress of the structure is less than elastic limit. So the method of finding fatigue life is chosen as stress life analysis. Mean stress chosen as Alternating stress with σ_m=0 (fully reversed) and alternating stress ratio type (-1) has been taken for respective material S-N curves for calculating the fatigue life.

Mean stress = (σ_{max}+ σ_{min})/2.

Ratio = -1, indicates minimum stress starts from -1 and end with +1 which is equal to the fully reversed loading type. Here the loading scale ratio is ‘1’.Soderberg mean stress theory has been taken for this problem.

$$\frac{\sigma_m}{\sigma_{yt}} + \frac{\sigma_a}{\sigma_e} = 1$$

Semi Log interpolation method has been selected and fully reversed load is shown in the below Figure 2.

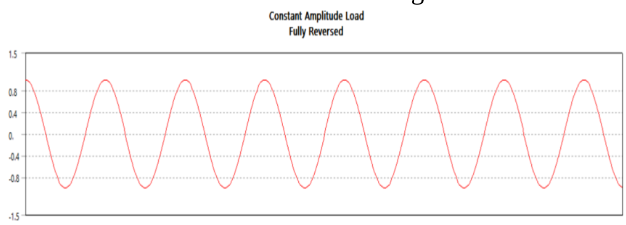
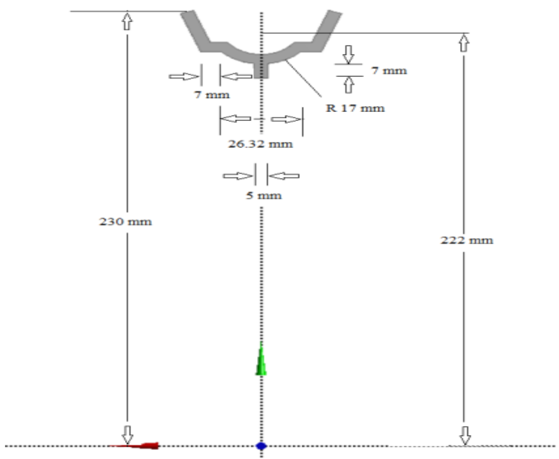


Figure 2. Fully Reversed load

IV. PROBLEM MODELING

A. Geometry

Motor cycle alloy wheel rim and hub along with different arrangements of the spokes are modeled on ANSYS workbench. The dimensions of the alloy wheel rim and hub are taken from [10] and Figure 3 illustrates the models created. The cross section of the wheel rim is also shown in Fig. 3(a).



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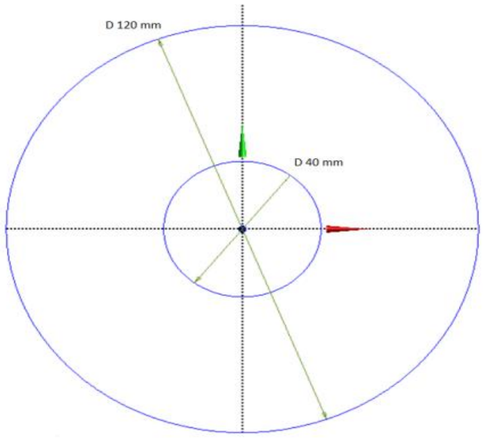

Figure 3. (a) Model of the wheel rim (b) Model of the wheel hub

Keeping the dimensions of the rim and hub fixed spokes of different shapes are arranged in various configurations as illustrated in the Fig. 4. The various configurations of spokes are so chosen such that the total volume of material in the spokes is the same in all models. This enables the study of effect of distribution of mass between the rim and hub independent of the total mass for a particular material under study.

V Shape with 3 and 5 Spokes

Inclined Shape with 3 and 5 Spokes

Y Shape with 3 and 5 Spokes

Triangle Shape with 3 and 5 Spokes

Curved Shaped with 3 and 5 Spokes

H Shaped with 3 and 5 Spokes

V Shape with pad with 3 and 5 Spokes

V curved shape with pad with 3 and 5 Spokes

Figure.4 Different spoke shapes of the alloy wheel

B. Meshing

It is the process of converting geometrical entities in to finite element entities [12]. For mesh convergence proper fine meshing was done. Eight node hexahedron and 5node tetrahedron elements are used for meshing operation with a size of 10 mm. Typical meshing of V shapes spoke alloy wheel is shown in the Figure 5.

Figure 5. Meshing for V curved shape with pad with 3 and 5 spokes

C. Loads and Boundary Conditions

Fixed support is given to the center of the hub where it is connected to the suspension system [10]. A Pressure of magnitude 6 MPa was applied on the outer surface of the wheel rim with fully reverse effect. It must be noted the actual pressure a wheel is subjected to in practice is different from the one applied in this study. This is acceptable since our aim is to study the general characteristic behavior of the alloy wheels subjected to different loading conditions. Figure 6 shows the Boundary conditions and loads applied on the V curved shape with PAD alloy wheel with 5 spokes.

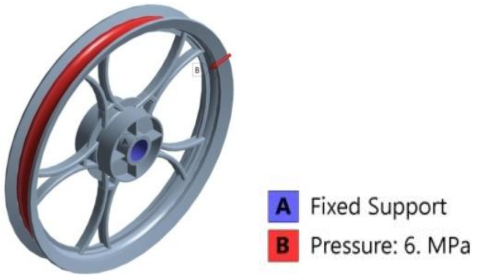

Figure 6. Schematic diagrams of loads and boundary conditions

D. Material:

The fatigue analysis is performed with three commonly used materials in the manufacture of commercial wheels viz. structural steel, aluminum alloy and magnesium alloy. Fourth material carbon steel is also used in the analysis for comparison purpose. The composition of the four materials is given in table 3.The mechanical properties of these four materials are listed in the Table 4.

Table 3: Composition of the wheel materials

S. No	Material Name	Elements
1	Structural Steel	Manganese, silicon, Phosphorus and Carbon.
2	Aluminum Alloy	Copper, Magnesium, Manganese, Silicon, Tin and Zinc.
3	Magnesium Alloy	Aluminum, Zinc, Manganese, Silicon, Copper and Zirconium
4	Carbon Steel	Carbon, Copper, Iron, Manganese, Phosphorous, Silicon and Sulfur

Table 4. Mechanical properties of the wheel materials

	Structural Steel	Aluminum Alloy	Magnesium Alloy	Carbon Steel
E (Mpa)	200000	71000	45000	96000
ρ (kg\m3)	7850	2770	1800	7300
μ	0.3	0.33	0.35	0.3
σ_{yt} (Mpa)	250	280	193	260

E. Fatigue Property (S-N curve)

Alternating stress vs. number of cycles (S-N) curve is a fatigue property for a specific material which is used in the time of fatigue analysis. S-N curve consists of total cyclic stress (S) on y-axis and number of cycles to failure on x-axis in logarithmic scale. In the S-N curve the fatigue life reduces with increasing in total cyclic stress. For ferrous metals S-N curve becomes asymptotic at 10^6cycles, represents endurance limit, but curve slopes gradually even after 10^6 cycles for non-ferrous metals. The S-N curve for the structural steel, aluminum alloy, magnesium alloy and carbon steel are taken from the simulation software and research article [16] and they are shown in the below figures.

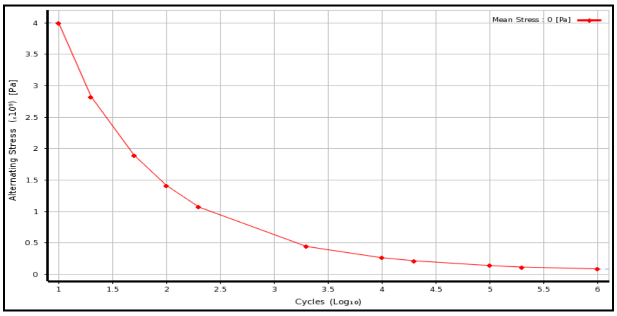

Figure 7. S-Ncurve for structural steel

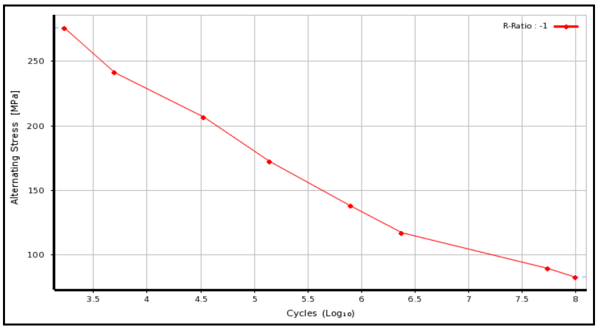

Figure 8. S-Ncurve for Aluminium Alloy

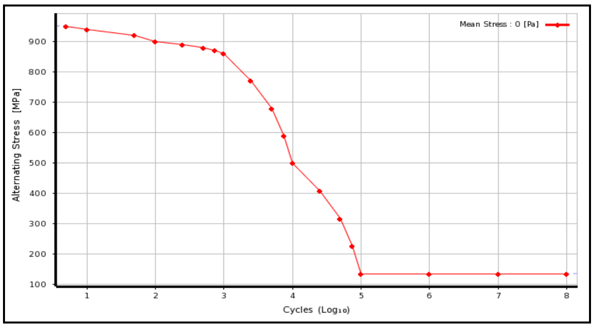

Figure 9. S-Ncurve for Magnesium Alloy

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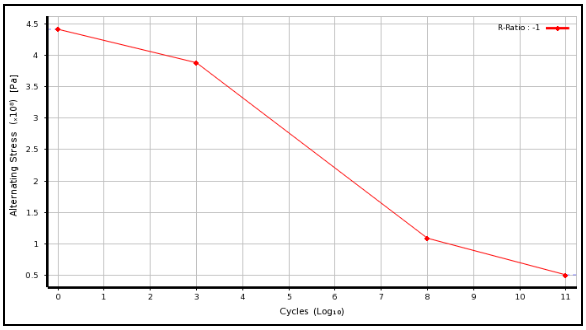

Figure 10. S-Ncurve for Carbon steel

V. Fatigue Results and Discussion

A. Life

Fatigue life is the obtainable life for the given fatigue analysis. Fatigue life can be over the individual part or assembly. In this problem the loading is constant amplitude, it indicates number of cycles until the part will fail against cyclic loading. The contour image of life of V curved with PAD shape with 3 and 5 spoke contours are shown in the Figure 11.

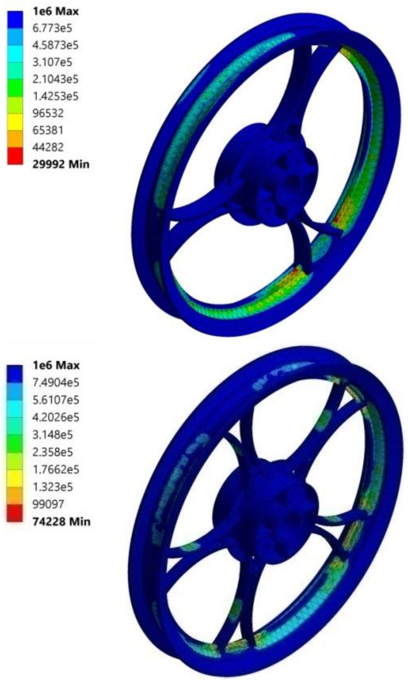

Figure 11. Life of the V-shape alloy wheel with 3 & 5 spokes

The life of the different spoke shapes of the alloy wheel with different materials are shown in the below Table.

Table 5. Life of Alloy Wheel with Structural Steel

Shape	Life (Cycles)	
	3 Spoke	5 Spoke
V shape	38104	58986
Curved	18459	31083
Inclined	17834	26585
Y shape	9896	30511
Triangle	15962	36639
H Shape	10254	13655
V with PAD	22337	56689
V curved with PAD	29992	74228

Table 6. Life of Alloy Wheel with Aluminum Alloy

Shape	Life (Cycles)	
	3 Spoke	5 Spoke
V shape	90199	209940
Curved	16707	59722
Inclined	13766	48425
Y shape	2503	58997
Triangle	9509	79403
H Shape	2489.2	4694.3
V with PAD	30489	216040
V curved with PAD	54889	416600

Table 7. Life of Alloy Wheel with Magnesium Alloy

Shape	Life (Cycles)	
	3 Spoke	5 Spoke
V shape	86028	90851
Curved	76600	83292
Inclined	75569	82023
Y shape	63410	83243
Triangle	73833	84948
H Shape	62824	68875
V with PAD	79256	91278
V curved with PAD	82663	95409

Table 8. Life of Alloy Wheel with Carbon Steel

Shape	Life (Cycles)	
	3 Spoke	5 Spoke
V shape	465030 0	1091100 0
Curved	105080 0	3125300
Inclined	952100	2303400
Y shape	173280	3013900
Triangle	693110	4307900
H Shape	195340	443440
V with PAD	164000 0	1009700 0
V curved with PAD	291470 0	1708700 0

From the above tables it was observed that, life of the 5-spokes design is better than the 3-spokes design in all proposed cases.

With reference to the shape of the spokes, V curved with PAD spoke wheels exhibit better performance, irrespective of the number of spokes and material of the wheel.

With reference to the materials, wheels of carbon steel are shown to give maximum fatigue life when compared to other materials irrespective of the number of spokes and shape of the spokes. Inspite of this observation carbon steel is not commonly used in manufacture of alloy wheels in commercial vehicles. This is due to its higher density leading to heavy mass of the vehicles which in turn increases the fuel consumption of the vehicle. In addition the carbon steel is subjected to corrosion when exposed to harsh environments for long periods. With regards to the remaining three materials which are in use aluminum is observed to have the maximum fatigue life followed by magnesium alloy and lastly structural steel.It can also be observed that the maximum improvement in the life with an increase in the number of spokes is maximum when using an aluminum alloy wheel and minimum when using magnesium alloy wheels irrespective of the shape of the spokes. The improvement obtained with structural steel wheels is better than magnesium wheels but less than that obtained with aluminum. For instance with V-shaped aluminum spoke wheel the improvement is close to 100%, that for V-shaped magnesium spoke wheel is close to 11% and whereas for a structural steel spoke wheel is close to 50%. For all the other shapes a similar trend is observed.

B. Damage

Fatigue Damage indicates the design life or available life. The design life is assigned to 10^6 cycles. The damage value greater than 1 indicates failure before infinite design life. The damage of the one of the shape i.e., V curved with PAD shape with 3 and 5 spoke alloy contours are shown in the Figure 12.

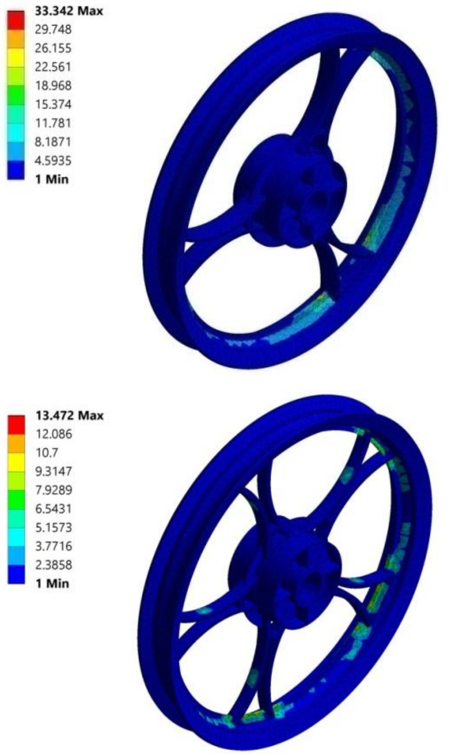

Figure 12. Damage of the 3 and 5 spoke of the V shape alloy

Table 9. Damage of Alloy Wheel with Structural Steel

Shape	Damage	
	Spoke	Spoke
V shape	26.244	16.953
Curved	54.173	32.171
Inclined	56.073	37.616
Y shape	101.05	32.775
Triangle	62.651	27.293
H Shape	97.523	73.232
V with PAD	44.768	17.64
curved with PAD	33.342	13.472

The damage of the different spoke shapes of the alloy wheel with different materials are shown in the below figures.

Table 10. Damage of Alloy Wheel with Aluminum Alloy

Shape	Damage	
	3 Spoke	5 Spoke
V shape	11.087	4.7633
Curved	59.854	16.744
Inclined	72.643	20.65
Y shape	399.52	16.95
Triangle	105.16	12.594
H Shape	401.74	213.03
V with PAD	32.799	4.6288
V curved with PAD	18.219	2.4004

Table 11. Damage of Alloy Wheel with Magnesium Alloy

Shape	Damage	
	3 Spoke	5 Spoke
V shape	11.624	11.007
Curved	13.055	12.006
Inclined	13.233	12.192
Y shape	15.77	12.013
Triangle	13.544	11.772
H Shape	15.918	14.519
V with PAD	12.617	10.956
V curved with PAD	12.097	10.481

Table 12. Damage of Alloy Wheel with Carbon Steel

Shape	Damage	
	3 Spoke	5 Spoke
V shape	0.21504	0.09165
Curved	0.95165	0.31997
Inclined	1.0503	0.43414
Y shape	5.7711	0.33179
Triangle	1.4428	0.23213
H Shape	5.1194	2.2551

V with PAD	0.60976	0.099039
V curved with PAD	0.34309	0.058524

From the table it was observed that, 5-spokes design having the less damage when compared with 3- spokes design. In view of the shapes, V Curved with PAD shape having the lesser damage among the shapes considered. In material point of view, carbon steel having the lower damage value when compared to remaining materials.

C. Fatigue Safety Factor

Fatigue safety factor is a factor of safety for a design life with respect to a fatigue failure. The maximum fatigue factor of safety is 15. Fatigue safety factor less than one indicate failure of the design before it going to reached infinite life. The safety factor of the one of the shape i.e., V curved with PAD shape with 3 and 5 spoke alloy contours are shown in the below Figure 13.

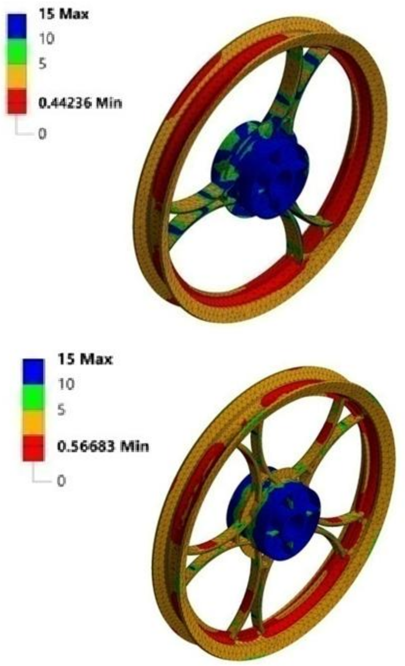

Figure 13. Safety Factor of the 3 and 5 spoke of the V shape alloy

Table 13. Safety Factor of Alloy Wheel with Structural Steel

Shape	Safety Factor	
	3 Spoke	5 Spoke
V shape	0.4696	0.52907
Curved	0.39262	0.44622
Inclined	0.3884	0.42979
Y shape	0.32755	0.4442
Triangle	0.3754	0.46491
H Shape	0.3312	0.35853
V with PAD	0.41287	0.52305
V curved with PAD	0.44236	0.56683

The Safety Factor of the different spoke shapes of the alloy wheel with different materials are shown in the below figures.

Table 14. Safety Factor of Alloy Wheel with Aluminum Alloy

Shape	Safety Factor	
	3 Spoke	5 Spoke
V shape	0.73024	0.81333
Curved	0.60885	0.69234
Inclined	0.59934	0.67454
Y shape	0.50752	0.69127
Triangle	0.58197	0.71808
H Shape	0.50718	0.54947
V with PAD	0.64042	0.81615
V curved with PAD	0.68506	0.88649

Table 15. Safety Factor of Alloy Wheel with Magnesium Alloy

Shape	Safety Factor	
	3 Spoke	5 Spoke
V shape	0.73876	0.81603
Curved	0.61489	0.69952
Inclined	0.60307	0.68231
Y shape	0.51131	0.69886
Triangle	0.58752	0.72292
H Shape	0.50729	0.55007
V with PAD	0.64673	0.82343
V curved with PAD	0.69092	0.90056

Table 16. Safety Factor of Alloy Wheel with Carbon Steel

Shape	Safety Factor	
	3 Spoke	5 Spoke
V shape	1.2026	1.3549
Curved	1.0055	1.1427
Inclined	0.99465	1.1007
Y shape	0.83883	1.1376
Triangle	0.96137	1.1906
H Shape	0.84818	0.91816
V with PAD	1.0573	1.3395
V curved with PAD	1.1328	1.4516

From the above tables, it is noticed that safety factor for 3and 5 spoke alloy with carbon steel is high compared to the remaining materials. All alloy shapes with 5 spokes are having higher safety factor than the 3 spokes. In shape point of view V curved with PAD shape alloy posses better safety factor compared to the remaining shapes.

VI. MASS OF THE ALLOY WHEEL

The mass of the alloy wheel with Structural steel, aluminum alloy, magnesium alloy and carbon steel is listed in the Table 17. Volume represents summation of rim, spokes and hub. This volume is same for all the cases considered.

Volume of the Alloy Wheel = 1.1461e006 mm^3

Mass of the 3 spoke wheel with different materials are listed in the below table 17.

Table 17. Mass of the 3-spoke Alloy wheel

	CS	Al	Mg	SS
V Shape	8.3674	3.175	2.0632	8.9979
Curved	8.3473	3.1674	2.0582	8.9762
Inclined	8.353	3.16396	2.0596	8.9823
Y shape	8.3384	3.164	2.056	8.9666
Triangle	8.3559	3.1707	2.0604	8.9855
H Shape	8.3511	3.1688	2.0592	8.9802
V With pad	8.2414	3.1272	2.0321	8.2414
V Curved With pad	8.3479	3.1717	2.061	8.9883

From above table, it was observed that in all cases magnesium alloy contains less weight and structural steel posses highest weight. Because of the same volume maintained for all shapes, the mass of the each shape is same.

Mass of the 5 spoke wheel with different materials are listed in the below table 18.

Table 18. Mass of the 5-spoke Alloy wheel

	CS	Al	Mg	SS
V Shape	8.3666	3.1747	2.063	8.997
Curved	8.3573	3.1712	2.0607	8.987
Inclined	8.3349	3.1627	2.0552	8.9628
Y shape	8.3391	3.1643	2.0562	8.9674
Triangle	8.3635	3.1736	2.0622	8.9937
H Shape	8.3572	3.1712	2.0607	8.9939
V With pad	8.36	3.1722	2.0614	8.9889
V Curved With pad	8.3479	3.1676	2.0584	8.9768

From the above table, it was observed that magnesium alloy having the less mass and structural steel posses highest mass when compared to remaining materials.

VII. WEIGHT OPTIMIZATION

By reducing the thickness of the spokes, the weight of the V Curved with pad shape is reduced and it is noted that the life, safety factor of the alloy wheel is increased. And at the same time damage of the alloy wheel is reduced. So, weight and fatigue life point of view this design is recommended. The design of the v curved with pad shaped alloy wheel is shown in the below figure.

Figure 14. Optimized design of the V curved with PAD shape

The fatigue life, damage and safety factor of the optimized v curved shape with pad alloy wheel are listed in the table 19.

Table 19. Fatigue results of the optimized wheel design

Material	Life (Cycles)	Damage	Safety Factor
SS	90673	11.029	0.60439
Al Alloy	666560	1.5002	0.94476
Mg Alloy	98206	10.183	0.95921
CS	25251000	0.03960	1.5478

From the table 19, it is observed that carbon steel posses high life and safety factor with low damage. Structural steel posse's low life and safety factor with high damage.Static analysis results i.e., von-mises stresses and total deformation for optimized design of the motor cycle alloy wheel are listed in the Table 20.

Table 20. Static results of the optimized wheel design

Material	Von-Mises Stresses (MPa)	Total Deformation (mm)	Mass (kg)
SS	142.62	0.13039	8.7848
Al Alloy	141.51	0.36667	3.0999
Mg Alloy	140.74	0.5777	2.0144
Carbon Steel	142.62	0.12598	8.1693

From the table 20, it is noticed that magnesium alloy having lesser von-mises stress and carbon steel having high stress value. The total deformation is high in magnesium alloy and low in carbon steel.The volume of the actual and optimized design of the V curved with pad spoke alloy wheel is listed in the table 21.

Table. 21 Volume of the Actual and Optimized design

Design	Volume (mm^3)
Actual Design	1.15E+06
Optimized Design	1.12E+06

From the table 21, it is observed that 2.6 % of the volume reduction is done.

VIII. CONCLUSIONS

The following conclusions are drawn from the present work.
It is concluded that, V curved with PAD shape alloy containing 5 spokes with carbon steel having good fatigue properties when compared to the remaining cases.
In shape point of view in all cases V shaped alloys (V curved with PAD, V shape with PAD and ordinary V Shape) having better fatigue properties compared to the remaining shapes. H shaped alloy in all cases posses worse properties compared to the remaining shapes.
In material point of view, carbon posses good fatigue properties and structural steel possess worse fatigue properties. In contrast, carbon steel having the higher mass.
In spokes point of view, 5 spokes alloys are giving better fatigue results compared to the 3 spoke alloys under uniform volume rate.
In mass point of view, optimized V curved with PAD shape showing less mass compared to all cases and having better fatigue properties.
So it is recommended to use optimized V curved with PAD for better fatigue property and less mass applications.

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