Novel Adaptive Mesh Refinement Technique for Dynamic Structural Analysis of Connecting Rod

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Abstract— **Since connecting rod is to subjected complex loading conditions, for which realistic stress prediction is a challenging task. Though the Finite Element Method (FEM) is widely used, but its results contain some inaccuracies that comes from various sources, out of them discretization error is considered to be major source. Present study aims to enhance FE solution accuracy through adopting newly developed Adaptive Mesh Refinement (AMR) technique. In present studydynamic structural behavior of connecting rod is evaluated through conventional and advanced AMR discretization technique. In this research analysis of connecting rod conducted for 1.3 second where cyclic loads have been applied within 13 sub steps at various crankshaft positions. It is observed through analysis results, that maximum stresses have been produced in connecting rod at shank and at big end during compressive and tensile loads respectively. While comparing results obtained from conventional and advanced AMR discretization technique it is observed that 15.7% increase in Von-Mises stresses was noticed by applying AMR technique during compressive loads. Whereas in case of tensile loading no effect was observed.**

Index Terms— *Adaptive mesh refinement; Dynamic loading; Connecting rod; Von-Mises stresses*.

I. Introduction

CONNECTING rod is most valuable part of IC engine therefore it is necessary to focus on its profile designing. As it is used to transmit reciprocating motion of piston in to rotary motion, therefore calculation of sustainability of this part for complicated loading is great importance [1]. Their research describes about the importance of Connecting rod optimization, load analysis, stress analysis during the operation through FEA [2] performed FE analysis of connecting rod under static and quasi-static equilibrium to predict axial as well as bending stresses. Their analysis results reveal that significant bending stresses are produced; this should be taken into account during design of connecting rod. They also compared the results of static and quasi-static equilibrium simulation and found that significant difference occurs in results of both type of analysis [3] illustrated in their research that during operation of IC engine connecting rod is subjected to tensile and compressive loads but compressive loads have greater magnitude than tensile load. This part is assumed to be a part of great importance due to complex loading nature [4] illustrated in their research that the proper design of connecting rod plays more important role to avoid the failure. While designing connecting rod the material's properties, strength economy of material are necessary factors.

[5] introduced the new method of manufacturing connecting rod through fracture splitting method. In this method they focused the use forged steel and powder metals but found these materials with poor fatigue characteristics, therefore researchers suggested for the use of micro-alloyed steel for manufacturing of connecting rod with the help of this method [6] carried out research to compare the traditional method of connecting rod manufacturing against fracture splitting method. It was found through their research that fracture splitting method is proved to be cost efficient and improve the quality of connecting rod [7] In their research they focused that the inertial forces developed due to reciprocating motion of piston and stresses developed in the form of bending and axial stresses and affect fillet section of the big end and small end of connecting rod. In this research they explained that for the modeling of connecting rod the CATIA software can be used and analysis can be done with the use of ANSYS software to get the optimum parameters for design of connecting rod. In their research they suggested that these methods can be used for designing of this part with minimum / reduced weight and cost without affecting its life. They also illustrated that fatigue crack occur at the transition zone between small end and shank can be analyzed through FEA, which is best suitable method for analysis and design of this part.

[8]-[9]described in their research that for the improvements of performance of connecting rod only experimental studies by following the micro structural examination and analysis are not sufficient. But due to complications in analysis through experimental data they suggested that for the enhancement of design strategy of connecting rod and fatigue fracture evaluation, Finite Element Model (FEM) plays an important role [10]. They mentioned in their research that the finite element analysis carried out for a high-speed diesel engine connecting rod by following three dimensional analysis. The experimental measurement carried out to analyze the maximum compressive and tensile loads respectively which are essentially the inertia loads of the piston assembly mass. Also the experimental determination conducted to find the distribution of load on piston pin and crank end. For further analysis they used beam element and multi point constraint equation for getting the results of applied load on the bolt and separate modeled connecting rod cap.

[11]-[12] illustrated that improper material selection, defected fabrication, poor designs are the key parameters that lead toward fatigue failure.

[13] In this research they focused on the analysis of connecting rod to evaluate the fatigue life and alternating stress development due to service load with variation in load distribution. For getting the results related to the mentioned parameters they modeled the connecting rod by using CATIA software and FE analysis done by using ANSYS software [14] illustrated that by using nonlinear finite element model with exact geometry of fine details this researcher concluded that failure of connecting rod happened due to fatigue failure. He also suggested that improvement of life of this part is possible when fatigue calculation will be adopted[15] identified the reason of failure and to check the fatigue performance of the faulty connecting rod. By using standard failure analysis method and assessment of factors affecting failure including structural design, material type and dynamic loading.

The weight optimization of connecting rod is of too very importance factor without compromising the strength, stiffness and fatigue life [16] developed the approximate mathematical formula for predicting weight and material cost for connecting rod. In this research they described that by using geometric programming technique, optimization of connecting rod can be achieved. In their research they focused that during the design of this part with compression stress, bearing pressure at the crank and piston pin ends must be evaluated. Researchers also explained that for obtaining optimized weight of connecting rod and cost function expression must be mentioned in exponential form with geometric parameters[17]conducted research to optimize the weight of connecting rod designed by using the materials i-e Aluminum alloy, Titanium and Forged steel. They concluded that:

- The mass of the connecting rod optimized up to 483 grams and the optimized geometry of connecting rod is about to 10.38% lighter than of original connecting rod.
- In the forged steel connecting rod the maximum stresses developed at transition area between pin end, crank end and shank. The applied allowable limit of below 250MPa at the middle of the shank region as the stress value [18] conducted static and quasi-dynamic analysis of connecting rod to optimize its fatigue life, reduce weight and compared obtained results of static and quasi-dynamic approaches. Their research concluded that results of static and quasi-dynamic analysis possess significant difference. The designed connecting rod that is 10% lighter in weight than original and 25% less expensive.
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[19] attributed that strength, stiffness and fatigue behavior are the key properties for selection of material.

[20] conducted transient FE analysis of connecting rod made up of Aluminum alloy. In this research he also illustrated that maximum deformation occurs at the center of small and big end bearing. It could be concluded through the results of this research that the major connecting rod failures occur due to buckling under critical loads.

[21] in this research the he focused on static and quasi-dynamic structural analysis of connecting rod by using different materials for obtaining optimized results in premises of weight and cost. In this research it is concluded that static analysis results are not sufficient to design connecting rod

Shenoy also compared results of static and quasi-dynamic results and found significant difference in results and suggested that results of quasi-dynamic analysis (using the C-70 Steel material) are the best suitable for optimization of connecting rod.

From extensive literature it is found that connecting rod is almost focused by the manyresearchers. Despite of that connecting rod failure still occur with high frequency, therefore realistic and accurate stress prediction are of great importance for efficient and reliable design of connecting rod. Though the Finite Element Method (FEM) is widely used but its results contain some inaccuracies that come from various sources, out of these techniques AMR is suitable discretization technique for evaluation of error of connecting rod during analysis. Present study aims to enhance FE solution accuracy through adopting newly developed Adaptive Mesh Refinement (AMR) technique.

II. FEA Governing Equations

Finite element method is numerical method to solve structural problems involving stress, deformation, resonance and amplitude prediction. In FE analysis continuum approach is used to solve structural problem, where geometry of physical problem is divided into number of small elements known as finite element. Those all the elements were connected at common point known as node. The link that connect two nodes known as element which is assumed to elastic springs. The whole system behavior is governed by following equation.

$$\{F\} = [K]\{u\} \tag{1}$$

In case of finite element analysis each element is represented by different equation and finally makes thousand equations. For all cases two variables are known and third one has to be determined therefore equation can be written as.

$$\{u\} = [K]^{-1}\{F\} \tag{2}$$

In this form above equation looks very easy and can be solved easily but these equations are interconnected at each node and their displacement as well as force transmission affects each other. The given below is case of single spring loaded and distort at both nodes by force f_1, f_2 and distorts by displacement u_1 *and* u_2 then equation can be written as

$$\begin{aligned} f_1 &= -k(u_2 - u_1) \\ f_2 &= k(u_2 - u_1) \end{aligned} \tag{3}$$

These equations can be written in matrix form as

$$\begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} \tag{4}$$

Or

$[k_e]\{\mathrm{u}\} = \{F\}$ Whereas $k_e = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix}$

Therefore for three springs in combination then,

$$\begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix} \tag{5}$$

In this way all the equation of discretized domain are connected, solved by Newton Raphson method as follow.

$$X_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{6}$$

III. Modeling and Meshing

In order to achieve the objective of research connecting rod is modeled in Pro-Engineering software by using engine specification given in Table. 2. The 3D model of connecting rod was imported in ANSYS software in order to predict structural behavior under loads. The gird generation would be the extremely important step of FE analysis, in present study grid was generated through conventional grid generation technique as well as advanced Adaptive Mesh Refinement (AMR) technique. The adaptive mesh refinement technique generates highly refined mesh in the areas of high stress concentration. AMR technique further enhance solution accuracy with the use of medium computing resources, because it manage number of elements in such a way that region of stress concentration have finest elemental size while other have coarse one. Tetrahedral beam elements are used to generate mesh. Mesh details are given in Table. 1. Fig.1 and Fig.2 shows the generated mesh on connecting rod through the conventional and AMR technique.

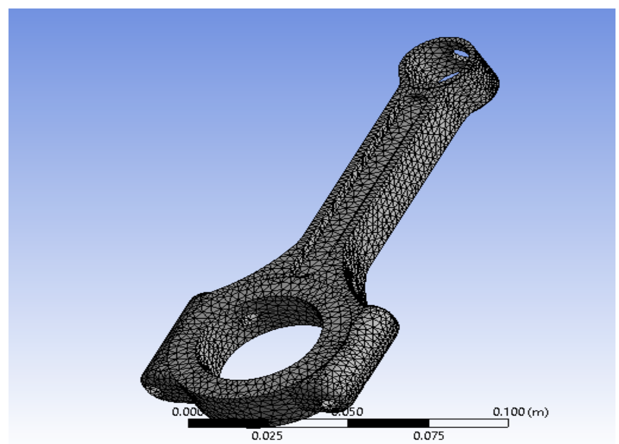

Fig. 1 Meshed model of connecting rod without using AMR

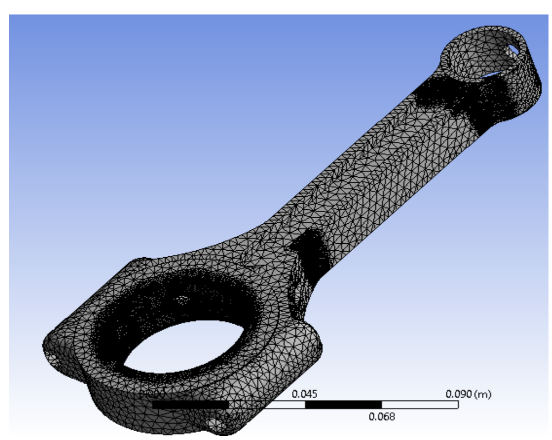

Fig. 2 Meshed model of connecting rod with using AMR

A. *Load Analysis*

In order to predict dynamic structural response of connecting rod throughout the cycle, forces acting on the connecting rod are calculated by using pressure of burnt inside the engine cylinder vs crank angle diagram. Since connecting rod experiences tensile and compressive loads due to inertia of reciprocating components and gas pressure at various instants during cycle, these forces are highly time dependent.

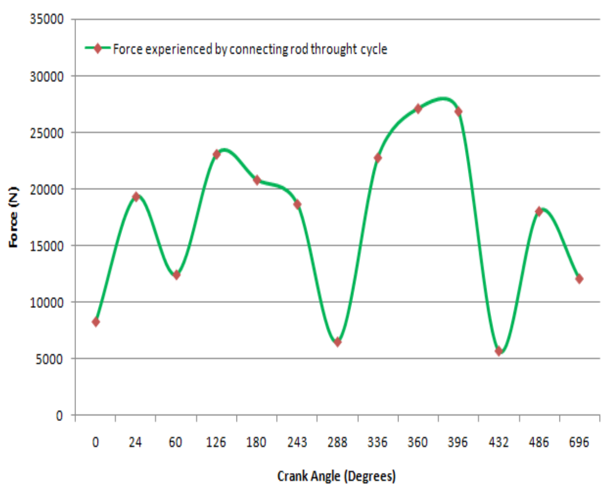

Fig. 3 Load curve (graph) on the connecting rod against different crank angles

In present study tensile forces are considered to be dynamic, whereas compressive forces are assumed to be static. The behavior prediction of connecting rod under tensile and compressive forces has been focused, the effect of inertial forces, damping forces and structural non-linearity are also considered. Analysis of connecting rod has been conducted for 1.3 seconds, where the cycle loads are applied within the 13 sub steps at various crankshaft positions (crank angles). Variation in force has been observed when the load is applied on the connecting rod against different crank angles as shown in Fig.3. It is observed from load curve (graph) shown in Fig.3, that the maximum force is going to be developed when connecting rod reaches at the 360° and experiences minimum force at 432° crank angle.

B. *Applied loads and Boundary conditions*

In FEA analysis accuracy of numerical solution is highly affected by applied restrained and load distributions. The constraints as well as loads are applied according to the underlying physics of problem. As the connecting rod is subjected to compression and tension during its operation, therefore it is necessary to conduct its analysis during these both nature of loads. During analysis of connecting rod its behavior prediction under tensile forces taken into account, the effect of inertial forces, damping forces and structural non-linearity are also considered in this research. The tensile as well as compressive loads have been applied on the connecting rod over 180° at crank contact surface. During the analysis it has been observed that both the tensile and compressive loads are distributed uniformly over the crank contact surface. The connecting rod at the piston pin is assumed to be fixed in the both cases, therefore restrained load is applied over 180° surface area at the piston pin.

IV. RESULTS AND DISCUSSION

In this section result of dynamic structural analysis of connecting rod has been presented. In first passage results of stresses and deformation produced are present, which are obtained due to tensile forces applied on connecting rod during its analysis. Fig.4 and Fig.5 shows Von-Mises stress distribution in connecting rod for conventional and AMR meshing techniques respectively.

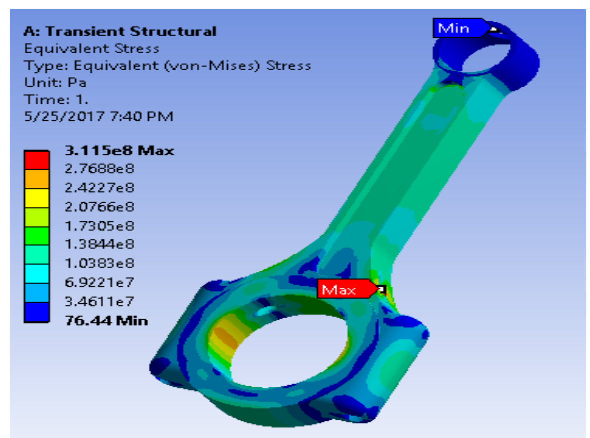

Fig. 4 Von-Mises stress distribution in connecting meshed with conventional technique

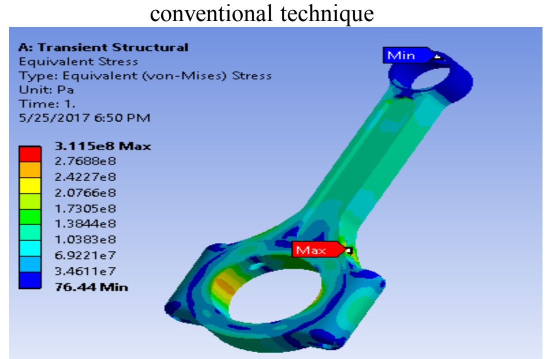

Fig. 5 Von-Mises stress distribution in connecting meshed through AMR technique

From the analysis results related to stress distribution in connecting rod due to tensile loading, it is clear that development of maximum stresses found at its big end. From Fig. 4 and Fig.5 it is observed that by adopting conventional

FEA and AMR meshing techniques no significant difference found in stress values different points. So on the basis the of above analysis results it is concluded that both techniques have somehow equal importance in case of calculation of values of stresses at different points.

In Fig.6 and Fig.7 it is shown that deformation produced in connecting rod when the its analysis under tensile loads has been performed by following conventional and AMR meshing techniques respectively. While performing deformation analysis produced in connecting rod, it is noticed that maximum deformation occurs at the cap of big end side of the connecting rod. By comparing values of deformation at different points obtained during the analysis shown in Fig.6 and Fig.7 it is noticed that there is no any difference in values of deformation observed during the analysis carried out through conventional and AMR meshing techniques.

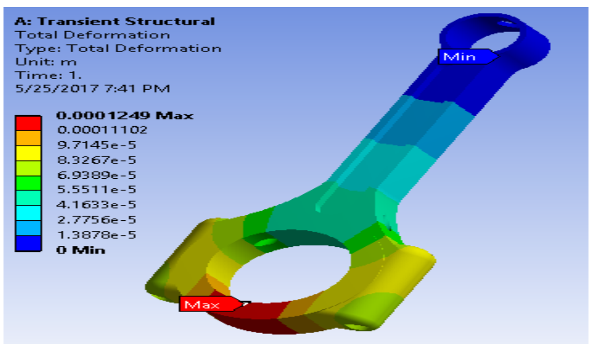

Fig. 6 Deformation in connecting meshed with conventional technique

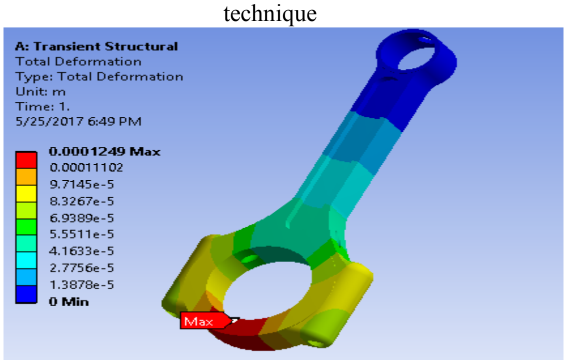

Fig. 7 Deformation in connecting meshed through AMR technique

In this section stresses and deformation produced in connecting rod due to compressive force are present. It has been already discussed that compressive load is assumed to be static. In Fig.8 & Fig.9 Von-Mises stresses induced in connecting rod are shown, which are obtained by performing its analysis during convectional FEA and AMR meshing techniques.

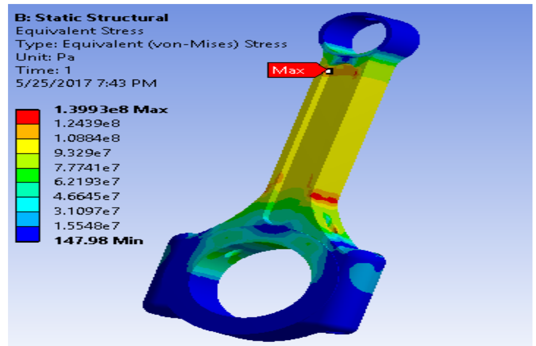

Fig. 8 Von-Mises stress distribution in connecting meshed with conventional technique

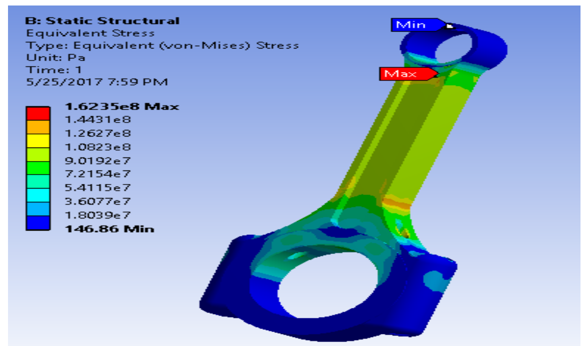

Fig. 9 Von-Mises stress distribution in connecting meshed through AMR technique

From Fig.8 and Fig.9 it is also noticed that maximum stresses produced in the connecting rod at its shank under compressive loading. By comparing results of stress at different poits obtained through convectional FEA and AMR meshing techniques, it is observed that maximum stresses produced in connecting rod when a load of 22 MPa has been applied during its analysis.

Fig.10 and Fig.11 shows values of deformation under the compressive loads when analysis of connecting rod has been carried out by applying conventional FEA and AMR meshing methods. From Fig.10 and Fig.11 it is observed that maximum deformation occur at big end of connecting rod and it decreases at the piston pin end. By comparing deformation analysis results obtained by applying conventional FEA and AMR meshing methods, it has been observed that values of deformation obtained during analysis are same for both meshing methods.

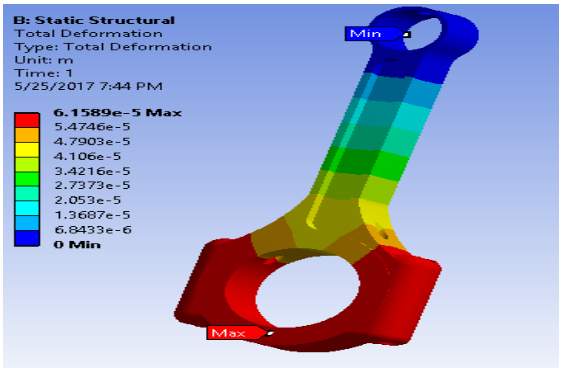

Fig. 10 Deformation in connecting meshed with conventional technique

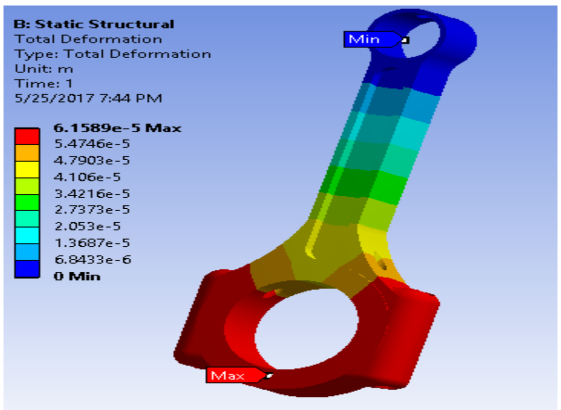

Fig. 11 Deformation in connecting meshed through AMR technique

In Fig.12 comparison of stress results are shown for conventional FEA and AMR meshing methods. By comparing analysis for values of stresses (i-e von-mises and shear stress) at different points in the graph, it is noticed that values of stresses predicted through conventional meshing technique has close relationship with AMR meshing results. From the Fig.12 it is also analyzed that values of stresses increase non-linearly with time for both types of meshing methods

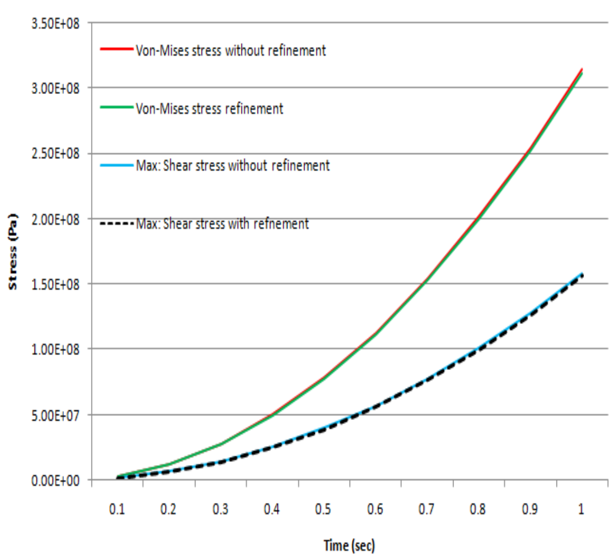

Fig. 12 Showing the comparison of stress results of conventional and AMR meshes

V. Conclusion

Present study aims to enhance FE solution accuracy through adopting newly developed Adaptive Mesh Refinement (AMR) technique. Dynamic structural behavior of connecting rod under time varying loads is evaluated through conventional and advanced AMR discretization technique. In this research also the dynamic structural analysis of connecting rod has been conducted for maximum tensile and compressive forces experienced throughout the cycle. It is predicted through the analysis results that maximum stresses have been produced in connecting rod at shank and big end for compressive and tensile loads respectively. While comparing results obtained through conventional and advanced AMR discretization technique, it is observed that 15.7% increase in Von-Mises stresses has been noticed by applying AMR technique for compressive loads. Whereas in case of tensile loading no effect is observed

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