Finite Element Analysis of Pre-Tensioning of Exhaust Manifold

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Abstract- Finite element analysis (FEA) can be used to calculate stresses acting on the exhaust manifold when prescribed bolt forces acting on it, thus provide realistic evaluation of its structural strength and durability performance. This makes it possible to analyse many critical design iteration even before one prototype is built. FEA can provide valuable information that assist in finding the root cause of the failure and providing design improvement directions. The present work describes that in first case neglecting the effect of temperature the calculation of stresses acting on the exhaust manifold when bolt forces are applied on it. In second case considering the effect of temperature calculation of stresses acting on the exhaust manifold when bolt forces applied on it. Both analyses can be carried out with three different materials like Gray cast iron, stainless steel and carbon-carbon composite material. The results obtained assure the one is the best material among three for the exhaust manifold.

Keywords:- ***Finite element analysis (FEA), bolt forces & carbon-carbon composite material.***

1. INTRODUCTION

The exhaust manifold is a tube for carrying the exhaust gases away from the engine cylinders and further through the muffler into the atmosphere. It is bolted to the side of the cylinder block on L-head engines and to the side of the cylinder head on I-head engines. On V-8 engines, there are two exhaust manifolds, one for each bank of cylinders. On some V-8 engines, each manifold is connected to a separate exhaust pipe, muffler and tail pipe. On others, they are connected by a crossover pipe and exhaust through a common muffler and tail pipe.

The exhaust manifolds are designed to avoid overlapping of exhaust strokes, as far as possible, thus keeping the back pressure to minimum this is often done by dividing the exhaust manifold into two or more branches, so that two cylinders willn't exhaust into the same branch at the same time. Large radius bends are provided in the design to eliminate any restriction to flow. A heat tube may also be provided to furnish heat to the built-in automatic choke unit of the carburetor.

Exhaust pipes are generally of 50mm in outside diameter having 1.5 mm wall thickness. Exhaust pipe is connected with the exhaust manifold through a flange and studs and nuts. Both exhaust pipe and muffler are mounted to prevent vibration and exhaust noise. Exhaust pipe is supported with the chassis and supports allow engine movement and expansion and contraction with temperature change.

2. LITERATURE REVIEW

Cristiana Delpretea, Raffaella Sesanaa, Andrea Vercellia[1] studied the stress and stains on the exhaust manifold subjected to thermo-mechanical fatigue loading. Due to the complexity of the components geometry, stresses and strains field becomes multiaxial, worsening the fatigue resistance. In this paper several damage models are applied and compared on a case study.

Xueyuan Zhang, Yu Luo, Jianhua Wang[2] investigated the welding residual stress distribution along the structure was predicted by thermo-elastic-plastic finite element method. Then, in attempt to simulate the thermal boundary co-efficient of the exhaust manifold wall under actual loading conditions, the internal flow fields are obtained using computational fluid dynamics software. The film heat transfer coefficient and the temperature of fluid boundaries were calculated. Furthermore, the thermal boundary conditions and welding residual stresses are mapped to the structural element surfaces of the exhaust manifold based on the commercial FE code ABAQUS. The temperature field of the exhaust manifold as well as the thermal stresses and distortions were simulated. Meanwhile the welding residual stresses effects on the modal analysis and thermal stresses were also performed.

Benoit, M. H. Maitournam, L. Remy, Oger[3] studied elastic viscoplastic structure subjected to cyclic loading, can present different asymptotic behaviors, namely: elastic shake- down which special case is perfect elasticity, plastic shakedown and ratchetting. These plastic strain behaviors are closely related to the damage induced at the macroscopic scale. At the microscopic scale, the role of microplasticity in the different mechanisms of fatigue crack nucleation and propagation has been extensively analysed through microstructure-sensitive simulations.

Brian Daniels, Rob Mitchell[4] studied high temperature durability assessment techniques, such as strain-range partitioning, it will be possible to derive CAE metrics to allow the optimisation of engine components to robustly meet the in-service performance requirements at the design stage. Requirement for component test bed development and on-road testing will also be much reduced. Further the reduction in the reliance on prototype build and testing should reduce the time to market by stabilising the design earlier and eliminating late program design change. Virtual Design Validation (VDV) for high temperature components with regard to the new design of exhaust manifolds using a cast iron material traditionally used for manifold design at lower temperatures. Moving away from a design process which relied primarily on component testing towards a predictive capability based on standardised material data and computer predicted performance of components has resulted in reductions in development costs and time scale.

Andrei Constantinesc, Eric Charkaluk, Guy Lederer, Laetitia Verger[5] studied the damaging cycle of an exhaust manifold corresponds to the start–full load–stop cycle of the engine. The manifold is subjected to huge temperature changes, implying that at low temperatures the structure has elastoplastic behaviour and that at high temperatures the structure has viscoplastic behaviour. The thermal and mechanical finite element analysis and fatigue analysis can be carried for the life prediction of the structure.

3. METHODOLOGY

Finite element method has become a very powerful tool for a wide range of engineering problems. Applications range from deformation and stress analysis of automotive, aircraft, building and bridge structures.

In this method of analysis, a complex region defining a continuum is discredited into simple geometric shapes called finite elements. The element material property and the governing relationships are considered over these elements and expressed in terms of unknown values at nodes. An assembly process, duly considering the loading and constraints, results in the set of equations. Solution of this equation gives an approximate behaviour of the continuum.

- Generating the finite element model of the exhaust manifold.
- Finding out the temperature distribution in the Exhaust manifold.
- Stress analysis can be carried out on the exhaust manifold.

4. GEOMETRY AND MODEL

The exhaust manifold assemblage being analyzed shown in Figure 1. It consists of a four tube exhaust manifold with three flanges, bolted with seven bolts to a small section of the engine head. The manifold is cast from gray iron with a Young's modulus of 138 GPa, a Poisson's ratio of 0.283, and a coefficient of thermal expansion of 13.8 x $10^{-6}/^{o}$c.

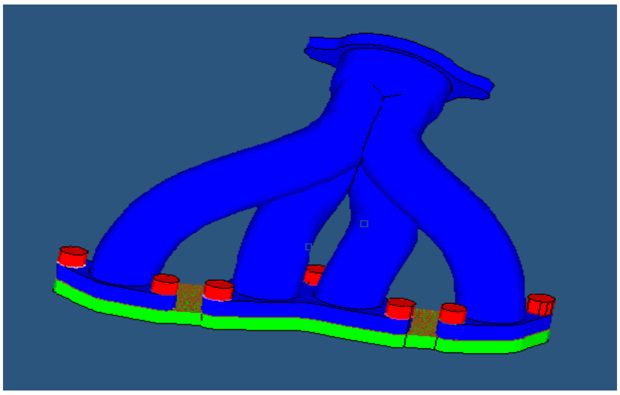


Fig. 1 Geometry of the Exhaust Manifold

The three manifold flanges contain a total of seven bolt holes. The 9.0 mm diameter of these bolt holes is slightly greater than the 8.0 mm diameter of the bolt shanks to allow for some unobstructed lateral motion of the manifold. The head is made from aluminium, with a Young's modulus of 69 GPa, a Poisson's ratio of 0.33, and a coefficient of thermal expansion of 22.9 x $10^{-6}/^{o}$c. Seven bolts fasten the manifold to the head. The bolts are made from steel, with a Young's modulus of 207 GPa, a Poisson's ratio of 0.3, and a coefficient of thermal expansion of 13.8 x $10^{-6}/^{o}$c. The bolt shanks have a diameter of 8 mm. The bolt head diameters are 16 mm. All three structural components (manifold, head, and bolts) are modelled with three-dimensional continuum elements. The model consists of 7450 first-order brick elements

LOADING AND BOUNDARY CONDITIONS

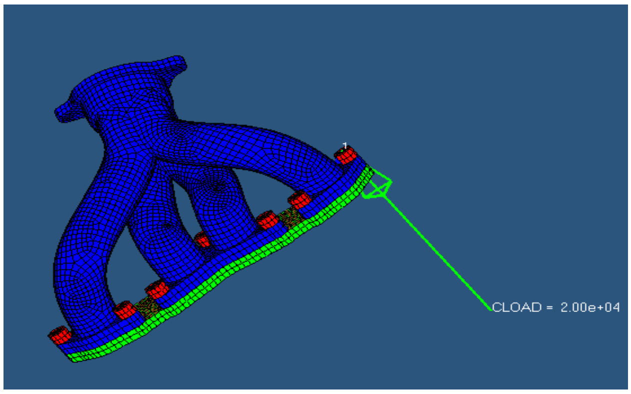


Fig. 2 Loading and Boundary Conditions

It is assumed that the engine head is securely fixed to a stiff and bulky engine block, so the nodes along the base of the head are secured in the direction normal to the base (the global x-direction) but are free to move in the two lateral directions to account for thermal expansion. It is also assumed that the bolts are threaded tightly into the engine head, with the bolt threads beginning directly beneath the section of engine head modelled. Therefore, the nodes at the bottom of the bolt shanks are shared with the nodes of the surrounding engine head elements and are also secured in the global x-direction. The manifold flanges are sandwiched between the top of the engine head and the base of the bolt heads using contact pairs. The line of action of the bolt forces (bolt shank axes) is along the global x degree of freedom.

In the first step of the analysis each of the seven bolts is tightened to a uniform bolt force of 20 kN. For each bolt we define a “cut,” or pre-tension section, and subject the section to a specified tensile load. As a result, the length of the bolt at the pre-tension section will change by the amount necessary to carry the prescribed load, while accounting for the compliance of the rest of the system. In the next step the prescribed bolt loads are replaced by the condition that the length changes calculated in the previous step remain fixed. The remainder of the bolt is free to deform.

The same procedure is used for all seven bolts. First, pre-tension sections are defined as “cuts” that are perpendicular to the bolt shank axes by defining surfaces on the faces of a group of elements within each bolt shank. The line of action of the bolt force is in the direction that is normal to this surface. Next, each bolt is assigned an arbitrary, independent node that possesses one degree of freedom (dof 1), to which the bolt force will be applied. These nodes are called the “pre-tension nodes”.

In Step 1 of the analysis a concentrated clamping load of 20 kN is applied to each of the pre-tension nodes in node set BOLTS. In Step 2 the concentrated load from Step 1 is removed and replaced by a “fixed” boundary condition that will hold the pre-tension section length changes from Step 1 fixed. Over the course of a step in which a load is replaced by a boundary condition, CF1 is ramped down, while RF1 is ramped up to replace it. Therefore, the total force across the bolt is the sum of the concentrated force (CF1) and the reaction force (RF1) on the pre-tension node. This total force is available as TF1.

5. STATIC ANALYSIS

5.1 Without considering the temperature effect

Static analysis is performed to know the maximum stress as well as maximum deformation developed on the exhaust manifold. The name static indicates that the load is constant, that is load not varying with respect to time.

In the first step of structural analysis, bolt forces are applied. The assembly of the exhaust manifold with bolts is torque driven in general, where the bolts are tightened into yield. Based on bolt dimension, strength class information, thread pitch, friction coefficient on the mating surfaces and assembly torque (and its tolerances) an initial estimation of the bolt force variation can be calculated.

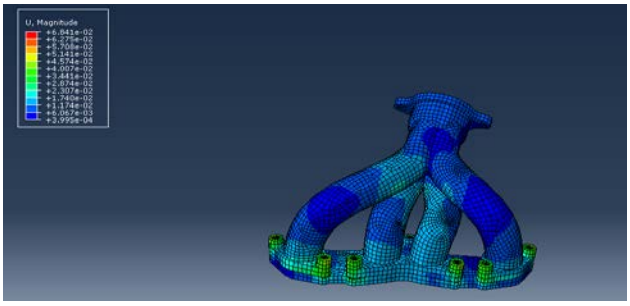


Fig. 3 Deformation counter plot for exhaust manifold with cast iron material

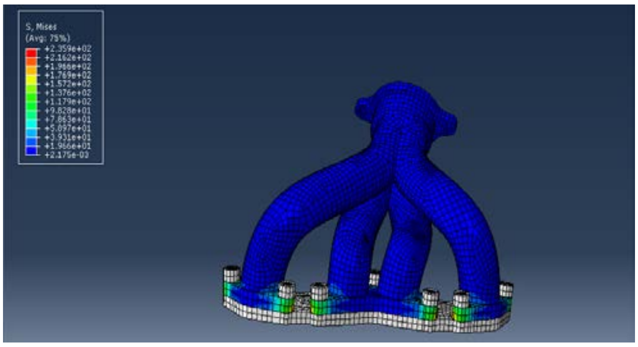


Fig. 4 Von-Mises stress counter plot for exhaust manifold with cast iron material

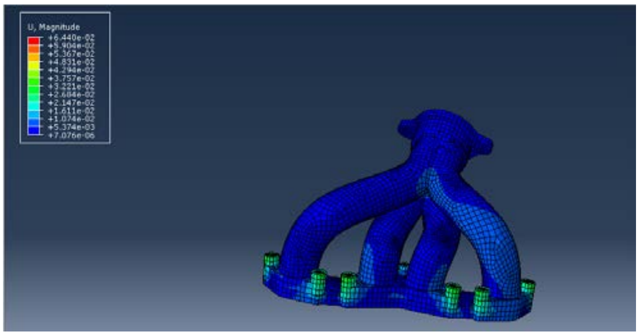


Fig. 5 Deformation counter plot for exhaust manifold with stainless steel material

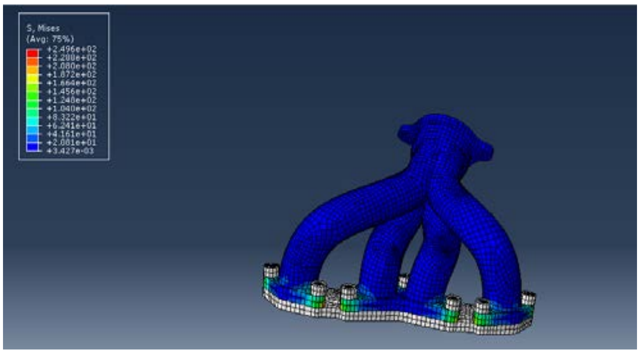


Fig. 6 Von-Mises stress counter plot for exhaust manifold with stainless steel material

5.2 With considering the temperature effect

The temperature distribution is the most important boundary condition to drive the structural analysis. During an engine development process, different levels of thermal boundary conditions are used. In a very early stage of a development, only a rough initial geometry is available. In this stage a combustion process is being developed and might not be fixed. Analytical results are not available to deduce differentiated boundary conditions for a thermal analysis. Boundary conditions are initially derived based on benchmarking of similar designs and estimated gas peak temperatures. At a later point in time, the combustion process is simulated by analysis. This gives the opportunity to develop a more detailed set of boundary conditions for thermal analysis.

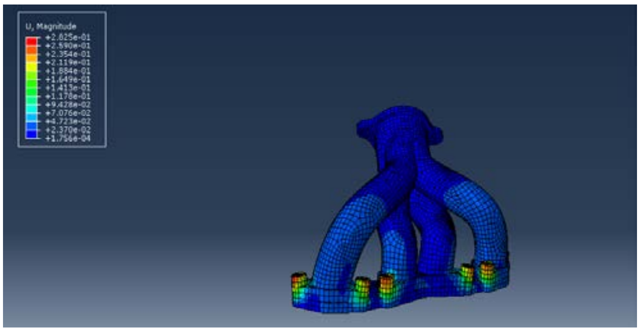


Fig. 7 Deformation counter plot for exhaust manifold with carbon-carbon composite material

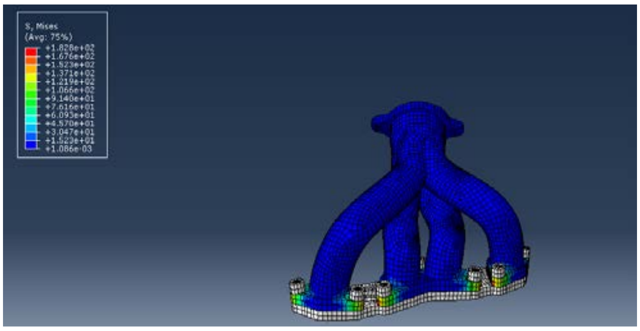


Fig. 8 Von-Mises stress counter plot for exhaust manifold with carbon-carbon composite material

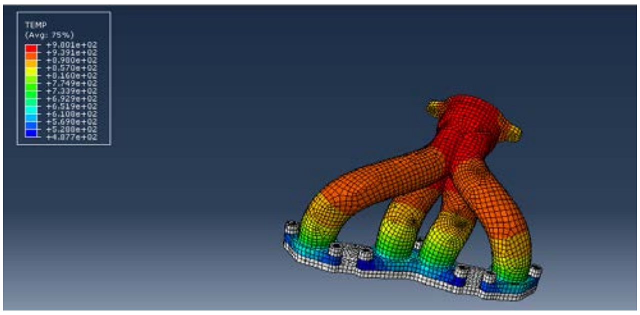


Fig. 9 Temperature distribution in exhaust manifold

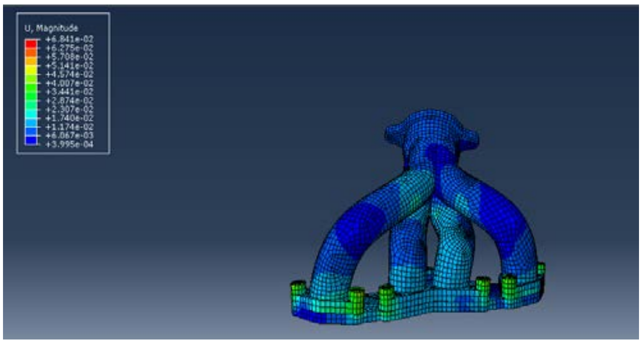
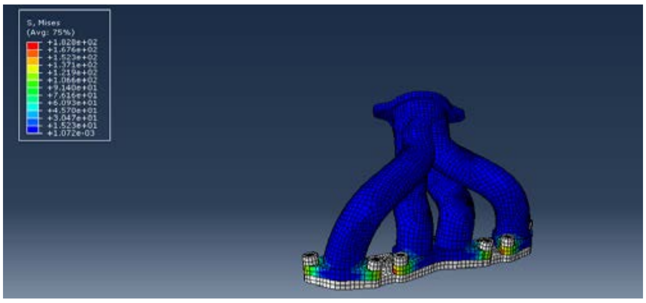


Fig. 10 Deformation of exhaust manifold with cast iron material



Von-Mises stress counter plot for exhaust manifold with cast iron material

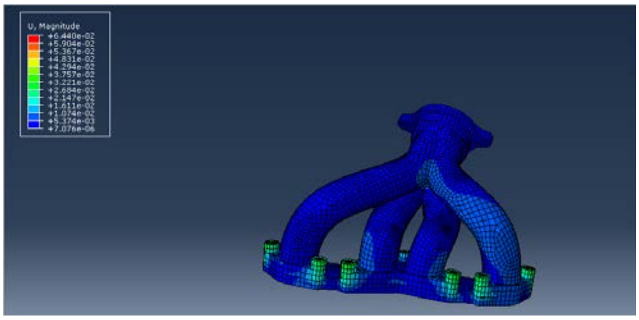


Fig. 11 Deformation counter plot for exhaust manifold with stainless steel material

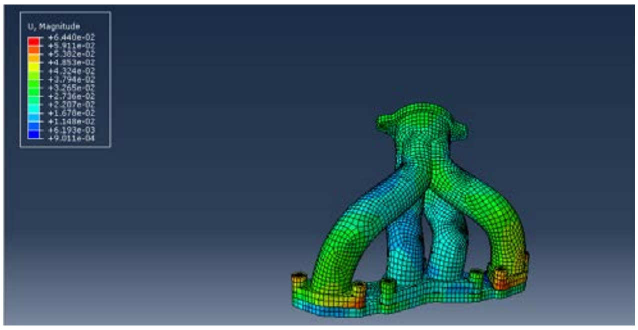


Fig. 12 Von-Mises stress counter plot for exhaust manifold with stainless steel material

During thermal cycling, in addition to inelastic deformations, also the evolution of bolt pretension is to be monitored. When the structure is heated up, axial and lateral deformations of the manifold cause the stresses in the bolt to increase. Once the yield limit of the bolt is exceeded, a noticeable pretension loss could be observed in cold state.

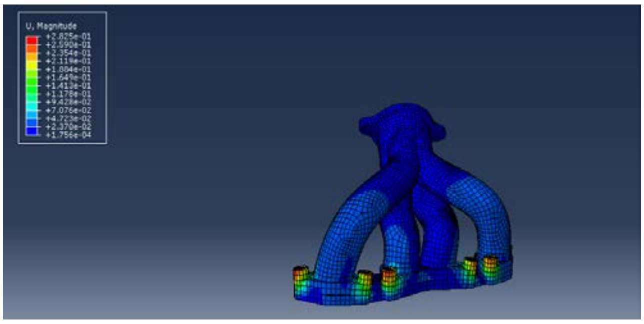


Fig. 13 Deformation counter plot for exhaust manifold with carbon- carbon composite material

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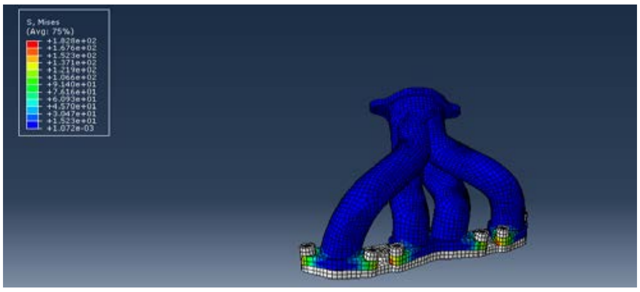

Fig. 14 Von-Mises stress counter plot for exhaust manifold with carbon-carbon composite material

6. NORMAL MODE ANALYSIS

The usual first step in performing a dynamic analysis is determining the natural frequencies and mode shapes of the structure with damping neglected. These results characterize the basic dynamic behaviour of the structure and are an indication of how the structure will respond to dynamic loading.

Natural Frequency: The natural frequency of a structure is the frequencies at which the structure naturally tends to vibrate if it is subjected to a disturbance. For example, the strings of a piano are each tuned to vibrate at a specific frequency. Some alternate terms for the natural frequency are characteristic frequency, fundamental frequency, resonance frequency and normal frequency.

Mode Shapes: The deformed shape of the structure at a specific natural frequency of vibration is termed its normal mode shape of vibration. Some other terms used to describe the normal mode are mode shape, characteristic shape and fundamental shape. Each mode shape is associated with a specific natural frequency. Natural frequencies and mode shapes are functions of the structural properties and boundary conditions.

Reasons to Compute Normal Modes

There are many reasons to compute the natural frequencies and mode shapes of a structure. One reason is to assess the dynamic interaction between a component and its supporting structure. For example, if a rotating machine, such as an air conditioner fan, is to be installed on the roof of a building, it is necessary to determine if the operating frequency of the rotating fan is close to one of the natural frequencies of the building. If the frequencies are close, the operation of the fan may lead to structural damage or failure.

The results of dynamic analysis are sometimes compared to the physical test results. A normal modes analysis can be used to guide the experiments. In the pre-test planning stages, a normal modes analysis can be used to indicate the best location for the accelerometers. After the test, a normal modes analysis can be used as a means to correlate the test results to the analysis results.

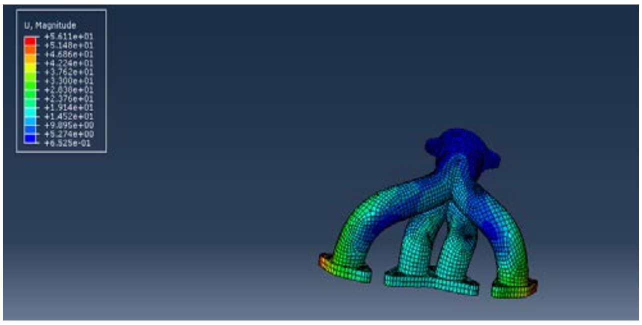

Fig. 15 1st mode shape with natural frequency 289.48 Hz

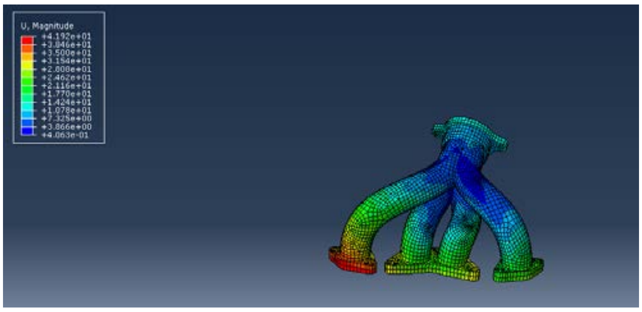

Fig. 16 2nd mode shape with natural frequency 365.11 Hz

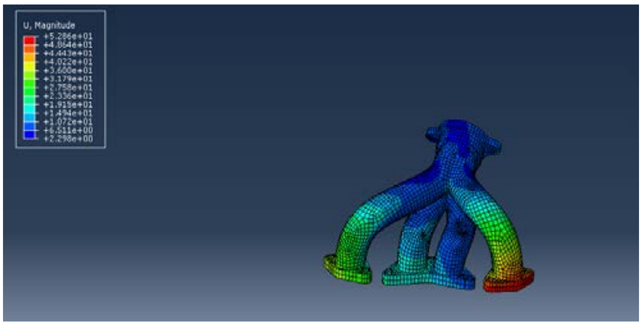

Fig. 17 3rd mode shape with natural frequency 417.20 Hz

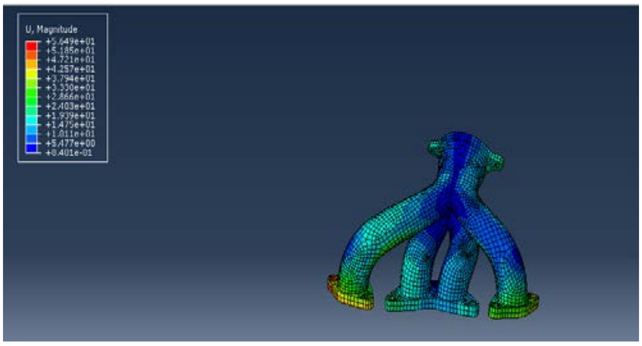

Fig. 18 4th mode shape with natural frequency 576.15 Hz

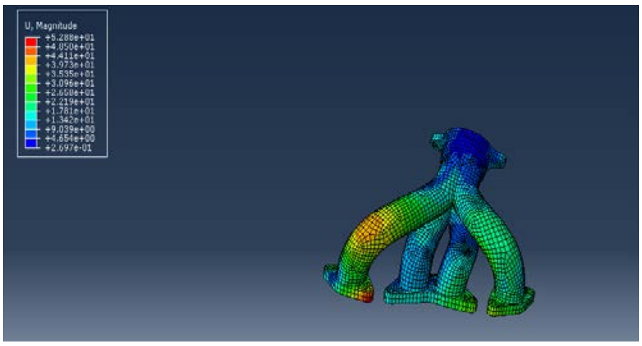

Fig. 19 5th mode shape with natural frequency 670.81Hz

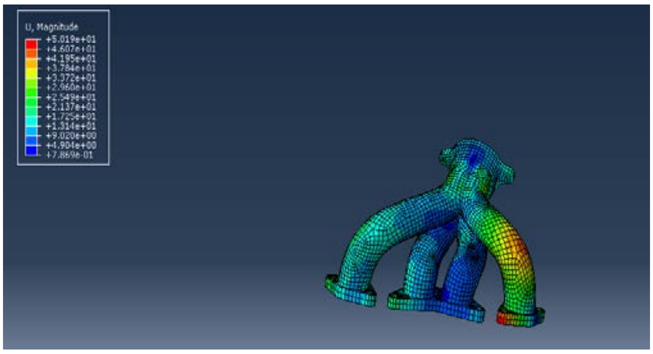

Fig. 20 6th mode shape with natural frequency 794.52 Hz

Design changes can also be evaluated by using natural frequencies and normal modes. Does a particular design modification cause an increase in dynamic response Normal modes analysis can often provide an indication.

7. CONCLUSION

- Finite element approach is used for analysis of the exhaust manifold
- Meshed model of exhaust manifold satisfied all the quality criteria's, hence results are accurate.
- The natural frequency and mode shape of exhaust manifold obtained by normal mode analysis. Depending upon the natural frequency of exhaust manifold it is easy to avoid resonance condition during the assembly exhaust manifold to the engine head.
- When we consider the first case that is by neglecting the temperature the min stress value observed in carbon-carbon composite material this is because the young modulus is smaller compare to gray cast iron and steel.
- In second case we consider the temperature effect in this max stress observed in cast iron material because thermal conductivity value should be higher than steel and carbon-carbon composite material this results faster heat dissipation hence max stress value observed in gray cast iron material but thermal conductivity value is smaller for carbon-carbon composite material hence minimum stress value observed in this material
- But because of high cost, low shear strength and susceptibility to oxidations at high temperatures and yield strength is very low hence carbon-carbon composite material is not used.
- The yield strength of the steel is much higher than other two material and also tensile yield strength should be higher for steel this allows material to withstand much higher tensile loads and also higher tensile strength will give a lower stress concentration hence from this discussion stain steel is best material to use.
- The max stress values observed in the analysis are well within the yield strength hence the design is safe.

8. FUTURE SCOPE

- Similar analysis can be followed by changing the orientation of the tubes with different angles.
- Dynamic analysis can be carried out for the impact loading and random changes of the load on exhaust manifold.
- Fatigue life estimation of the exhaust manifold can be performed.

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