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Optimization Analysis of Automobile Tie Rod using FEA and Experimental Approach

Madhuri B. Thombare[1], Prof P. S. Talmale[2]
ME Student[1], Assistant Professor[2]
Department of Mechanical Engineering
K.C.T.'S Late G.N. Sapkal College of Engineering, Savitribai Phule Pune University, Nasik, India

Abstract:
Tie rods are important part of the suspension system. The primary function of tie rod is to transfer motion. The working of the end of the rod keeps the wheels aligned. As name suggest tie rod ties vehicle's steering arm to steering knuckle. Structural performance of any mechanical component is measured basically in terms of its natural frequency, deformation, stiffness, maximum stress level, fatigue life etc. In case of vehicle suspension system; tie rod is capable of carrying compressive and fluctuating loads. When steering turn the vehicle, tie rod comes under compressive load and when vehicle running on rough road there is fluctuating forces. As there is need of minimizing weight and cost of tie rod, the design space is needed to be considered. Weight reduction will reduce fuel efficiency, efforts to reduce emission & therefore save environment. In order to achieve these targets we have to optimize parameters that affect the structural performance of tie rod. Results obtaining from the FEA are validated by using the experimental results. In case of buckling analysis, the buckling load factor obtained for optimized tie rod from buckling mode and critical buckling load is calculated. Results obtaining from the Finite element analysis are validated by using the theoretical results.

Keywords: Dynamic Analysis, FEA, Fluctuating Forces, Optimization, Tie Rod etc.

I. INTRODUCTION

Tie rod is mechanical component which is used to connect central link to steering knuckle transferring forces to turn wheel in conventional suspension system. And also rack to the steering knuckle in McPherson suspension system [2]. Functionality of suspension system is one of the key parameter in automobile to determine safety and reliability. So it is important that tie rod operates reliably severe working conditions, and this depends on proper design for optimization under such conditions. As shown in Fig. 1. Tie rod is spherical rod with threaded parts having outer and inner ends [2, 4, and 5].

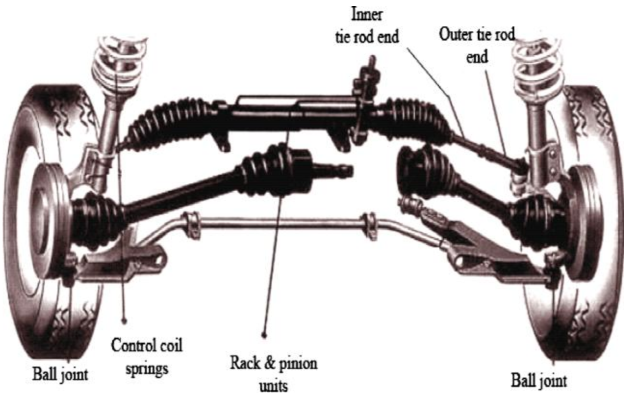


Figure.1. McPherson suspension with rack and pinion.

As tie rod is purely structural member, a robust knowledge of design loads is required to ensure that the part will satisfy its function on the aircraft and automobile. Tie rods are connected to both ends of steering rack which helps to pull and push the front tires as the steering wheel is turns. Force from rack gear to the steering knuckle is transmitted by tie rod to turn the wheels. Tie rod directs the steering of a vehicle and turn the tire. These devices exist on every tire in pairs. Tie rod allows angling and cornering of tire without causing much torque on wheel without affecting the depth of turn. If tie rod fails, there might be chances of an accident due to instability of vehicle. So to check the strength of tie rod is important. If a tie rod end fails completely a driver will lose the ability to steer and control the vehicle. Mostly the load on tie rod is compressive. The stationery car requires comparatively more efforts to turn than moving car. Tie rods are made thicker at the ends so they will not become weaker after threads are cut into it. After threading the ends may passed through shackles or drilled holes, and then it is retained by nuts which are screwed on the ends. The point of loading may be altered if the ends are threaded right hand and left hand. Erratic steering and major tire wear can be caused by a worn tie rod. There inner and outer ends in a tie rod. Inner end connects to an adjusting sleeve which keeps length of tie rod adjustable. This adjustment is helps to do set angle of vehicle's alignment. Worn tie rod can create wandering so the suspension system and steering of car should be checked periodically. As the steering wheel of car is connected to the steering gear, which helps the steering wheel turn the wheels. Tie rod end ensure the alignment of wheels and also provides adjustment for wheel alignment to prevent tires wearing on inner and outer edges.

II. LITERATURE REVIEW

Shripad Mungi [1] this paper emphasizes on optimistic way of designing the tie rod that ultimately yields the effective and efficient performance of Tie rod. They studied various types of sections proposed for design of tie rod. An objective of their research is a weight optimization. Here they proposed the optimized design of tie rod that has a minimum weight and maximum critical buckling load carrying capacity. This paper in future scope suggested that, completely hollow sections can be suitable for tie rod design. But for actual OEM, with the availability of good set up and for large scale manufacturing, full hollow shaft can be manufactured which can further reduce the weight. Mr. P. R. Vithalkar [2] this paper focuses on the study of buckling load on the tie rod of steering system that undergoes an axial compression. Because of the external factors like road condition, different driving situations, different road adhesion, traffic conditions, vibrations and sudden jerks are sets up in tie rod. Tie rod generally buckle under the action of compressive force due to the large ratio of tie rod length to its radius of gyration. When it becomes worn out, steering will become more difficult and the vehicle will also typically be pulling or dragging to either side. Thus in this project they analyze tie rod to improve the mass and buckling load of tie rod and to find out maximum deformation and stress. They conducted survey amongst the buses and examine the causes of failure and design and analysis to recommend best possible alternatives of Tie Rod with the aid of advanced design tools like CAD. Tie Rod failure is one of the major problems facing for MSRTC workshop supervisor. Mr. P M Chavan, Prof. MM Patnaik [3] studied buckling strength and compared performance of buckling for Tie rod for different materials. It is found that the mode shape, natural frequency, stiffness value and capacity for buckling load are high for carbon steel. So author concluded and validates that Carbon steel material is suitable for the manufacture of the Tie rod of vehicle as it shows better mechanical properties compared to cast iron and aluminum alloy material. Malge Sangeeta [4] carried out Structural analyses such as Static-Structural, Modal Analysis of a steering rod are done. Static-structural analysis is capable to find out deformation in body in which Von-mises stress are calculated and this state that up to what extent the deformation in the rod occurs, while modal analysis is important in vibration point of view. i.e. Vibrations in body can be calculated up to what frequency the steering rod can sustain the load or Harmonic frequency of the body from above optimization of steering rod can be done. In this paper author have done structural analysis of ford fiesta classic car steering rod to optimize the steering rod with better results than existing one. Purushottam Dumbre [5] Weight reduction of steering knuckle is the objective of this exercise for optimization using FEM software. Steering Knuckle is a non-standard part and subjected to various loads at different conditions. The targeted weight or mass reduction for this exercise is about 5% without compromising on the structural strength. Manik A. Patil [6] concluded that, through distribution of stress and deformation do not exceed the yield strength value and that there was neither damages nor failure of Tie rod, still correctness and accuracy of computing results was depends on the selection of various modeling parameters. Some of the most important aspect such as boundary conditions or correct mesh and type of elements were performing a decisive role in achieving of correct results. According to deformation, stress and natural frequency result tie rod taking for analysis is safe. Nerio Tullini [7] author have given static method for the axial load identification of prismatic structural analysis with known elastic and geometric properties. In three cross sections traversal static force and flexural displacement is measured. For validation author gave numerical and experimental tests. Only for low value of axial force reliable results are got and for others unreliable results are obtained. Suraj Joshi et al [8] author suggested that to minimize the bending failure and probability of shear occurring in engaged thread teeth on a steel tie rod, lower the number of engaged threads than 8. This experiment gives strength to minimize number of turns of thread engagement so it will prevent thread teeth of steel rod from failure.

III. PROBLEM DEFINITION

1. Failure of tie rod may cause instability of vehicle and can cause an accident. So it’s important to check the strength of tie rod. The load coming on tie rod is mostly compressive. The efforts required where car is moving are comparatively less with stationary car. The working strength of the tie rod is that of the product of the allowable working stress and the minimum cross-sectional area.
2. Failure of tie rod may occur due to improper material selection, poor design, fatigue load and wear of tie rod. Also the indications given by the tie rod before failure is very less so it can be risky.
3. The main task in this study is to find the deformation and stresses induced in the Tie rod for various material combinations. The 3-D model is prepared for Tie-rod. Different types of materials are assigned and FEA analysis is carried out. Also hollow section with specific inner diameter is made for optimization of design. Pre-processing is carried out using finite element analysis software named ANSYS. The results are compared with experimental results. From the variables optimized tie rod are selected and evaluated

A. Objectives of the research work

The main Objectives of this research work are:

1. To calculate the critical load for tie rod for finding the stresses and deformation.
2. Study and selection of materials for tie rod and suggest the best material.
3. Design the tie rod for weight optimization considering different inner diameters.
4. Transient dynamic analysis using FEA an experimental approach.
5. Analytical and FEA approach for finding the critical buckling load.

B. Methodology

In this work, finite element analyses were carried out to determine the characteristics of the Tie rod. All methodology principles and theories discussed were utilized to achieve the objectives. The combination of all the analysis results were used to develop virtual model created using FEM tools and the model was updated based on the correlation process. The research methodology flowchart for this project was shown in the below Fig.2

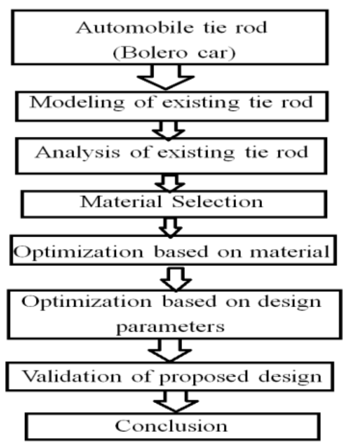


Figure.2. Flow Chart of Methodology Adopted in Research Work

IV. GEOMETRICAL CONFIGURATION

A. CAD Model

Bolero vehicles tie rod having length 405 mm and diameter is 19 mm. Also it is initially solid. The 2-D CAD model of bolero car's tie rod is considered for analysis. Tie rod drawing with dimension is as shown in Fig.3

- **2-D Drafted CAD Model**

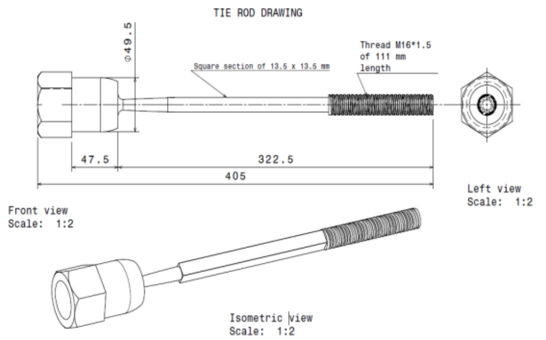


Figure.3. Tie rod drawing

- 3D CatiaV-5 Model

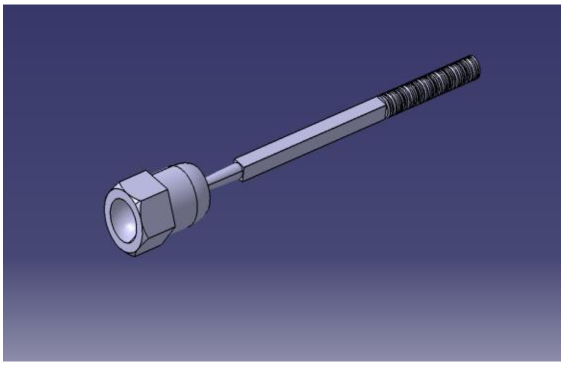


Figure.4. Representation of Tie rod in 3D view

B. Steering movement ratio and Force calculation on Tie Rod

The rack and pinion mechanism is designed to transfer the circular input motion of the pinion into linear output movement of the rack.

1. For a full travel of the rack of 130 mm the pinion has to be rotated 3.0 turns.

Therefore for one turn, the rack travel will be

$$X_0 = \frac{\text{Full travel of the rack}}{\text{No. of rotations of pinion}} \quad (1)$$

= 43.33 mm

2. If considered the pinion to make one revolution, the input steering movement is

$$X_i = 2\pi R \quad (2)$$

= 973.89

Where, R = 155 mm is the radius of the steering wheel.

3. And the output rack movement is

$$X_o = 2\pi r \quad (3)$$

$$43.33 = 2\pi r$$

4. Then, the movement ratio (MR) can be calculated as input movement over output:

$$MR = \frac{X_i}{X_o} \quad (4)$$

= 22.48

Therefore the movement ratio is 22.48: 1

In order to know the output load transmitted to tie rod for given input load we needed to know movement ratio.

5. For an effort of 40 N applied by both hands on the steering wheel and considering no friction, the output load will be:

$$F_o = F_i \times MR \quad (5)$$

= 899.2 N

6. Therefore the load transmitted to the tie rods is 899.2 N.

$$F_{Critical} = 2\,F_o \quad (6)$$

= 1798.4 N = 1800 N

V. OPTIMIZATION ANALYSIS OF TIE ROD FOR DIFFERENT MATERIALS

For this analysis the tie rod with diameter 19 mm and length 405 mm of bolero car is considered. The tie rod is made up of steel material. For material analysis we are considering different materials for FEA.

A. Sample Analysis of Steel Tie Rod

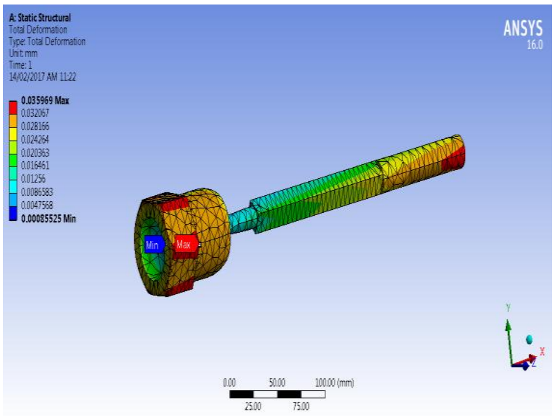


Figure. 5. Result for Deformation

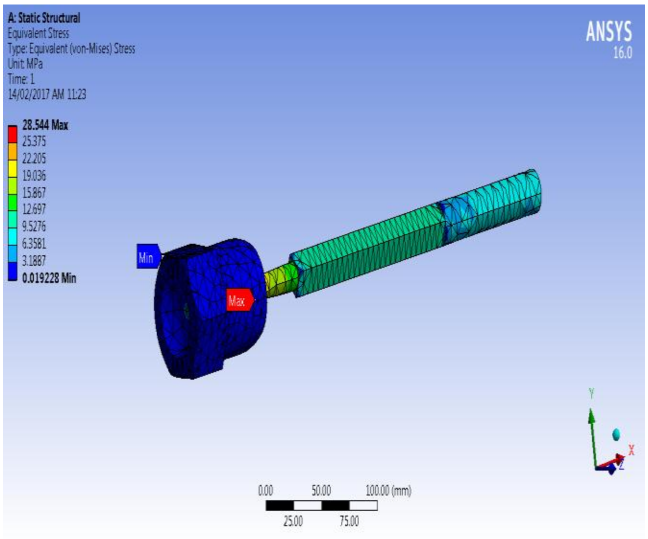


Figure.6. Result for Von-mises stresses for Deformation

Similarly analysis is done for various materials and results are given in below TABLE II

VI. OPTIMIZATION ANALYSIS OF TIE ROD BASED ON DIMENSIONAL PARAMETERS

For optimization analysis we have made a hollow section with parameters as diameter 19 mm and length 405 mm. For this we have taken different inner diameters for analysis. From previous material analysis steel tie rod is selected.

Allowable Stress = Yield / FOS

= 343/3

= 114.33 MPa

Following TABLE I shows different inner diameters for FEA

TABLE. I. VARIOUS ID'S FOR ANALYSIS

Case No.	Hole ID (mm)	Thickness (mm)
Case 1	5	7
Case 2	6	6.5
Case 3	7	6
Case 4	8	5.5
Case 5	9	5
Case 6	10	4.5
Case 7	11	4
Case 8	12	3.5

A. Sample analysis for case 1

Considering CAD model with ID 11 mm is imported in ANSYS workbench for FEA. Following diagrams shows their stress and deformation results.

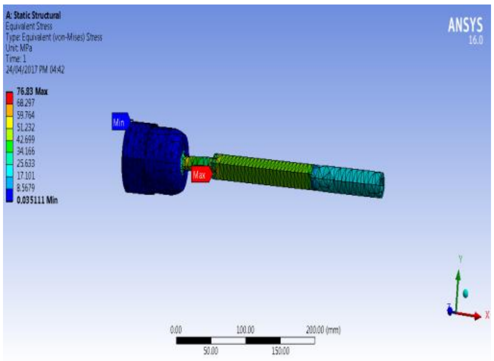


Figure.7. Stress in Tie Rod

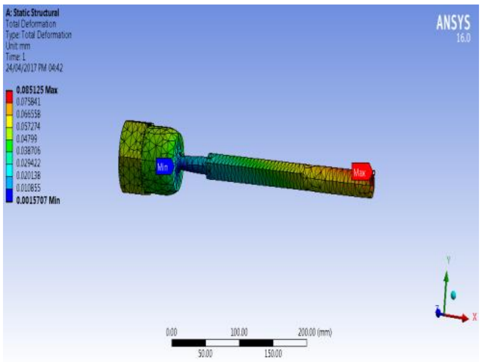


Figure.8. Deformation in Tie Rod

Similarly analysis is done for various ID's and results are given in below TABLE III Tie Rod Considering Circular Section and ID From FEA analysis inner diameter of hollow section 11 mm is found as optimized and circular section is taken for simple design.

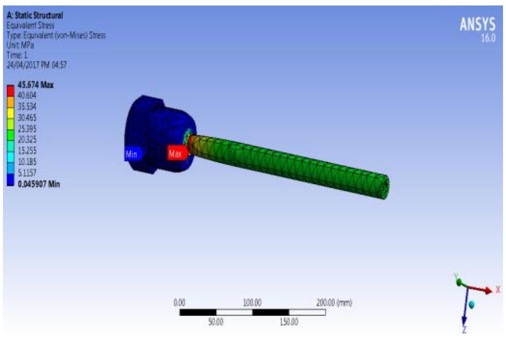


Figure.9. Stress in Tie Rod

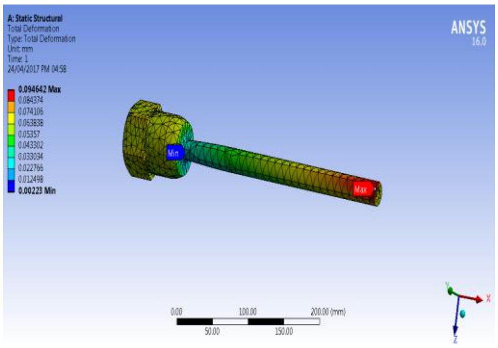


Figure.10. Deformation in Tie Rod

From above results we can see that circular tie rod give 37.50 % less stress and 62.0 % less deformation compared to square rod. But these are well within allowable limit. Weight of circular tie rod is 18.15 % less than square tie rod; and hence selecting the same for testing.

VII. TRANSIENT DYNAMIC ANALYSIS OF FINALLY SELECTED TIE ROD

The technique used to determine dynamic response of a structure under the action of any time dependent load is called transient dynamic analysis or time-history analysis. This analysis is done to determine time varying displacement, strain and forces in structure as it respond to any combination of transient, static, and harmonic load. The time scale of the loading is such that the inertia or damping effect is considered to be important.

A. Following tasks are consisting in procedure of transient analysis

- To build the FEA Model
- To set Solution Controls
- To set Additional Solutions Options
- To apply the loads (Time varying)
- To solve the Analysis
- To review the Results

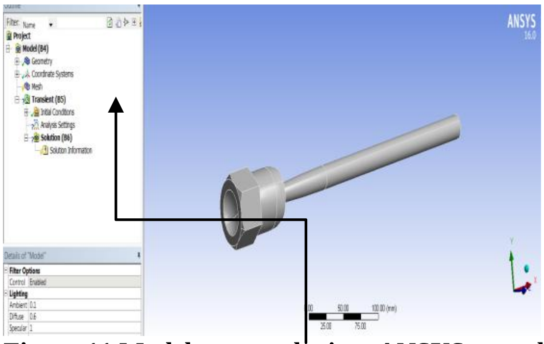


Figure.11.Model opened in ANSYS workbench for dynamic analysis

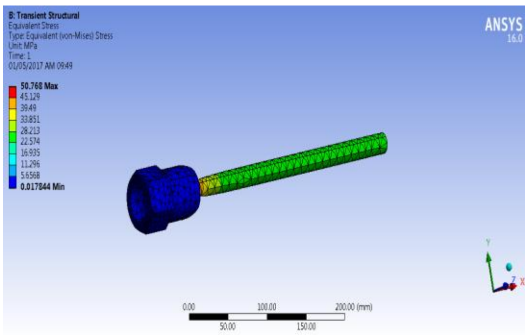


Figure.12. Stress Results

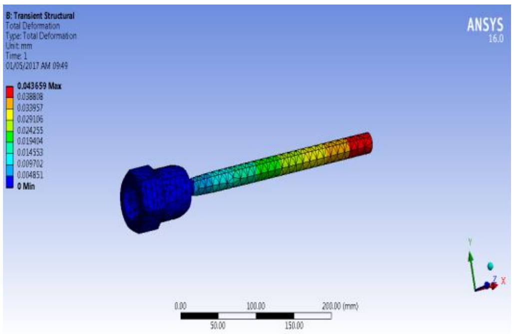


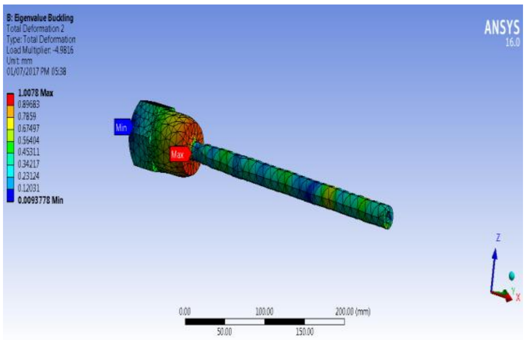
Figure.13. Deformation results

VIII. BUCKLING FE ANALYSIS FOR TIE ROD

Buckling can be observed on geometry of a structure when the radius is smaller than the length. Buckling of a tie rod distortion in its equilibrium position can result in catastrophic failure, which makes bulking an imperative parameter for engineers to consider during design. Basically, buckling occurs in a rod due to instability. This means that a rod does not always buckle at the force that will correspond to the yield stress. Instead it will buckle at what is called the buckling force.

A. FE buckling Analysis Results for Tie Rod

Following Fig 14 shows buckling mode shape of circular tie rod with 11 mm ID.



Figur.14. Buckling Mode Shape for optimized Tie Rod

B. Max. /Critical Buckling Load Pcr for Tie Rod using FE Results

The critical buckling load (the estimated load that induces buckling) as calculated using the methodology of linear buckling analysis is equal to the second mode eigenvalue multiplied by the applied load. Therefore, the Max. /Critical Buckling load for Tie rod is given by

P_{cr} = Load factor X Applied load

The critical buckling load obtained for optimized Tie rod is 89.66 KN.

C. Calculations to find Critical Buckling Load for Tie Rod

A calculation is made using Euler's buckling equation to predict the theoretical linear critical buckling load. Euler's buckling equation for a cylindrical column is shown below [3]

$$P_{cr} = \pi^2 \times E \times I / L^2$$

Where,

P_{cr}= Critical/Max. Load in N.

E =Modulus of Elasticity in N/mm^2.

I = Moment of Inertia in mm^4.

L = Actual length in mm.

Using this formula the critical buckling load for Tie rod is 71.9846 KN

IX. EXPERIMENTAL SET UP AND RESULT

Test trial conducted on actual vehicle quarter model, here the pneumatic excitation is given to tie rod as initiation force (F_{cr}) and readings are taken for deformation in tie rod using gauge. In this setup tie rods one end is connected to the wheel and other to the pneumatic actuator. As steering knuckle applies force on tie rod end and tie rod transfer it to the wheel so here pneumatic actuator apply the force on tie rod end which is F_{cr} =1800N.

Figure.15. Special designed test rig for testing of Tie Rod

X. RESULTS AND DISCUSSION

A. Static Analysis

1. FE Material analysis results

From FE analysis of all material their weight, deformation and stress results are tabulated in following TABLE II

TABLE. II. MATERIAL ANALYSIS RESULT

Sr. No	Material	Weight, kg	Deformation, mm	Stress, MPa
1	Steel	1.7517	0.035969	28.544
2	Aluminum alloy	0.6181	0.10143	28.516
3	Gray Cast Iron	1.6066	0.065264	28.567
4	Titanium alloy	1.0309	0.074889	28.494

Figure.16. and 17 shows graph of stress and deformation results.

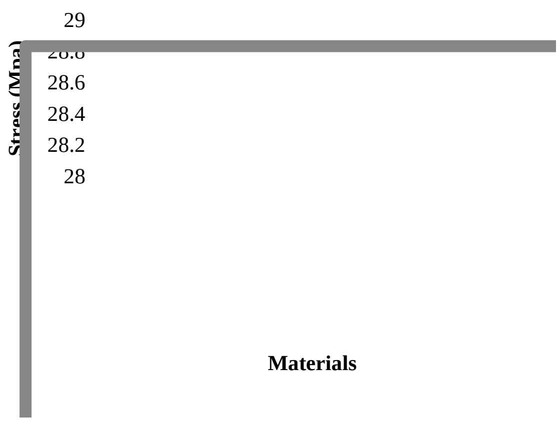


Figure.16. FE Stress Results of Various Materials for Tie Rod

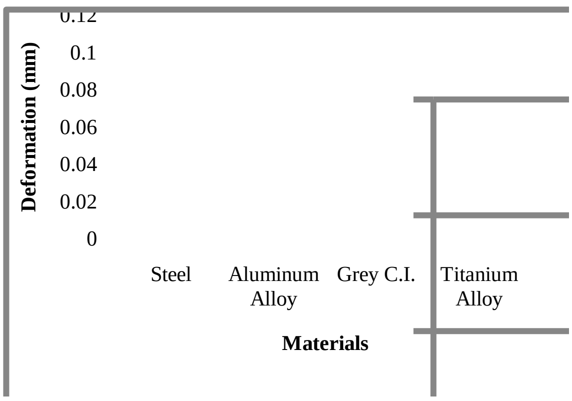


Figure.17. FE Deformation Results of Various Materials for Tie Rod

From above Fig. 16 and 17 we can see that stress is not point to consider as it's nearly same for all materials. Considering deformation as main criteria steel having less deformation as compared so steel is selected.

2. Optimization based on Dimensional Parameters

From above FE analysis of tie rod for different inner diameters we find FE results in terms of weight, stress and deformation are as shown in following TABLE III

TABLE. III. ANALYSIS OF VARIOUS ID'S

Case No.	Hole ID, mm	Thickness, mm	Weight, kg	Stress, MPa	Deformation, mm
Case 1	5	7	1.688	31.337	0.05303
Case 2	6	6.5	1.6697	34.479	0.057947
Case 3	7	6	1.6482	39.431	0.093825
Case 4	8	5.5	1.6234	44.111	0.078838
Case 5	9	5	1.5952	50.611	0.076896
Case 6	10	4.5	1.5638	60.173	0.071284
Case 7	11	4	1.529	76.83	0.085125
Case 8	12	3.5	1.4909	198.49	0.15311

Following graph shows stress and deformation results for various ID's.

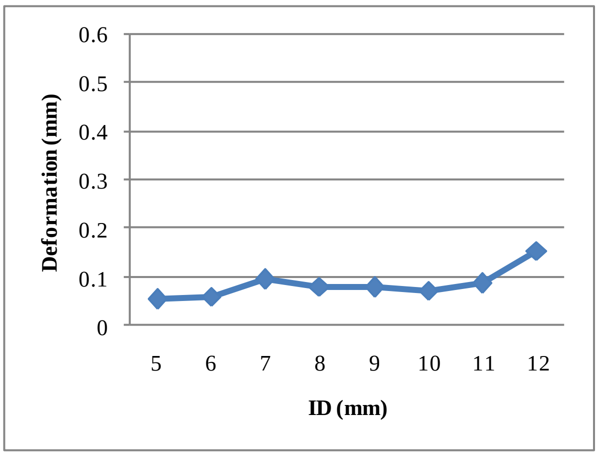


Figure.18. FE deformation results for different inner diameters of tie rod

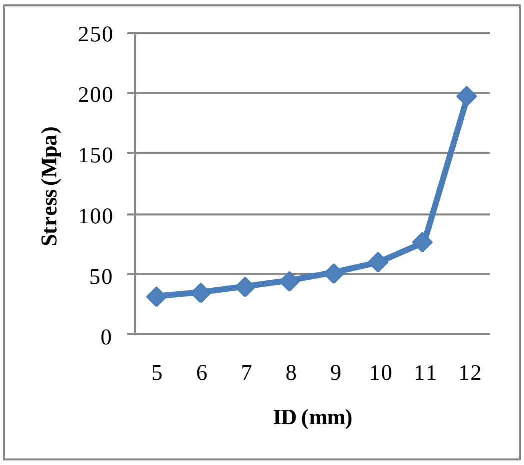


Figure.19. FE stress results for different inner diameters of tie rod

From above graph we can see that 11 mm ID (inner diameter) tie rod gives better results for both stresses and deformation. Whereas ID 12 mm shows failure i.e. much more stress than allowable stress , Hence considering 11 mm ID rod for further work.

B. Transient Dynamic Analysis Results

Following TABLE IV shows result of dynamic analysis in terms of stress and deformation.

TABLE .IV. RESULT FOR DYNAMIC ANALYSIS OF OPTIMIZED TIE ROD

Sr. No.	Deformation (mm)	Stress (MPa)
1	Dynamic Deformation is 0.043659	Dynamic Von-mises Stress is 50.768

From above results we can see that their no much difference between static condition and dynamic condition analysis.

C. Experimental Test Results

When pneumatic actuator applying load on tie rod end then their deformation results are measured by gauge is shown in following TABLE V

TABLE .V. EXPERIMENTAL TEST RESULTS

Sr. no	Condition	ID, mm	Material	Deformation (mm)			
				Trial 1	Trial 2	Trial 3	Avg.
1	New Design	11	Steel-SM45C (Circular with hole)	0.0455	0.0452	0.0455	0.0454

From above results find that, Experimental results meet FEA deformation results, error is only 1.03%

D. Buckling Analysis Results for optimized Tie Rod

The critical buckling load results for optimized Tie rod are given in the TABLE VI

TABLE.VI. CRITICAL BUCKLING LOAD RESULTS FOR OPTIMIZED TIE ROD

Sr. no.	Analysis	Theoretical Analysis	FE Analysis
1	Critical Buckling load P_{cr} in KN	71.9846	89.66

It has been found by the above TABLE VI the critical buckling load results for car Tie rod meets the theoretical analysis and FE analysis results by 12.53% error.

E. Comparative Results of Existing and Optimized Tie Rod

Comparative results between existing and optimized tie rod in terms of % change in weight, stress, and deflection is shown in TABLE VII

TABLE .VII. RESULT COMPARISON OF EXISTING AND OPTIMIZED TIE ROD

Sr. No	Parameters	Existing Rod	Suggested Rod	% Change
1	Material	Steel-SM45C (Rectangular + circular and Solid)	Steel-SM45C (Circular + Hollow-ID 11 mm)	
2	Weight	1.7517 kg	1.4338 kg	Hollow Tie rod is 18.15 % lighter than solid
3	Stress (Static)	28.544 MPa	45.674 MPa	Hollow tie rod has 37.50 % more Stress than solid but its within allowable limit
4	Stress (Dynamic)	31.695 MPa	50.768 MPa	Hollow tie rod has 37.57 % more Stress than solid but its within allowable limit
5	Deflection (Static)	0.035969 mm	0.094642 mm	Hollow tie rod has 62.0 % More deflection than Solid but it's within allowable limit
6	Deflection (Dynamic)	0.038174 mm	0.043659 mm	Hollow tie rod has 12.56 % More deflection than Solid but it's within allowable limit

XI. CONCLUSION

- Tie rod with hollow ID- 11 mm shows safe results and is selected for further work. Circular section and Hollow tie rod at 11 mm ID shows less weight (18.15 %) compare to Rectangular + Circular and solid and hence finally suggested for improvement of weight reduction application.
- Hollow tie rod at 11 mm ID shows high Stress (37.50 %) and deflection (62.0 %) values compare to existing but those are within limit. Fabrication of Tie rod with square and circular section is complex than only circular shape. Hence this new selection will also save time.
- Final design selection has static stress more by 10.03% than dynamic stress. Final design selection has deformation less by 53.87% than dynamic deformation.
- The theoretical calculated critical buckling load for optimized Tie rod is 71.98 KN closely meets with the FEA critical buckling load for optimized Tie rod is 89.66 KN.
- The error between the experimental and FEA critical buckling load is 12.53%, which is acceptable error.

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