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Investigation of Metal Stiffeners in FRP Composite Gears for Increasing Tooth Bending Strength

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Abstract: Gears are an integral and necessary component in our everyday lives. Most of the work performed in plastic and metal but very few works available in combine effect of plastic and metal gears. The main problem while referring plastic gear is the bending strength and in case of metal gear is cost. Hence, the work is performed on metal plastic composite gear to get benefit of both. Here use the combination of fiber reinforced plastic (FRP) and metal. After considering all the merits and demerits of plastic gear use of new gear technology that is metal plastic composite gear is beneficial. The problem under consideration is to enhance further the tooth bending strength of fibre reinforced plastic gears by intrusion of metal stiffeners inside the geometry of each tooth. This includes studying effect of various cross sections for stiffener geometry and various materials used for remaining part of gear, on tooth bending strength with the help of FEA results. The FEA result obtained for optimal combination gear is then compare with only plastic (FRP) gear and observed that tooth bending strength increases. The outputs are measured in the form of contact force, section force and torque carrying capacity. Ls-Dyna and HYPERMESH software are used for FEA study.

Keywords: Plastic gear, Metal Stiffener, Tooth bending strength.

I. INTRODUCTION

Gears are an integral and necessary component in our everyday lives. They are present in the automobiles and bicycles we travel with, satellites we communicate with, and computers we work with. The intension of this investigation is to find out the optimum stiffener cross section & material options for Plastic (FRP)-Metal hybrid composite gear for improved tooth bending strength. Plastic gears are commonly used in today's industry, and not only for lightly loaded applications like household appliances, tools, and toys, but also in more demanding automotive applications like electronic power steering, electronic throttle control, and starter motors.

Plastic gears are continuing to displace metal gears in a large variety of applications due to its various advantages compared with steel gears, such as reduced weight, self-lubrication, lower inertia, quieter running and lower manufacturing costs. However, the applications of plastic gears are limited due to a low load-carrying capacity, wear resistance and sensibility to increased temperature conditions. Therefore, reinforcement materials such as glass, carbon and aramid are added to polymer materials to overcome these obstacles to certain extent.

Previous studies on plastic gears investigated following aspects. In the 1980s Yelle and Burns [1] conducted substantial research to give a more fundamental base to plastic gearing. In their approach they succeeded in taking into account the tooth bending of plastic gears and to calculate real contact ratios for this type of transmission. With the ongoing development of finite element software packages and improved algorithms, accompanied by sufficient computing power in the 1990s, it became possible to solve complex contact problems like meshing (plastic) gears [2 to 5]. In the group of Walton at the University of Birmingham, the experimental research on plastic gears was combined with numerical work [2, 6 to 8]. They confirmed the analytical findings of Yelle and Burns by FEA and showed that load sharing changes dramatically for plastic gears. Kapelevich and co-workers used FEA to modify tooth shapes and optimize the tooth geometry specific for plastic gears [2].

The present study includes studying effect of various cross sections for stiffener geometry and various materials used for remaining part of gear, on tooth bending strength and to ensure correctness of the FEA results, these results are correlates with available material test data.

II. MATERIAL TESTING

The material testing is takes place to check the correctness of the FEA results. For material testing the tensile test is performed on ISO standard specimen.

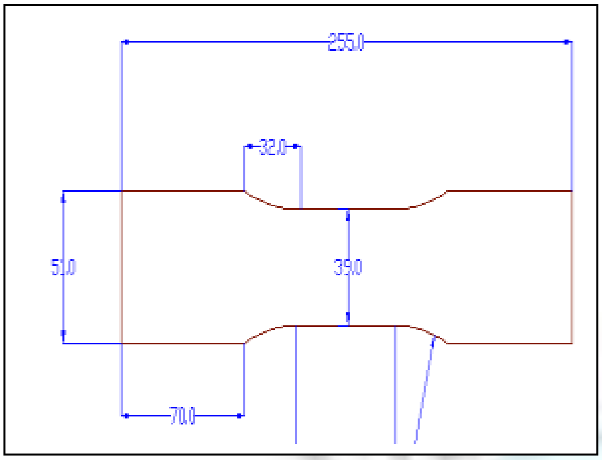


Fig.1: Tensile Test Specimen Dimensions

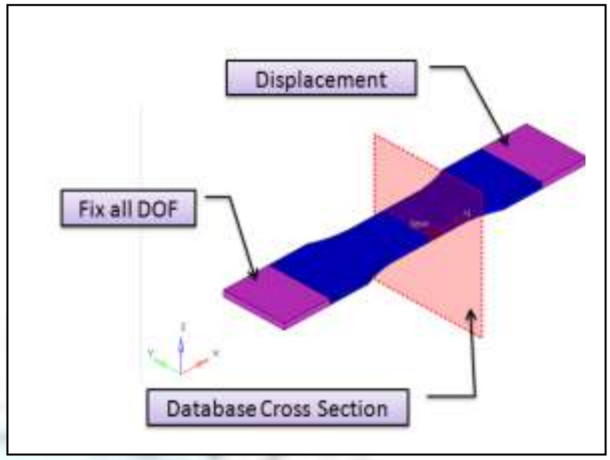
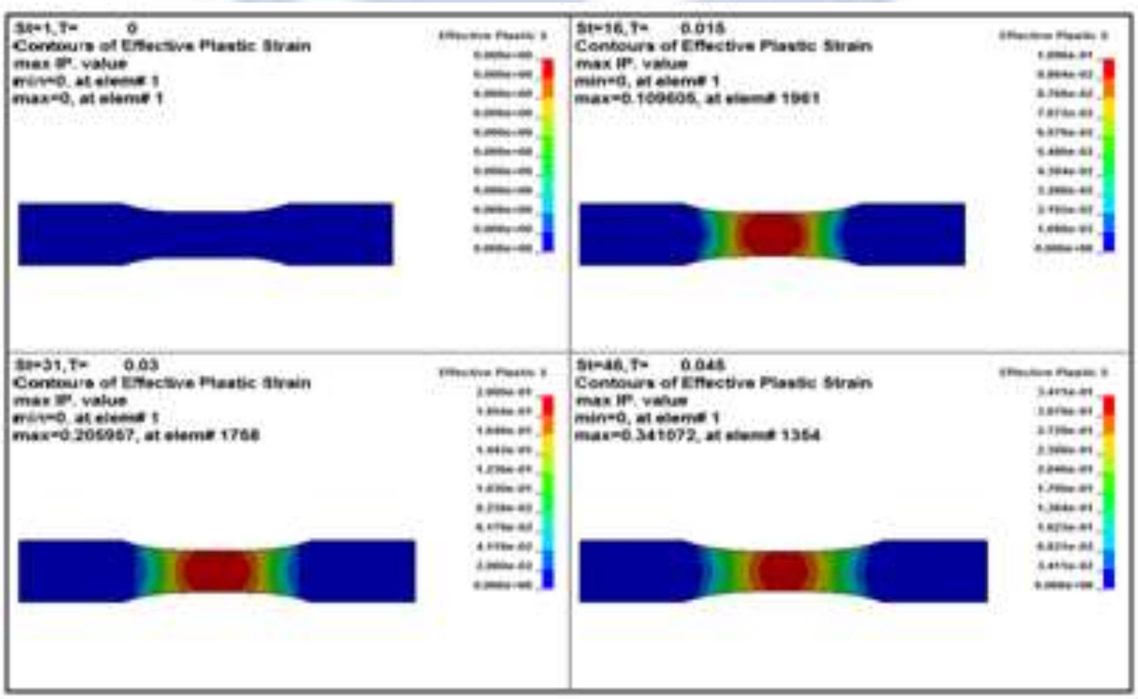


Fig.2: FE Model Set-up

The specimen to be tested is taken as per the dimensions specified in ISO standard. The input material data is taken from actual test data converted in true stress and true strain using Mat24 LS-Dyna Material format. A Database Cross Section is defined at the centre to extract the cross sectional forces. The displacement is measured at the moving end. Fig.1 shows the tensile test specimen and fig.2 shows the actual model on which FE analysis is carried out. In FE analysis both metal as well as plastic material specimen is tested.

A. MATERIAL SAE J2340 340XF PLASTIC STRAIN PLOT

The tensile test is performed for material SAE J2340 340XF. Plastic strain plots shows elongation occurs in test specimen. The red region indicates breaking point. The maximum load applied is 70151N. The strain generated in specimen is shown in the fig. 3.



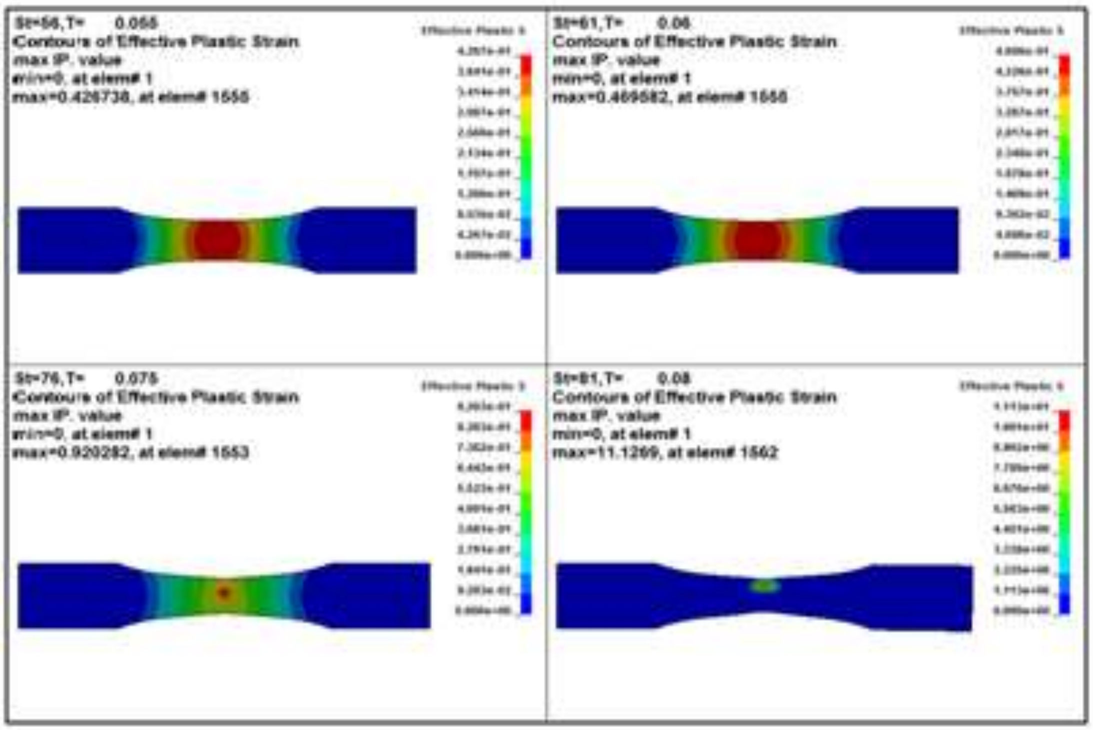
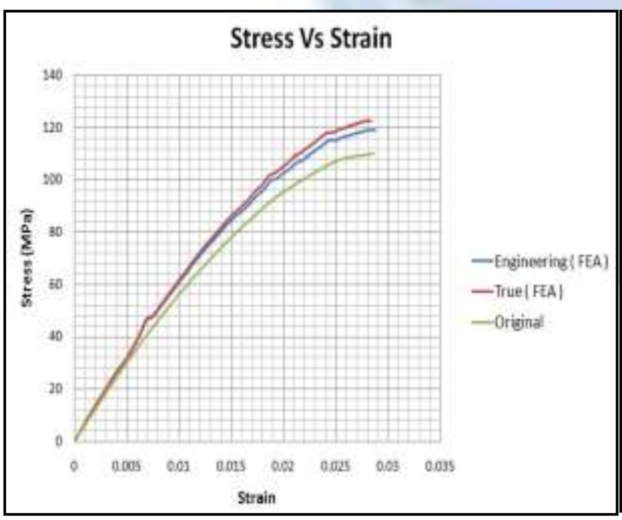


Fig.3: Specimen Plastic Strain Plot

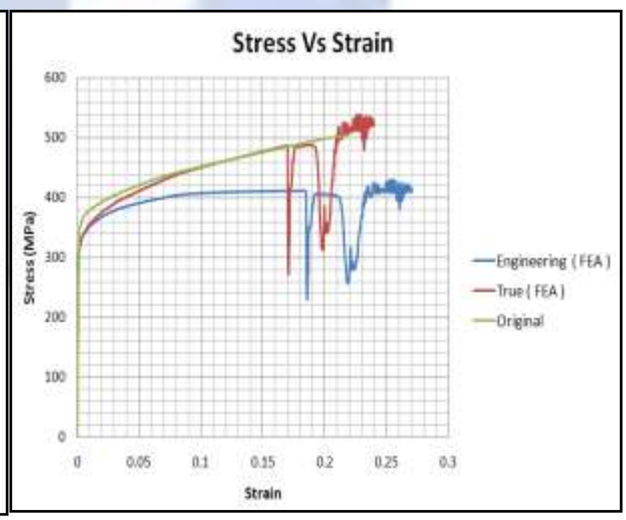
Similar procedure followed for material Ultramid 8272G HS BK -102 (PA6 + GF 12) and plastic strain plot.

B. COMPARISON OF TEST Vs FEA

After performing FE analysis the results are formulated in terms of stress Vs strain graph. This graph helps for getting actual difference in between test and FEA results.



SAE Graph 1: Comparison of Test Vs FEA Results for J2340 340XF



Graph 2: Comparison of Test Vs FEA Results for Ultramid 8272G HS BK -102 (PA6 + GF 12)

From the graph 1 and 2 it is concluded that the Test Data input used for Material closely correlates when the data used in Mat24 format. The difference at initial level may be due to the discretization error, round off errors, etc. which are typical errors introduced in numerical techniques.

III. RESULT AND DISCUSSION

Objective of work is to study intruded gear. Here, it will be considering three different type of profile for stiffener geometry and five different type of plastic material. The type of gears selected for this work is spur gears. Detailed regarding dimensions as shown in fig. below.

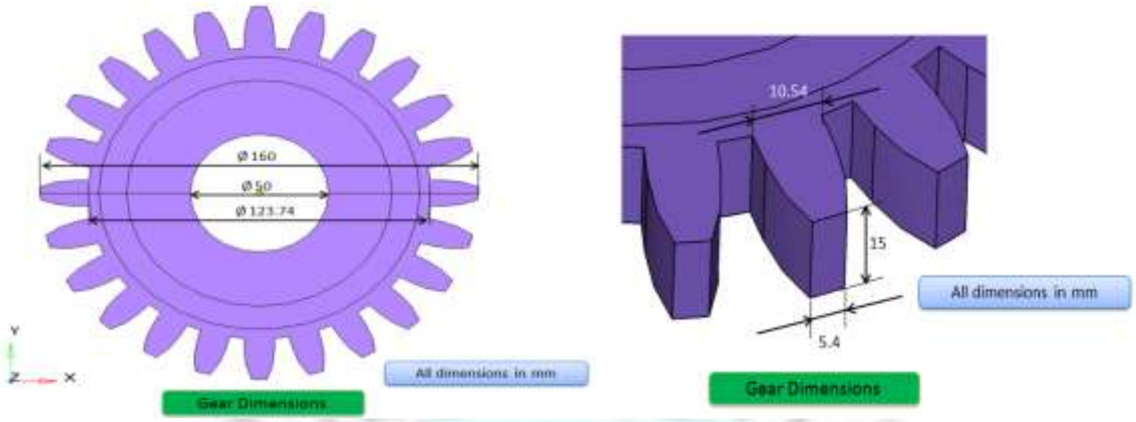


Fig. 4: Gear Dimensions

A. MATERIAL DATA

The material used for stiffener is metal. The metal insert is of Steel SAE J2340 340 XF having following properties.

Density = 7.85×10^{-9} Tonns/mm^3

Young's Moulus = 2.1×10^5 N/mm^2

Poissons ratio = 0.3

Yield Stress = 340 MPa

The fiber reinforced plastic material is used for the remaining part of gear. The details of the FRP Material are given below.

Density = 1.23×10^{-9} Tonns/mm^3

Young's Moulus = 5.5×10^5 N/mm^2

Poissons ratio = 0.35

Five different FRP materials are used. The stress strain values for respective materials are shown as follows.

Table 1: Material Stress Strain values

Sr. No.	Material	Stress(MPa)	Strain(%)
1	Ultramid 8272G HS BK -102 (PA6 + GF 12) --MAT1	15.6	0.25
2	Ultramid A3EG5 (PA66 + GF 25) --MAT2	74.8	0.9
3	Ultramid A3EG6 (PA66 + GF 30) -- MAT3	62.8	0.62
4	Ultramid A3EG7 (PA66 + GF 35) -- MAT4	42.1	0.35
5	Ultramid A3EG10 (PA66 + GF 50) -- MAT5	107	0.66

B. METAL STIFFENER PROFILE GEOMETRY

Three types of Profiles are tested.

i. Profile1: Offset involute profile   ii. Profle2: Square   iii. Profile3: Trapezoidal

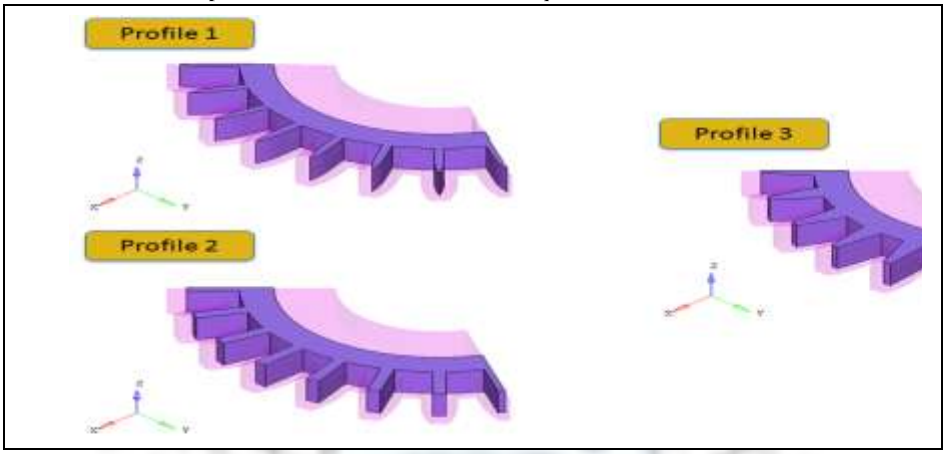


Fig. 5: Profile Geometry

C. DESIGN OF EXPERIMENTS MATRIX

It shows the combinations of metal insert profile and material, on which the numerical test is performed. Total number of combinations shows in below table are nothing but 15.

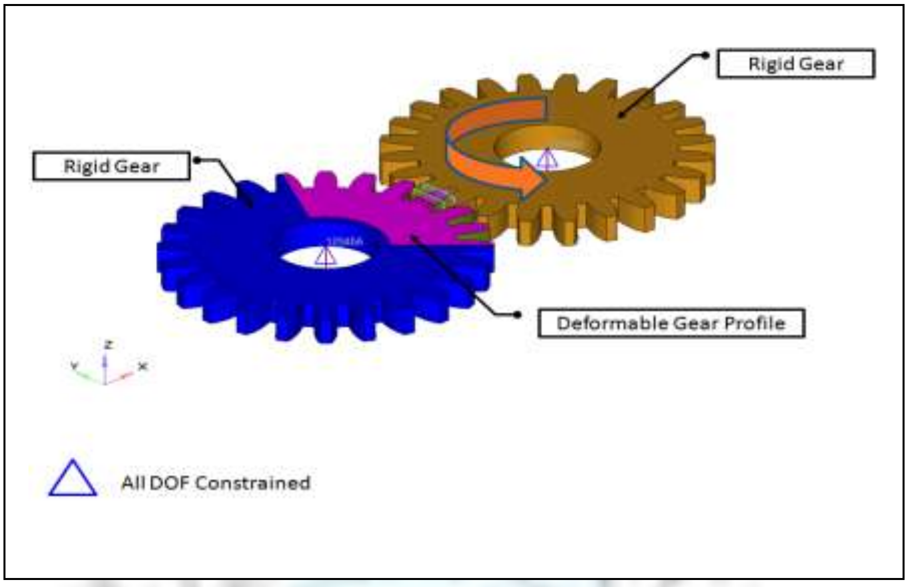
Table 2: DOE Matrix

Nomenclature

Design of Experiments Matrix	Mat 1 Ultramid 8272G HS BK -102 (PA6 + GF 12)	Mat 2 Ultramid A3EG5 (PA66 + GF 25)	Mat 3 Ultramid A3EG6 (PA66 + GF 30)	Mat 4 Ultramid A3EG7 (PA66 + GF 35)	Mat 5 Ultramid A3EG10 (PA66 + GF 50)
Profile 1	P1M1	P1M2	P1M3	P1M4	P1M5
Profile 2	P2M1	P2M2	P2M3	P2M4	P2M5
Profile 3	P3M1	P3M2	P3M3	P3M4	P3M5

D. NUMERICAL TEST SET- UP

The numerical test was performed on the meshed model. For the test, simple set-up is prepared which reduces complexity in results. In this set-up, two contacting gears are taken out of that one is kept as rigid and other gear is considered as test gear. The contacting part of test gear is kept as deformable. This deformable gear sector is chosen as test area is completed by rigid gear. It is then loaded by another rigid gear by giving incremental displacement. The tested part is shown in pink colour of following fig.



. **Fig. 6: Numerical Test Set-up**

E. STEPS F0R GEAR FINITE ELEMENT ANALYSIS

The finite element analysis is performed on 17 combinations. The Finite Element Analysis is performed on the gear step by step which has shown as follows.

1. Import CAD model in the hypermesh.
2. Discretization (meshing) of CAD domain using hexahedral & 1D elements.
3. Assign material and property to the mesh.
4. Apply boundary conditions
   a. All degrees of freedom locked at center beam.
   b. Define BOUNDARY PRESCRIBED MOTION card to describe input rotation.
5. Define Contacts between gears.

The model after assigning material and property, boundary conditions and contacts between gears are shown in following fig.

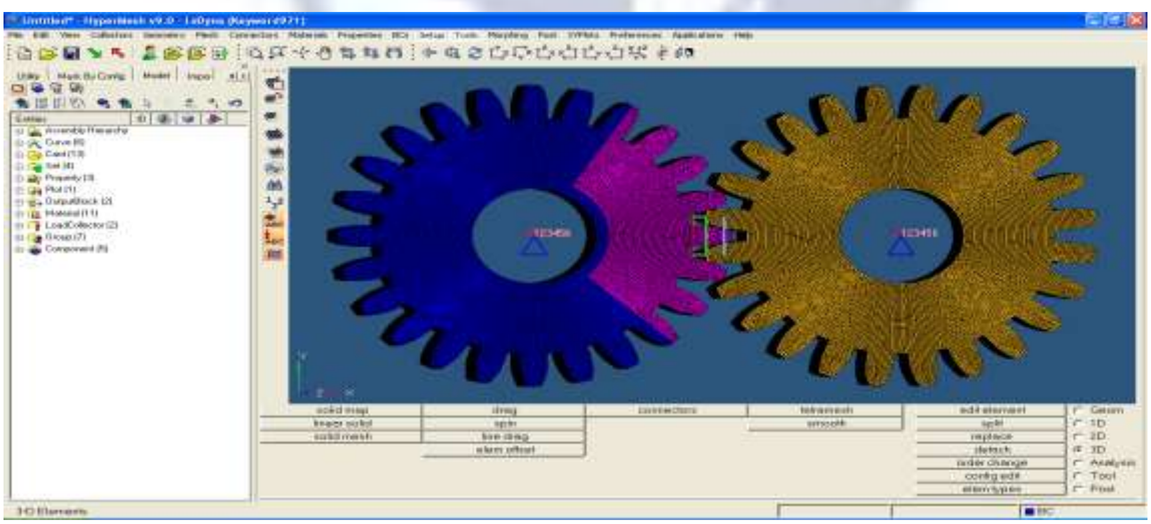


Fig. 7: Model after assigning material, property, boundary conditions and contacts between gears

6. Define Output requests –

Outputs are requested by three different ways.

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i. Cross Section Forces Measurement

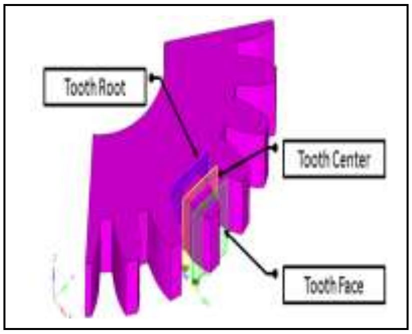


Fig.8: Database Cross Section Output Location

ii. Torque Measurement

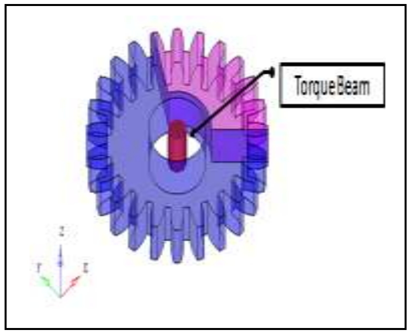


Fig. 9: Torque Beam Output

iii. Contact Force Measurement

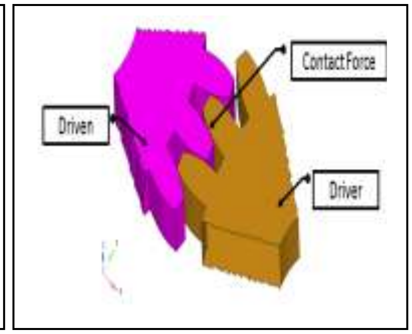


Fig. 10: Contact Force Measurement

Three Database Cross sections are defined so as to extract the cross-sectional forces experienced by gear tooth during the test as shown in fig. 8. The centre shaft is modelled as 1D beam so as to measure torque taken by gear as shown in fig.9. The contact force between the engaged teeth are measured as shown in fig.10.

7. After assigning all parameters the model export and run submission to FEA solver LS-Dyna.
8. Interpretation of results.

F. BASELINE RESULTS (ONLY METAL AND ONLY PLASTIC)

After performing all the procedure mentioned in above points the model is run in the FEA solver LS-Dyna. The outputs are drawn from the LS-Prepost. The outputs are taken on which basis is already mentioned in the above point. First the tests perform on only metal and only plastic. The results for this two are shown as follows.

1. Only Metal Gear

The test is perform on the gear of material SAE J2340 340XF. In this the rigid gear is rotate and due to this the strain and stress occur in the fix test gear. The plastic strain and stress occurs in metal gear for different time step is shown in following fig.

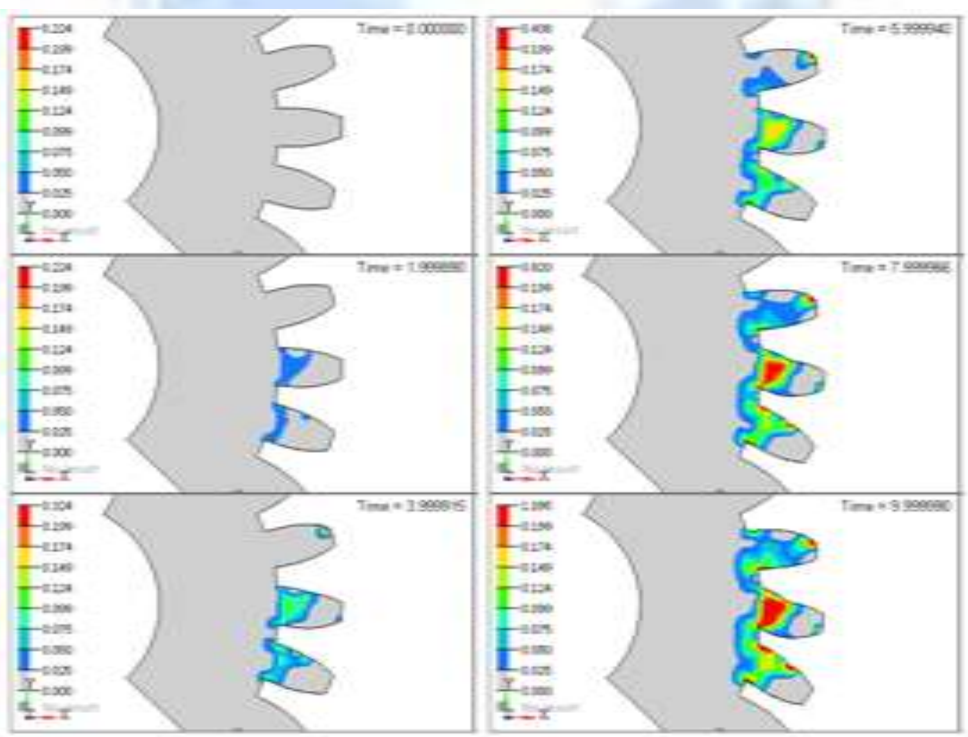


Fig. 11: Plastic Strain

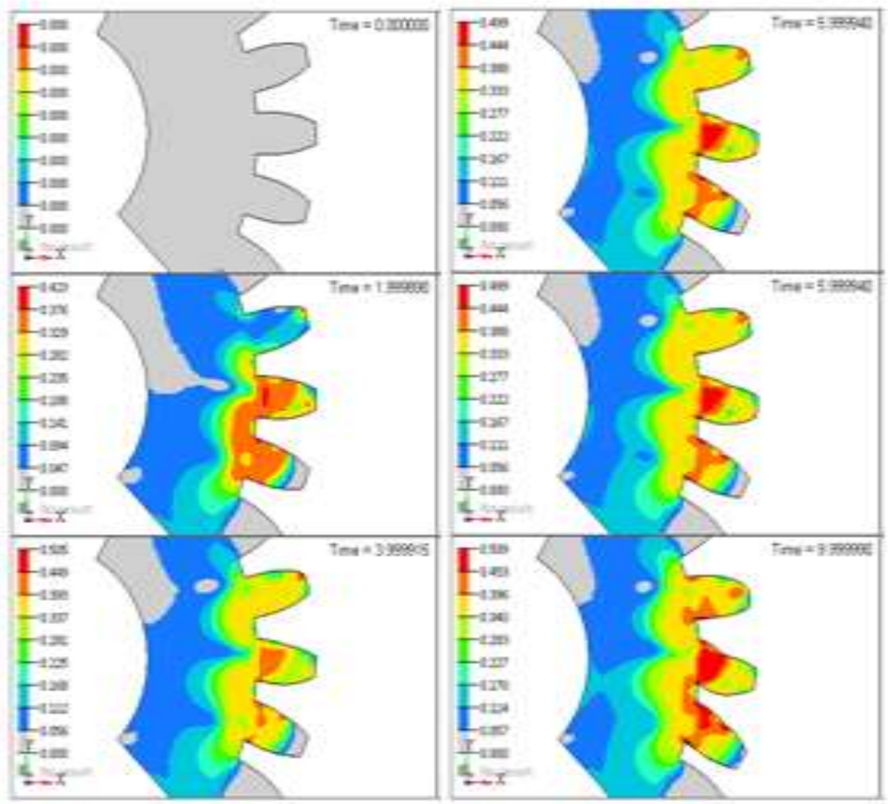
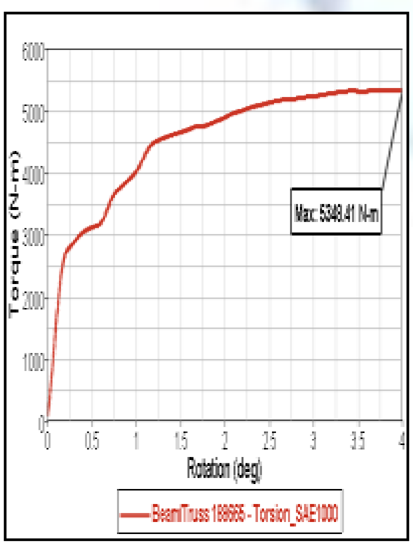


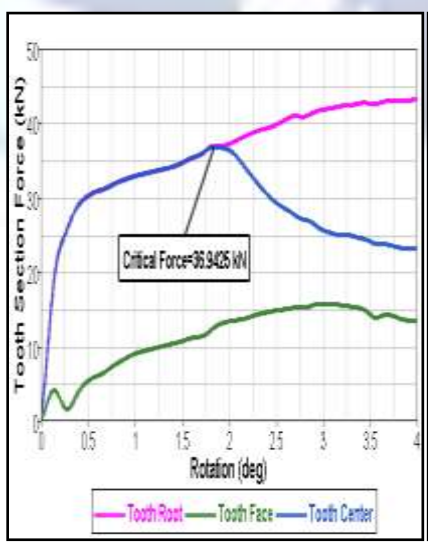
Fig. 12: Stress

Graphs

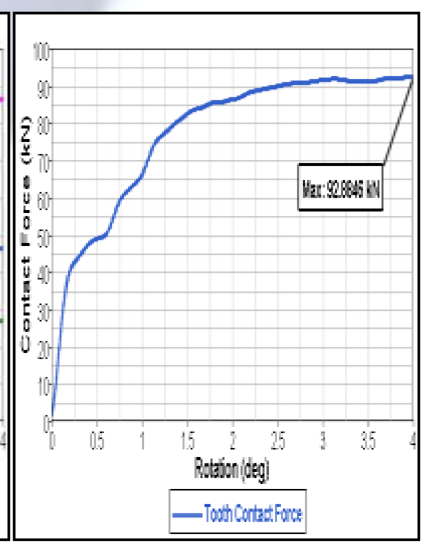
The outputs are taken from the graphs. After solving the model in LS-Dyna, graphs are drawn from LS-Prepost. At the initial stage this graphs are obtain across the time that is torque Vs time, section force Vs time, contact force Vs time. The required data is across the rotation, hence the cross plot of input and output curve are taken. Input curve is nothing but rotation Vs time curve. After taking cross plot the graphs are obtain as torque Vs rotation, section force Vs rotation, and contact force Vs rotation. This graphs gives the maximum value occurs just before the failure of part.



Graph 3: Torque Vs Rotation



Graph 4: Section Force Vs Rotation



Graph 5: Contact Force Vs Rotation

The above graph gives the maximum value of torque, section force and contact force respectively.

2. Only Plastic Gear (MAT1)

The procedure follow for the material MAT1 that is Ultramid 8272G HS BK -102 (PA6 + GF 12) is similar to the material SAE J2340 340XF. The values obtained for torque, section force and contact force are 1651.5 N-m, 12.1208 kN, 27.1217 kN respectively.

G. RESULTS OF FINITE ELEMENT ANALYSIS

The finite element analysis is performed for the different combinations. These combinations are explaining detail in the Design of Experiments Matrix. The results obtained for the total 15 combination of fiber reinforced plastic and stiffener profile geometry are shown here.

Iteration P1M1

The plastic strain and stress occurs in combination of Offset involute profile (P1) metal stiffener and Ultramid 8272G HS BK -102 (PA6 + GF 12) plastic material (M1) gear with respect to time is shown in following fig.

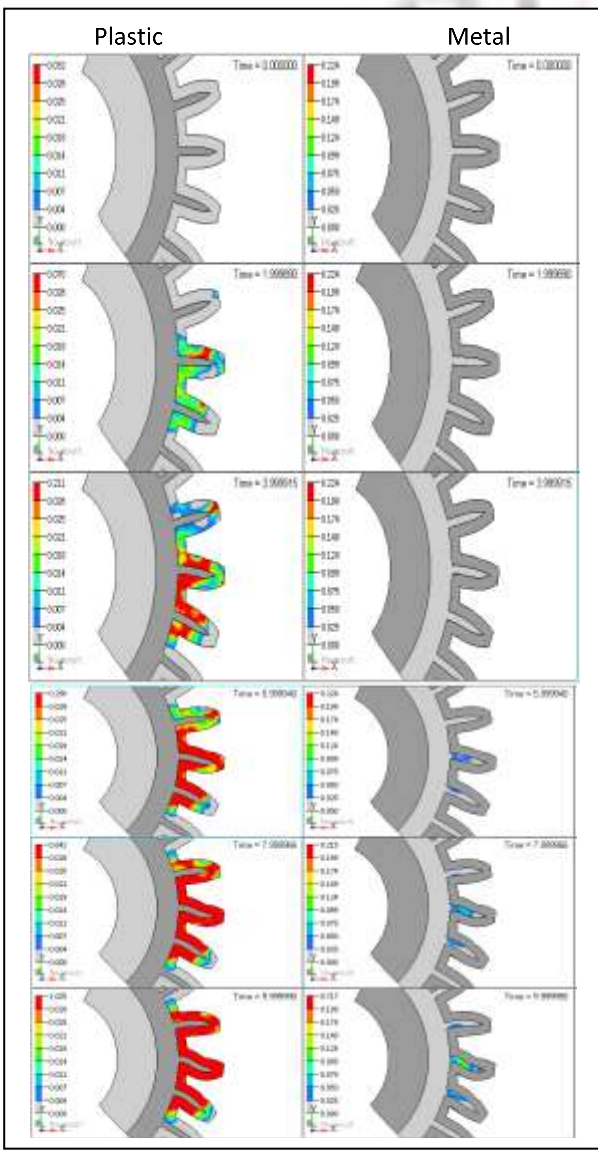


Fig. 13: Plastic Strain

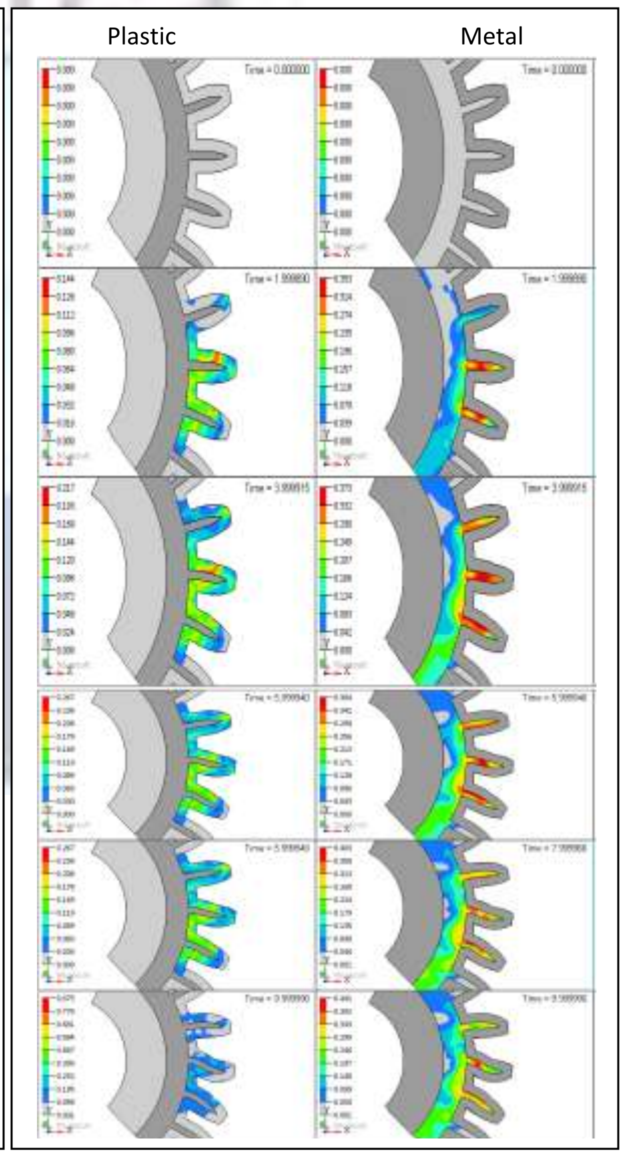


Fig. 14: Stress

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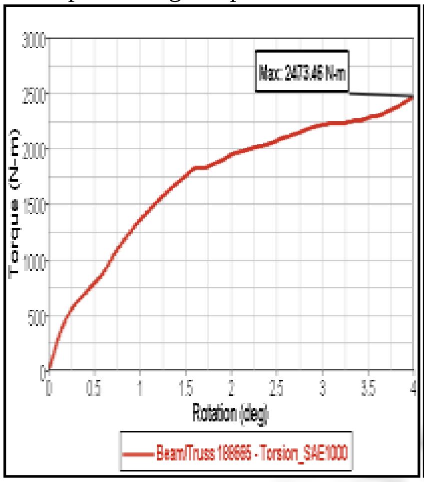
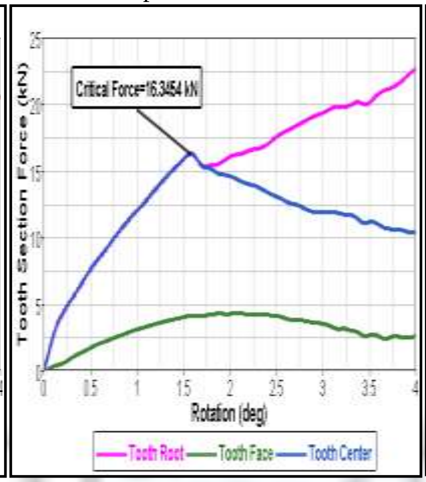
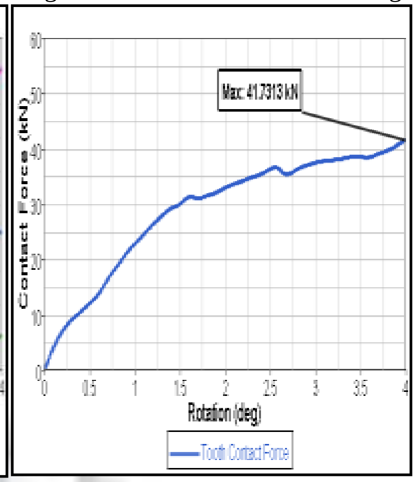
Graphs

After processing outputs are drawn from LS-Prepost for P1M1combination gear which shows in following graphs.







Graph 6: Torque Vs Rotation **Graph 7: Section Force Vs Rotation** **Graph 8: Contact Force Vs Rotation**

Similar procedure followed for the following iterations:

1. P1M2 2.P1M3 3.P1M4 4.P1M5 5.P2M1 6.P2M2 7.P2M3
8. P2M4 9.P2M5 10.P3M1 11.P3M2 12.P3M3 13.P3M4 14.P3M5

After performing all iterations results are formulated and this is shown in result table.

H. RESULT TABLE

Including only metal and only plastic total 17 iterations are performed and result of this is shown in following table.

Table 3: Result Table

Sr. No.	Iteration	Torque(N-m)	Tooth Cross-Section Critical Force(KN)	Tooth Contact Force(KN)
1.	Only Metal	5348.41	36.94	92.88
2.	Only Plastic	1651.5	12.12	27.12
3.	P1M1	2473.46	16.34	41.73
4.	P1M2	3842.8	24.98	64.89
5.	P1M3	3364.89	23.16	57.44
6.	P1M4	3502.54	25.13	58.96
7.	P1M5	4625.9	33.04	78.67
8.	P2M1	2710.17	20.93	46.68
9.	P2M2	4146.15	27.3	72
10.	P2M3	3726.61	26.88	64.8
11.	P2M4	3891.48	28.19	68.97
12.	P2M5	4813.13	34.06	84.06
13.	P3M1	2890.44	19.63	49.98
14.	P3M2	4202.4	27.44	71.18
15.	P3M3	3597.55	25.95	62.6
16.	P3M4	3914.58	27.85	67.64
17.	P3M5	4633.57	33.56	78.81

Following observations are formulated from the result table 3.

- The tooth cross section critical force indicates that the failure of gear. The tooth cross section critical force for plastic gear is 12.12 kN and metal gear is 36.94 kN. It shows that the plastic gear fails earlier as compared to metal gear.
- Torque carrying capacity of gear is drawn just before the failure of gear. Only Plastic Gear (T= 1651.5 Nm) has very less Torque carrying capacity as compared to Only Metal Gear (T= 5348.41 Nm).
- Addition of metal stiffener increases the Torque carrying capacity substantially.
- From FEA results (with combination of 3 different metal stiffener profiles and 5 different materials) it is observed that,

  Tooth cross section critical force:

  P2M5 (34.06) > P3M5 (33.56) > P1M5 (33.04)

  It shows that failure of combination P2M5 (Metal Stiffener Square profile and material Ultramid A3EG10 (PA66 + GF 50)) is after long time as compared to plastic gear.

  Torque carrying capacity:

  P2M5 (4813.13) > P3M5 (4633.57) > P1M5 (4625.9)
- The combination P2M5 (Metal Stiffener Square profile and material Ultramid A3EG10 (PA66 + GF 50)) has highest torque carrying capacity (T = 4813.13 Nm) among all possible combinations. It is very large as compared to plastic gear torque carrying capacity (T= 1651.5 Nm).

It shows that material Ultramid A3EG10 (PA66 + GF 50) gives good result with combination of metal stiffener square profile(P2) as compared to trapezoidal(P3) and offset involute (P1) profile.

CONCLUSION

One of the most effective parameter on performance of plastic gear is nothing but very less load carrying capacity. To overcome this drawback there is necessity to increase the tooth bending strength of plastic gear. Adoption of plastic metal composite gear technology shows better mechanical behaviour as compared to plastic gear. It helps to increase the strength of gear. After intrusion of metal stiffener inside the geometry of each tooth of fiber reinforced plastic (FRP) gear, the tooth bending strength of gear increases. The cross section force measurement is used to find out failure of gear. The torque carrying capacity is measured just before the failure of gear. The torque carrying capacity of intruded metal stiffener FRP gear is three times larger than the FRP gear.The change in FRP material and metal stiffener profile geometry affects the torque carrying capacity. Metal stiffener profile geometry is important factor in designing composite gear and eventually, deciding gear failure. The sudden failure of gear is occurs at the tooth centre. Proper selection of fiber reinforced plastic material plays a vital role in composite gear design. Compare to other combination P2M5 (Metal Stiffener Square profile and material Ultramid A3EG10 (PA66 + GF 50)) gives highest results.

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