ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A HEAVY DUTY DIESEL ENGINE EXHAUST MANIFOLD THERMO MECHANICAL FATIGUE TEST RIG DESIGN, ANALYSIS AND VERIFICATION

M.Sc. THESIS

Uğur ERKEN

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

AĞIR VASITA DİZEL MOTOR EGZOZ MANİFOLDU TERMOMEKANİK YORULMA TEST SİSTEMİ TASARIMI, ANALİZİ VE DOĞRULANMASI

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EKİM 2015

Uğur ERKEN, a **M.Sc.** student of ITU **Institute of Science Engineering And Technology** student ID **503121513**, successfully defended the **thesis/dissertation** entitled "**A HEAVY DUTY DIESEL ENGINE EXHAUST MANIFOLD THERMO MECHANICAL FATIGUE TEST RIG DESIGN, ANALYSIS AND VERIFICATION**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family,

FOREWORD

I would like to express my reverence for my advisor Prof.Dr. Ata MUĞAN and co-advisor Dr.Umud Esat ÖZTÜRK who had great affect and intentness on this study. They did many critical touch on this study, I am grateful for all.
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ABBREVIATIONS

TMF **:** Thermo-Mechanical Fatigue
LCF **:** Low Cycle Fatigue
HCF **:** High Cycle Fatigue
CAD **:** Computer-Aided Drawing
CAE **:** Computer-Aided Engineering
FEA **:** Finite Element Analysis
FEM **:** Finite Element Method
RPM **:** Round Per Minute
SAE **:** Society of Automotive Engineers
DOF **:** Degree of Freedom
ASTM **:** American Society for Testing and Materials
CFD **:** Computational Fluid Dynamics
CHT **:** Conjugate Heat Transfer
CNG **:** Compressed Natural Gas
HiSiMo **:** High Silicon Molybdenum
DCI **:** Ductile Cast Irons
PEEQ **:** Equivalent Plastic Strain
CEEQ **:** Equivalent Creep Strain
HTC **:** Heat Transfer Coefficients

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A HEAVY DUTY DIESEL ENGINE EXHAUST MANIFOLD THERMO-MECHANICAL FATIGUE TEST RIG DESIGN, ANALYSIS AND VERIFICATION

SUMMARY

In past decades, there is a significant improvement in every respect of automotive industry. New special materials have been started to use. New technologies are also started to use in automotive industry. The engine is most important part of a vehicle for all time. With competition in the market, engine manufacturers need to manufacture more economically while guaranteeing higher performance and reducing exhaust emissions due to legal regulations and environmental issues.

The main goal is to produce silent, low-cost and lighter new generation green engines with low exhaust emissions that also present higher performance and consume less fuel. There are many research studies on this issue and progresses to meet expectations. Increasing the peak firing pressure and improvements on the design has provided important solutions for these expectations. On the other side, thermal mechanical fatigue (TMF) occurring during the start-stop cycle of the engine has become an important issue with higher exhaust gas temperature and light designs. This issue should be taken into consideration more carefully with these modifications, increasing internal pressure and working temperature inside engines. Exhaust manifold is one of the parts exposed to the highest temperatures in a vehicle. In addition, its performance is very critical for new generation green engines. High silicon molybdenum (HiSiMo) ductile cast iron (DCI) is commonly used for high temperature engine parts, such as exhaust manifolds, which are also exposed to harsh thermal cycles. HiSiMo is an alloy developed specifically for such components. HiSiMo Grade 3 according to ASTM standards is the most powerful alloy used as exhaust manifold material. Materials show different mechanical and thermal properties with different temperature and working conditions. To obtain certain properties, physical tests with real working conditions and temperatures are necessary but costly and time-consuming.

Critical parts such as exhaust manifold must be guaranteed for satisfying thermal mechanical fatigue behavior. Best way for TMF behavior test is the use of a test vehicle or using engine dynamometers to simulate the real road and combustion conditions. All parameters have an effect on the fatigue life but some of them have higher priority. In reality, a test vehicle is very close to a mass production step. After this stage, making design changes are very difficult. Automotive manufacturers prefer to complete the testing of these critical parts with special test rigs. Despite the complete engine requirement for a test vehicle or engine dynamometers, specific test rigs could work without a complete engine but still simulates the real situation. In recent years, specific test rigs are become very important and useful for research projects. TMF tests are commonly very long time consuming and expensive.

Minimizing the test rig with only necessary parts and equipment provide more test opportunities with the same cost and facility. A new TMF test rig is designed for a heavy duty diesel engine exhaust manifold with using commercial CAD program CATIA V5. The TMF test rig will be installed at the Ford Otosan Kocaeli Plant Test Center. It is tried to use existing equipment such as natural gas burner and vibrational shaker. A finite element method program called HyperMesh is used for the calculation of natural frequencies of the new designed components and the design is revised to achieve the natural frequency targets.

On the other hand, it is possible to achieve great profit in the design stage with computer-aided analysis. With the correct material and working conditions data, advanced TMF analysis give accurate results. To compare the test and analysis results is important for future works. Due to the cost and long time-consuming behavior, it is not desired to test all the design changes. To observe the effects of the numerous design iterations, TMF analysis is the best practical way. However, to verify material and working condition properties, TMF tests are required at the beginning. Commercial CFD analysis program STAR CCM+ is used for heat transfer analysis inside exhaust manifold during hot gas transfer. These CFD results are used on HyperMesh model and applied to ABAQUS program for structural analysis. To calculate a fatigue life result, commercial analysis software nCODE DESIGNLIFE is used.

In this study, the main goal is to develop a methodology for thermal-mechanical fatigue life estimation of diesel engine components, design a thermal-mechanical fatigue test rig for exhaust manifold, simulate thermal-mechanical fatigue loading with some conditions in the software in a virtual environment to develop a reliable analysis methodology and verify the design of critical engine parts. In addition to cost advantages, pollution created by combustion of thousands of liters of fuel in engines will be reduced by using natural gas because the diesel/gasoline is not used in this TMF rig. Thus, an environmentally friendly test method is developed for green engines with less equipment and dependency to other engine parts.

AĞIR VASITA DİZEL MOTOR EGZOZ MANİFOLDU TERMOMEKANİK YORULMA TEST SİSTEMİ TASARIMI, ANALİZİ VE DOĞRULAMASI

ÖZET

Son dönemde otomotiv endüstrisinde her anlamda çok önemli gelişmeler yaşanmaktadır. Bilimsel ve teknolojik ilerlemenin sonucunda elde edilen yeni yöntemler, yazılımlar ve donanımlar için otomotiv her zaman iyi bir uygulama alanı olmuştur. Günümüzde farklı sınıf ve özellikteki araçlar hayatımızın vazgeçilmez bir parçası olmuştur. Gelişen ve büyüyen rekabetçi otomotiv piyasasında önemli bir rol sahibi olmak isteyen üreticiler de değişen çevre ve müşteri taleplerine göre sürekli kendilerini yenilemek ve geliştirmek için çalışmalarını sürdürmektedirler. Başlangıçtan itibaren motor bir aracın en önemli bileşenidir ve temel araştırma-geliştirme faaliyetleri burada yoğunlaşmıştır. Motor üreticileri her zaman daha yüksek performanslı motorlar yapmaya çalışırken aynı zamanda rakiplerine oranla maliyetlerini de daha düşük seviyede tutmaya çalışırlar. Öte yandan özellikle Avrupa ülkelerinin başını çektiği egzoz gazı emisyon oranlarını sağlamak ve çevreyle dost bir motor yapmak da artık bir gereklilik haline gelmiştir.

Motor üreticilerinin temel amacı sessiz, düşük maliyetli, hafif, emisyon seviyesi ve yakıt tüketimi düşük ancak yüksek performanslı uzun ömürlü çevre dostu ürünler ortaya çıkarmaktır. Bu konuda gerek akademik gerekse de uygulamalı olarak dünyanın her yanında çalışmalar halen devam etmektedir. Çalışmaların belirgin sonucunu olarak son 20 yıldaki motorların emisyon, yakıt tüketimi ve performans çıktılarına bakarak görebiliriz. Daha yüksek performanslar beraberinde daha yüksek yanma sıcaklıkları ve basınç değerleri getirmektedir. Motorda oluşan yüksek sıcaklık, malzemelerin mekanik davranışını ciddi oranda etkilemektedir. Bu yüzden daha önceden kullanılan malzemeler artık bu sıcaklık ve çalışma şartlarına cevap veremediği için özel alaşımlı malzemeler kullanılmaya başlanmıştır. Sıcaklık farklılıklarından dolayı oluşan yorulmaya termal-mekanik yorulma (Thermal Mechanical Fatigue-TMF) denir.

Motorlarda meydana gelen TMF durumu genelde kısa ömürlü yorulma olarak nitelendirilir ve etkiledikleri parçaların ömürleri 10^3-10^4 çevrim mertebesine kısaltırlar. Araç çalışmaya başladıktan sonra çalışmaya devam ettiği süre boyunca parçalar bu sıcaklıklara maruz kalır sonrasında araç durduğunda ise ortam sıcaklığına geri dönerler. Aracın her çalışıp durması bir çevrim olarak nitelendirilir. Hem termal-mekanik yorulma durumuna dayanıklı hem de yüksek performans taleplerine cevap verebilecek yeni nesil egzoz manifoldları için yüksek silisyum ve molibden (HiSiMo) alaşımlı sünek dökme demir en çok kullanılan malzemelerin başında gelir. Geliştirmeler sonucunda "Grade 3" olarak adlandırılan özel alaşım bu çalışmada incelenen ağır ticari dizel motorun egzoz manifoldunda da kullanılmıştır.Bu manifold yüksek sıcaklıklarda meydana gelen genleşmeleri sönümleyecek şekilde üç parçalı olarak tasarlanmıştır ancak parçaların kendi içinde birden fazla bağlantı

noktası olması sebebi ile birim şekil değişimleri ciddi gerilmeler meydana getirmektedir.

Yorulma analizlerinde karşılaşılan önemli sorunlardan biri de malzeme modellerinin oluşturulmasıdır. Malzeme modellemesi ile ilgili çok sayıda yaklaşım yapılmıştır. Yaklaşımlarda dikkate alınan faktörler artıkça malzeme modellerinin gerçeğe olan yakınlıkları da artmaktadır. Ancak modelin dikkate aldığı faktör sayısının artması aynı zamanda modeli oluşturmak için yapılacak deney sayısını ve maliyetini artırmaktadır. Özellikle malzemelerin sıcaklığa bağlı yorulma modellerinin oluşturulması oldukça uzun ve maliyetli bir iş olduğu için sadece belli başlı malzemelerin modelleri mevcuttur.

Seri üretimde motor kafa-blok, egzoz manifoldu, pistonlar gibi kritik parçaların dayanımından ve TMF ömründen emin olmak çok önemlidir. Bu tarz uzun ömürlü parçaların genelde aracın ömrü boyunca çalışması beklenir. Ancak ekonomi, hafiflik ve uzun ömürlülük kriterlerinin bir arada istendiği durumlarda optimum tasarımların yapılması önem kazanır yani parçanın öngörülen çevrim sayısına yakın bir değerde hasara uğraması başarılı bir tasarım olarak kabul edilir. Bu durumda parçaların ömürlerinin tahmin edilebilmesi önem kazanır. Farklı yaklaşım ve kabuller eşliğinde uzun yıllar mertebesinde olan çalışma ömürlerini haftalar içinde yapılan testlerle belirlemek mümkündür. Testlerin gerçekçi olması için en iyi seçenek gerçek araçlar ile özel yolların ve koşulların sağlanması veya motor dinamometrelerinde testlerin koşulmasıdır. Ancak bu yöntemler oldukça pahalı ve yüksek ilk yatırım maliyeti gerektirmektedir. Ayrıca test etmek istediğimiz parçanın ait olduğu araç veya motor hazır değilse test yapılamayacaktır. Test yapmak istediğimiz kritik parçanın hasara uğraması tüm testi sonlandıracağı için motor üreticileri motor bloğu, piston, krank mili, egzoz manifoldu gibi parçalarını tasarım geliştirme esnasında tekil olarak test edecekleri özel düzenekler kullanırlar. Parçaya veya sisteme ait bu test düzenekleri ile çok farklı koşullar altında farklı malzeme ve tasarıma sahip parçalar diğer değişkenlerin etkilerinden bağımsız olarak test edilebilir. Parçaya veya sisteme özel test düzeneklerinin gerçek çalışma şartlarını yansıtabilmesi için minimum dahil edilmesi gereken yardımcı sistemlerin ve oluşturulacak koşulların tespiti ve uygulanması kritik öneme sahiptir.

Bu tez kapsamında ağır ticari dizel motor egzoz manifoldu TMF ömür testleri için Ford Otosan Kocaeli Fabrikası bünyesinde bulunan test merkezinde kurulacak test düzeneğinin tasarımları ticari modelleme yazılımı olan CATIA kullanılarak yapılmıştır. Tasarımlarda daha önceden Ford Otosan ve İTÜ'nün ortaklaşa kurdukları motor kafa-blok TMF test donanımı önemli bir referans olmuştur. Mevcut doğalgaz brülörü ve 3 eksenli titreşimli sallayıcıyı kullanacak şekilde test odasındaki fiziki şartları dikkate alındı ve sallayıcının ağırlık kapasitesi içinde kalacak şekilde tasarım gerçekleştirildi. Tasarlanan sistemin statik ve titreşim karakteristiği HyperMesh ticari sonlu elemanlar programıyla hesaplandı ve tasarımlar hedefleri yakalamak için güncellendi.

Tasarım çalışmaları sırasında sallayıcı ekipmanın kapasite sınırları dolayısıyla egzoz manifoldunun normalde bağlandığı motor kafa-blok yapısı kullanılamamıştır. Onun yerine içinde soğutma kanalları olan bir yapı tasarlanmıştır. Egzoz manifoldunda normal çalışma şartlarında meydana gelen sıcaklık dağılımının test sırasında da gerçekleşmesi için her bir egzoz manifoldu girişine kontrollü debide yanmış gaz verecek şekilde valf sistemi yerleştirilmiştir. Egzoz manifoldunun bir görevi de turboyu taşımak olduğundan üzerinde ciddi gerilmeler oluşan bir parçadır. Bu yüzden egzoz manifoldu, turbo, egzoz boruları muffler (susturucu) kısmına kadar test sistemine dahil edilmiştir. Tasarımı yapılmış test düzeneğinde temel hedeflerden birisi egzoz manifoldu üzerinde oluşacak sıcaklık haritasının gerçek araç üzerindeki çalışma koşullarında meydaha gelen sıcaklık haritası ile mümkün olduğu kadar benzer olmasıdır. Bu sebeple tek bir doğal gaz yakıcısından altı silindir bağlantısına ayrılan gaz hattındaki debilerin homojen olması için hesaplamalı akışkanlar mekaniği (Computational Fluid Dynamics - CFD) programı yardımı ile tasarım optimizasyonu yapılmıştır. Ayrıca manifold portlarına giden kanallar üzerindeki valfler sayesinden egzoz manifoldunun gerçek çalışma koşullarındaki sıcaklık haritası yakalanmaya çalışılmıştır. Tasarlanmış TMF test sisteminin çok sayıda test sonrasında da işlevini koruması gerektiği için ilk yorulma analizleri test sistemi için yapılmıştır. Sistemin ağırlık hedeflerini aşmayacak şekilde yorulma ömrü yüksek bir sistem tasarımı yapılması amaçlanmıştır.

Öte yandan gelişen teknoloji ve bilgisayar yazılımları sayesinde TMF ömür hesaplaması konusunda da başarılı analizler yapılabilmektedir. Bu analizlerin başarısı çalışma sıcaklıklarına göre değişen malzeme özelliklerinin çok iyi belirlenmesinden ve gerçek çalışma şartlarına uygun olarak sistemin çok iyi modellenmesine bağlıdır. Özellikle ilk defa analizi yapılacak parçalar ve malzemeler için fiziksel testlerin varlığı çok önemlidir. Fiziksel testlerden alınacak sonuçlar analizlerle karşılaştırarak ileri seviyede güvenilir analiz modelleri oluşturulabilir. Sonraki süreçte oluşturulan analiz yöntemi ile tasarımdaki değişikliklerin ve yükleme şartlarındaki değişimlerin etkisi fiziksel olarak parçalara gerek duymadan çok düşük maliyetler ile hızlıca tespit edilebilir. Ticari CFD analiz yazılımı olarak STAR CCM+ egzoz manifoldu içerisinden geçen sıcak gazın oluşturduğu sıcaklık dağılımını tespit etmek için kullanıldı. Elde edilen sıcaklı dağılımları sonlu elemanlar yazılımı ABAQUS kullanılarak egzoz manifoldu geometrisinde meydana gelen şekil değişimleri ve gerilme değerleri tespit edildi. TMF ömür hesabı yapılabilmesi için yani parçanın kaç çevrimde hasar göreceğinin tespiti için ticari analiz yazılımı olan nCODE DESIGNLIFE kullanılmıştır. Bu program yapısal analiz programlarından farklı olarak söz konusu malzemenin sıcaklığa bağlı malzeme özelliklerinin çevrim sayısı ile değişimini gösteren eğriler kullanmaktadır. Bu eğriler, etkiyen yüklerin zamana ve çevrim karakteristiğine bağlı değişimini dikkate aldığından parça veya sistemlerde kritik bölgelerin kaç çevrim sonrasında hasara uğrayabileceğini söyleyebilmektedir.

Yapısal analizler sonucunda tespit edilen kritik bölgeler ile ömür analizinde en düşük çevrim sayısında hasara uğrayacağı tespit edilen belgeler büyük benzerlik göstermektedir. Ayrıca fiziksel testlerde tespit edilen çatlakların konumu ile analizler ile tespit edilen kritik bölgeler de yaklaşık benzer konumlardadır. Bu benzerlikler analizlerin güvenilirliğini ve yüksek doğruluğa sahip olduğunu ifade etmektedir.

Bu çalışmadaki temel hedef termal-mekanik yorulma ömrü hesabı için bir yöntem geliştirmek, bir dizel motor egzoz manifoldu için gerçek çalışma şartlarını yansıtan termal-mekanik yorulma test donanımı tasarımı yapmak, tasarımı yapılan sistemin test numunesinden ömür olarak çok daha iyi durumda olduğundan emin olmak için modal, satitik ve yorulma analizleri ile tasarım doğrulaması ve egzoz manifoldu için test sonuçlarıyla tutarlı bir analiz methodu geliştirmektir. Test ve analizlerin sonuçlarına göre parça için TMF yorulma ömrü belirleyerek parçanın tasarımının doğrulanması amaçlanmaktadır. Parçaya özel test düzeneğinin düşük maliyetinin yanında ayrıca çevre dostu olması da ön plandadır. Haftalarca süren araç veya motor dinamometre testlerinde çok fazla benzin/mazot tüketimi gerçekleşir ancak tasarımı yapılan sistem ile egzoz gazını temsil edecek olan yüksek sıcaklıktaki gaz, doğal gazın yakılması ile elde edilecektir. Hesaplanan yorulma ömürleri deney sonuçları ile karşılaştırılmış ve yaklaşık %15 hata payı ile sayısal sonuçların doğru olduğu bulunmuştur.

1. INTRODUCTION

From an industrial perfective, thermal mechanical fatigue (TMF) resistance of the components has become a very important issue in recent years. In a globalized world, reliability and substantiality have become very important for customers. In a competitive industry like the automotive sector, all critical parts must be high quality. Recalling vehicles for safety or other reasons are extremely embarrassing and loss of prestige. At the same time, with increasing performance and lower emission level targets, vehicle engines tend to work at higher temperatures and pressures during nominal working usage periods. Taking into account these evolutions, the choice of a design and of an associated material for an engine part has to be accurate in the early conception stages and engineers should have access to an efficient experimental basis to quickly assess alternative geometries, materials or processes [1].

An automotive engine is one of the most primitive technologies but after decades, new technologies and improvements are embedded into the basic engine concept. Now, an automotive engine is a very complex mechanic and electronic system. Cylinder head, engine block, crank case, pistons and manifolds are the main parts. They are subjected to many types of loading, determined by the normal use of the vehicle and a reduced number of exceptional or accidental events. The automotive industry produces worldwide tens of millions vehicles per year for which manufacturers must ensure a significant level of reliability while assuring the production costs as low as possible and production rates as high as possible. These constraints allow a few choices in terms of types of materials and manufacturing technologies. Undesirably, there is a significant increase in combustion temperatures and design trend going towards the light vehicles. Combustion temperatures increase because of reducing emissions but also controlling the fuel consumption. With higher temperatures and light designs, coupled thermal and mechanical stresses emerge on the critical parts such as cylinder head, pistons and exhaust manifold. Moreover, the steady increase in combustion temperatures coupled with high mechanical stresses on components such as cylinder heads, pistons and exhaust manifold superpose a serious risk of thermal mechanical fatigue [2].

Fatigue life prediction, (namely life cycle number), is very important during design procedure. Especially the critical parts for the vehicle should be verified before mass production in consideration of TMF issues. Stresses and strains computed by means of a complete structural analysis have to be post-processed in order to predict the component life. This procedure has to be performed before manufacturing component itself, allowing designers to make corrections during the design stage, when modifications are less costly. A lot of approaches and models to treat the problem are described in literature, taking into account as realistically as possible the phenomena and the influencing factors related to multiaxial fatigue, e.g., proportional or non-proportional loadings, working temperature, material characteristics including heat treatment, microstructure, anisotropy and environmental effects [3].

TMF life prediction is not so easy with classical methods because the changing material properties and working conditions are difficult to simulate or test. Temperature dependence of mechanical properties of 1040 Steel is shown in the Figure 1.1.

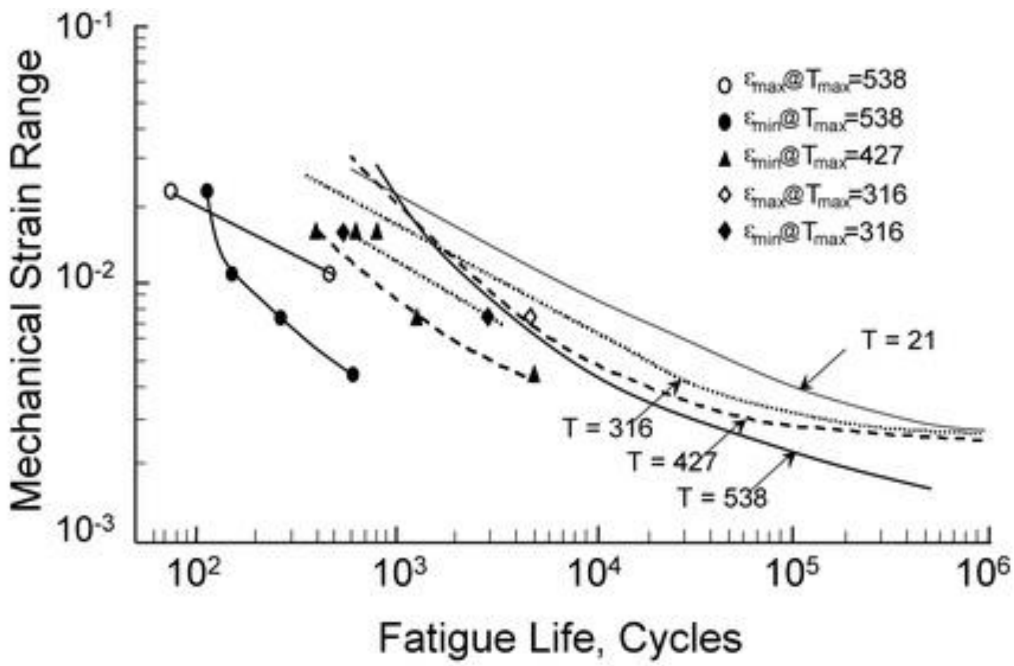

Figure 1.1 : TMF life cycle test results for 1010 Steel [4].

1.1 Fatigue

After decades, it is well understood that temperature affects dramatically the fatigue life of a structure. Under the same cyclic or repeated stress or strain loading conditions, fatigue life of a structure could vary significantly in different environment temperatures. Such an environment could be a merely low, moderate, high temperature or a cyclic temperature that may or may not couple with the cyclic loading. In the last decades, there are many research and projects about different fatigue mechanism with different materials. However, a universal theory to characterize quantitatively the temperature effect on fatigue has yet to be established, and such a theory that applies to all materials over a broad temperature range may never be established due to the complexity of the topic and significant differences among applications. The state of the art, at least for the time being, remains to be the semi-empirical approach to evaluate the effect of temperature on fatigue under specific application [4].

Figure 1.2 shows that in-phase and out-phase TMF waveform behavior of the strain and temperature.

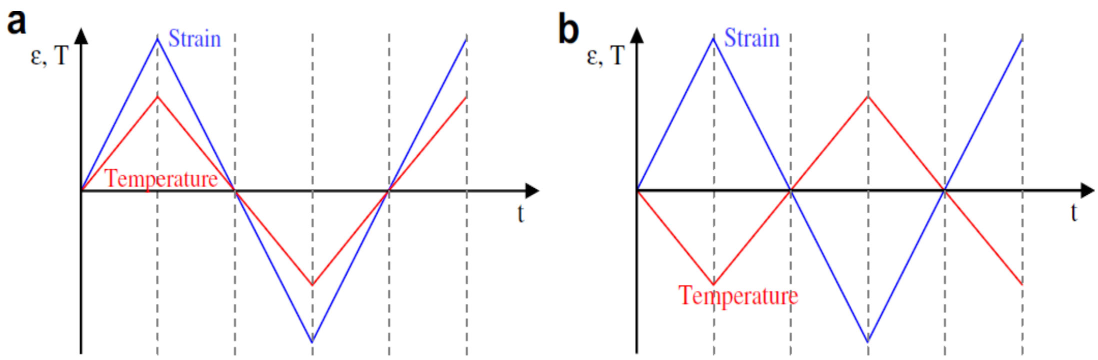

Figure 1.2 : Schematic representation of an; (a) in-phase TMF waveform, φ=0º and (b) out of-phase TMF waveform, φ=180º [5].

1.1.1 High cycle fatigue

Broadly, if the fatigue occurs at higher than 10^6 cycle, this is a high cycle fatigue (HCF) behavior. This applies to most of the machine parts and this can be analyzed by idealizing the S-N curve for, say, steel, as shown in Figure 1.3. The line between 10^3 and 10^6 cycles is taken to represent high cycle fatigue with finite life and this can be given by

$$\log S = b\log N + c \tag{1.1}$$

where S is the reversed stress, b and c are constants.

At point A log $(0.8\ \sigma_u) = b \log 10^3 + c$ where σ_u is the ultimate tensile stress while at point B $\log\sigma_e = b \log 10^6 + c$ where σ_e is the endurance limit [6].

From that;

$$b = -\frac{1}{3}\log\frac{0.8\sigma u}{\sigma e} \qquad c = \log\frac{(0.8\sigma u)^{\wedge}2}{\sigma e} \tag{1.2}$$

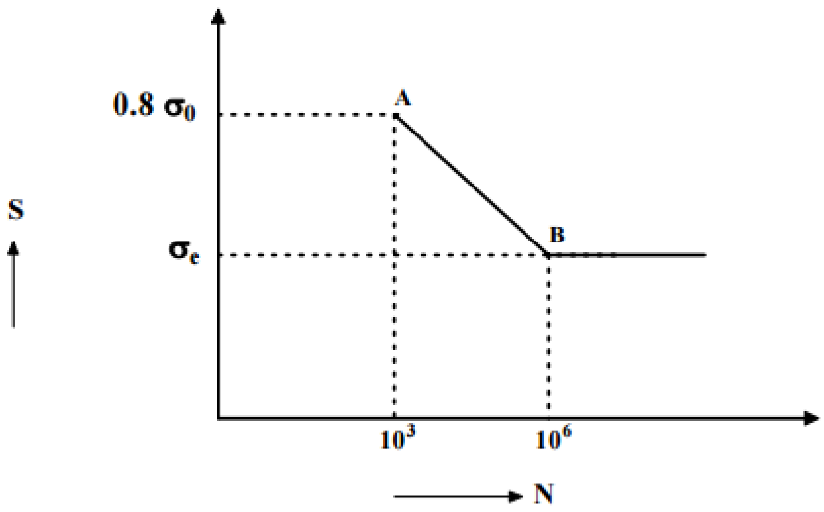

Figure 1.3 : A schematic plot of reversed stress against number of cycles to fail [6].

1.1.2 Low cycle fatigue

This is mainly applicable for short-lived devices where very large overloads may occur at low cycles. Commonly fatigue life cycles are lower than 10^4 for low cycle fatigue (LCF) behavior. Typical examples include the elements of control systems in mechanical devices. A fatigue failure mostly begins at a local discontinuity and when the stress at the discontinuity exceeds the elastic limit there is a plastic strain. The cyclic plastic strain is responsible for crack propagation and fracture. Experiments have been carried out with reversed loading and the true stress-strain hysteresis loops are shown in Figure 1.4. Due to the cyclic strain, the elastic limit increases for annealed steel and decreases for cold drawn steel. Low cycle fatigue is investigated in terms of cyclic strain. For this purpose, we consider a typical plot of strain amplitude versus number of stress reversals to fail for steel as shown in Figure 1.5 [6].

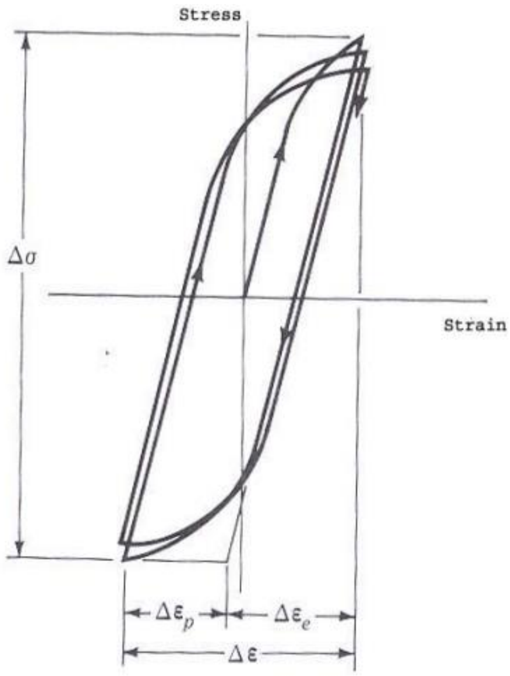

Figure 1.4 : A typical stress-strain plot with a number of stress reversals [6].

Here the stress range is Δσ. $\Delta\varepsilon_p$ and $\Delta\varepsilon_e$ are respectively the plastic and elastic strain ranges, and the total strain range being Δε. Considering that the total strain amplitude can be written as;

$$\Delta\varepsilon = \Delta\varepsilon_p + \Delta\varepsilon_e \tag{1.3}$$

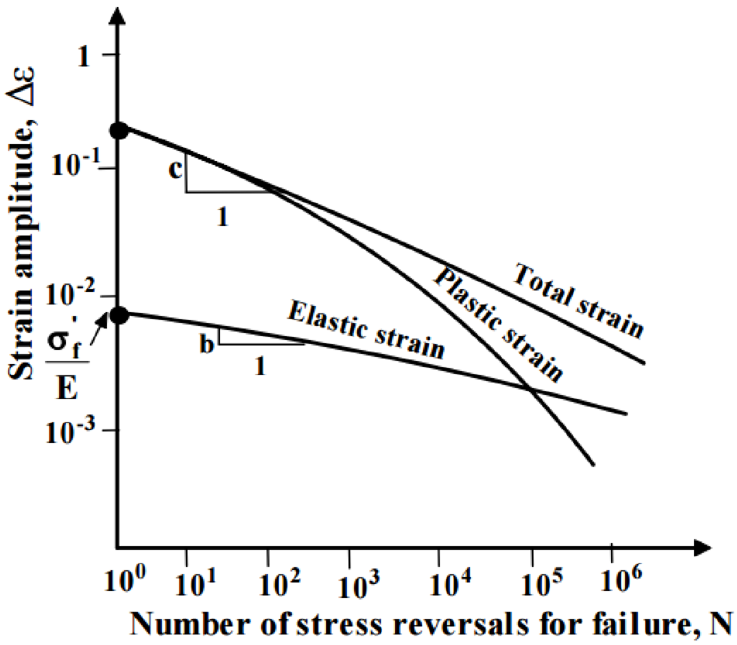

Figure 1.5 : Plots of strain amplitude v.s. number of stress reversals for failure [6].

A relationship between the strain and a number of stress reversals can be given as;

$$\Delta\varepsilon = \frac{\sigma_f^{'}}{E}(N)^a + \varepsilon_f^{'}(N)^b$$

(1.4)

Where N is the number of stress reversals, E is the elasticity modulus, σ_f and ε_f are the true stress and strain corresponding to fracture in one cycle and a, b are systems constants. The equations can simplified as follows:

$$\Delta\varepsilon = \frac{3.5\sigma_u}{EN^{0.12}} + \left(\frac{\varepsilon_p}{N}\right)^{0.6}$$

(1.5)

In this form, the equation can be readily used since σ_u, ε_p and E can be measured in a typical tensile test. However, in the presence of notches and cracks, determination of total strain is difficult.

1.2 Thermal Mechanical Fatigue

Thermal mechanical fatigue (TMF) means the damage caused by synchronous changing temperature and mechanical load conditions. For example, TMF loading occurs in hot section components of gas turbines such as turbine blades. The stress-strain responses of materials under TMF conditions are complex and depend on phasing between thermal and mechanical loads. Therefore, modeling TMF behavior is a challenge for life prediction of such kind of components [7].

From the early 1980s to the late 1990s, some frameworks for "unified constitutive laws of plasticity and creep" are developed, which are also applicable to thermomechanical fatigue. In these constitutive models, the inelastic strain rate is described by a flow equation, which depends on two state variables such as the back stress and drag stress that are responsible for kinematic hardening and isotropic hardening, respectively.

The specific forms of those hardening rules, i.e., governing equations for back/drag stresses, however, differ from a model to another model, and depend on several parameters, which are difficult to verify experimentally [8].

There are many different damage mechanisms occur during TMF behavior. In the Figure 1.6, most common types are showed such as pure fatigue, oxidation damage and creep damage.

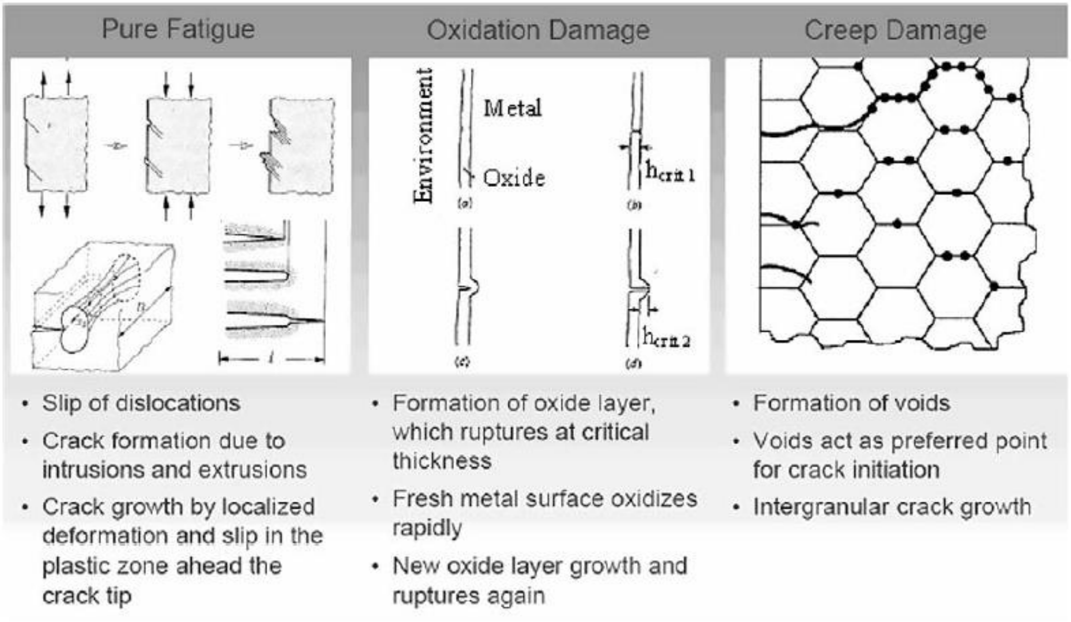

Figure 1.6 : The different damages involved in thermomechanical loading [9].

2. LITERATURE SURVEY

Because of increasing performance and emission demands, turbo charged gasoline engines are becoming popular in the passenger car market. These downsized engines have higher thermal loads and experience increased levels of vibration. The exhaust manifold metal temperature may rapidly increase from the ambient temperature to about 600°C and large transient temperature gradient may occur. The larger temperature variation causes a larger thermal stress on the structure. Due to cyclic thermal loads, thermal mechanical fatigue cracks on exhaust manifold and gasket sealing failure are often observed during engine durability tests, such as thermal shock test [10].

CAE engineers play an important role to find the weakness of an exhaust manifold layout at the early stage of the engine development. During the design phase of the exhaust manifold development, it is important to develop a concept, which allows local thermal mechanical restraining to be relieved and temperature level and temperature gradients to be lowered. Besides, the exhaust manifold has also to be designed to meet engine performance target and emissions target, in consideration of tight package requirements and challenging under hood cooling conditions with a large heat shield.

During the validation phase of the engine development process, exhaust manifold cracks and gasket leakage were observed during thermal shock tests. As shown in Figure 2.1, the crack locations are at (a) the collector rib, (b) the internal baffle and (c) the area on the exterior side of the internal baffle near the runner #3. To solve the test failure problems, CAE tools are used in the iterative design process, in which the analysis work supplements testing investigations and provides directions to design modification [10].

Under automotive operation conditions, thermal mechanical fatigue damage in exhaust manifolds is influenced by many factors, which include material properties, mechanical strain range, strain rate, temperature, and the phasing between temperature and mechanical strain.

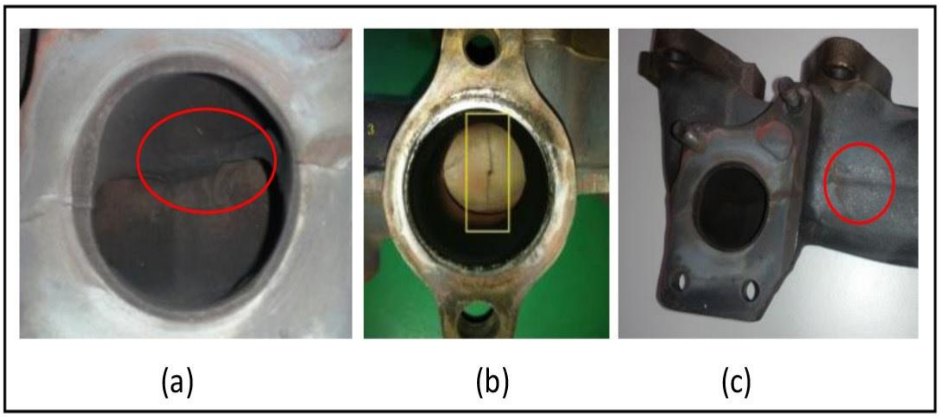

Figure 2.1 : Cracks on the exhaust manifold [10].

A TMF lifetime-prediction model needs to consider the damage through mechanical fatigue, creep and oxidation mechanisms and part of the interactions between these mechanisms. There is no TMF model which is valid under general load conditions for all types of materials. The uncertainty of TMF prediction is due to the factors such as temperature prediction accuracy, material properties, phase of temperature and mechanical loads, material variation, failure criteria, etc. according to Sehitoglu [11].

Damage from each mechanism is summed to get an estimation of the total fatigue life. Manson-Coffin formula is widely used to describe the fatigue life, in which plastic strain amplitude is used. The fatigue ductility coefficient and fatigue ductility exponent have to be obtained from TMF tests. Taira proposed a relation between thermal fatigue and low cycle fatigue durability [10].

This model is modified in as follows;

$$N = \lambda(T_{eq}) \cdot \Delta\varepsilon_{eq}^{\beta} \tag{2.1}$$

$$\Delta\varepsilon_{eq} = \int_{cycle} \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl}:\dot{\varepsilon}^{pl}}\, dt \tag{2.2}$$

There is a failure mode analysis results for cast iron exhaust manifold component in the Table 2.1.

Table 2.1 : Failure mode analysis of cast iron exhaust manifolds [10].

Type of Issues	Root causes	Influencing factors
Cracks on exhaust manifold	Extreme magnitude of gas temperature	Engine calibration
	High metal temperature gradient	Manifold shape design
	Extreme vibration level (HCF)	Vibration mode of exhaust system
	Material property not meet requirements	
	Local stress exceeds the yield stress under high thermal loading, cyclic plastic straining of the material (TMF)	Geometric shape and stiffness distribution, thermal expansion
	Casting defect	
	Wall thickness not meet design guideline	
Exhaust leak at the interface between cylinder head and exhaust manifold	Exhaust manifold flange distortion	Flange shape and thickness, bolt pattern, bolt number, Temperature distribution
	Interface deformation between cylinder head and exhaust manifold	Temperature distribution
	Exhaust gasket failure	Gasket material type, multi-layer gasket, bead design, coating
	Loosen bolts	Plastic deformation of bolt, thread length, anchor hole, engine vibration
	Loosen nuts	bolt pretention, tightening sequence, vibration level, washer, strength grade of nut
Exhaust leak at the interface between exhaust manifold and turbo housing	Flange distortions at the manifold side and/or at the turbo side	Bolt pattern, clapboard design, ribs from turbo housing flange to runners.
	gasket failure	Material type, layers, bead design, coating
	Loosen nuts	bolt pretention, tightening sequence, turbo bracket design, washer, strength grade of nut

Here N is the number of cycles to failure, $\Delta\varepsilon_{eq}$ is the equivalent plastic strain accumulated between two cycles. The coefficient $\lambda(T_{eq})$ is dependent on an equivalent temperature and several empirical constants. To determine these material constants, different thermal mechanical cyclic tests are required, in which different maximum temperatures and dwell times are considered. For simplicity and practicality, in this work the thermal fatigue life is estimated based on the equivalent plastic stain increment during the third cycle and the equivalent accumulated plastic strain in three cycles. In addition, the level of metal temperature is also considered for risk assessment. In the Figure 2.1, a growth crack which is happened due to TMF is showed.

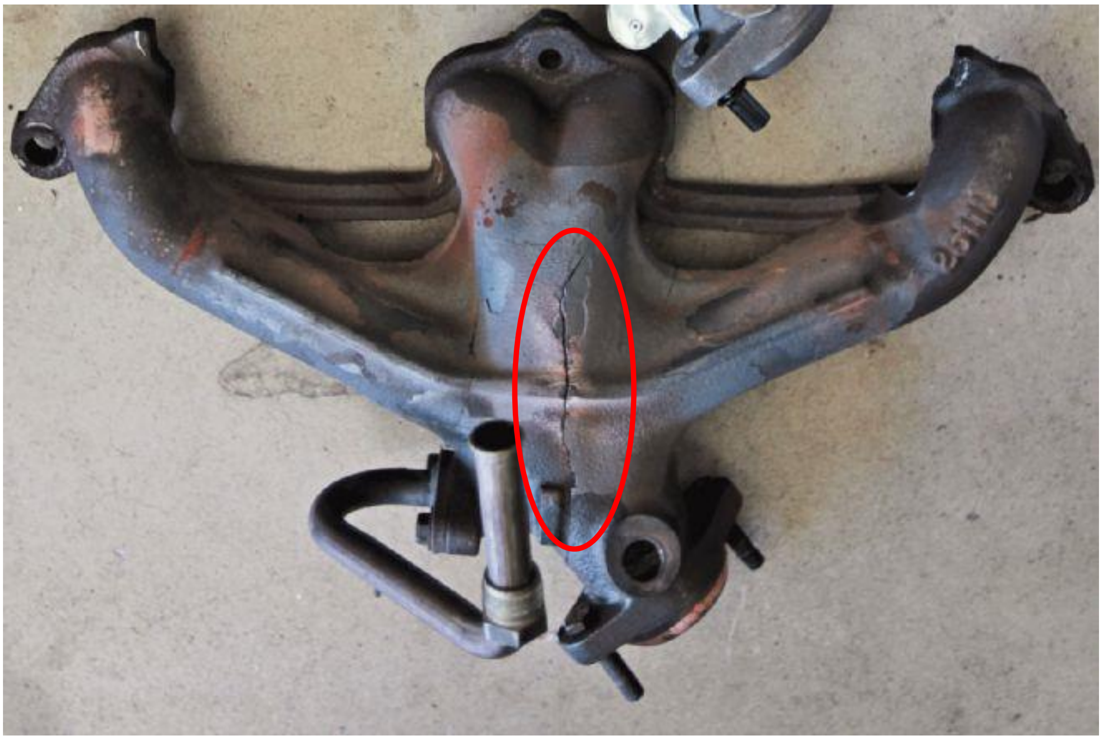

Figure 2.2 : An exhaust manifold part with TMF crack.

2.1 Fatigue Life Models

Four fatigue life models exist:

1. Nominal stress-life (S-N) method

- First formulated in the 1850s to 1870s.
- Uses nominal stresses and relates these to local fatigue strengths for notched and un-notched members.

2. Local strain-life (ε-N) method

- First formulated in the 1960s.
- Local strain at a notch is related to smooth specimen strain controlled fatigue behavior.
- Analytical models can be used to determine local strains from global or nominal stresses or strains.

3. Fatigue crack growth (da/dN-ΔK) method

- First formulated in the 1960s.
- Requires the use of fracture mechanics to obtain the number of cycles to grow a crack from a given length to another length and/or to fracture.
- This model can be considered as a total fatigue life model when used in conjunction with existing initial crack size following the manufacturing process.

4. Two-stage method by combining 2 and 3 to incorporate both fatigue crack nucleation and growth.

- Incorporates the local ε-N model to obtain the life to the formation of a small macro-crack and then integration of the fatigue crack growth rate equation for the remaining life.
- The two lives are added together to obtain the total fatigue life [12].

2.2 Fatigue Design Criteria

There are many fatigue criteria developed until now. Most of them still has its place for some aspects. It is also called infinite life to damage tolerance. The criteria for fatigue design include the usage of the four fatigue life models (S-N, ε-N, da/dN-ΔK, and the two-stage method) explained in the previous section. Mainly there are four fatigue design criteria according to fatigue life cycle counts [12].

2.2.1 Infinite-life design

Unlimited safety is the oldest criterion. It requires local stresses or strains to be essentially elastic and safely below the pertinent fatigue limit. For parts subjected to millions of cycles, like engine valve springs, this is still a good design criterion. However, most parts experience significant variable amplitude loading, and the pertinent fatigue limit is difficult to be defined or obtained. In addition, this criterion may not be economical or practical in many design situations. Examples include excessive weight of aircraft for impracticality and global competitiveness for cost effectiveness [12].

2.2.2 Safe-life design

Infinite-life design was appropriate for the railroad axles that Wohler investigated, but automobile designers learned to use parts that, if tested at the maximum expected stress or load, would last only hundreds of thousands of cycles instead of many millions. The maximum load or stress in a suspension spring or a reverse gear may occur only occasionally during the life of a car; designing for a finite life under such loads is quite satisfactory. The practice of designing for a finite life is known as "safe-life" design. It is used in many other industries too-for instance, in pressure vessel design and in jet engine design.

The safe life must, of course, include a margin for the scatter of fatigue results and for other unknown factors. The calculations may be based on stress-life, strain-life, or crack growth relations. Safe-life design may be based solely or partially on field and/or simulated testing. Examples of products in which field and simulated testing play a key role in safe-life determination are jet engines, gun tubes, and bearings. Here appropriate, regular inspections may not be practical or possible; hence, the allowable service life must be less than the test life or calculated life. For example, the U.S. Air Force historically has required that the full-scale fatigue test life of production aircraft/parts be four times longer than the expected or allowable service life. With gun tubes, the U.S. Army has required both actual firing tests and simulated laboratory pressure fatigue tests of six or more tubes to establish the allowable service life as a fraction of the mean test life. Ball bearings and roller bearings are noteworthy examples of safe-life design. The ratings for such bearings are often given in terms of a reference load that 90 percent of all bearings are expected to withstand for a given lifetime-for instance, 3000 hours at 500 RPM or 90 million revolutions. For different loads, lives or for different probabilities of failure, the bearing manufacturers list conversion formulas. They do not list any load for infinite life or for zero probability of failure at any life. In the Figure 2.3, sample product life design optimization process diagram is showed.

The margin of safety in safe-life design may be taken in terms of life (e.g., calculated life = 20 X desired life), in terms of load (e.g., assumed load = 2 X expected load), or by specifying that both margins must be satisfied, as in the ASME Boiler and Pressure Vessel Code [12].

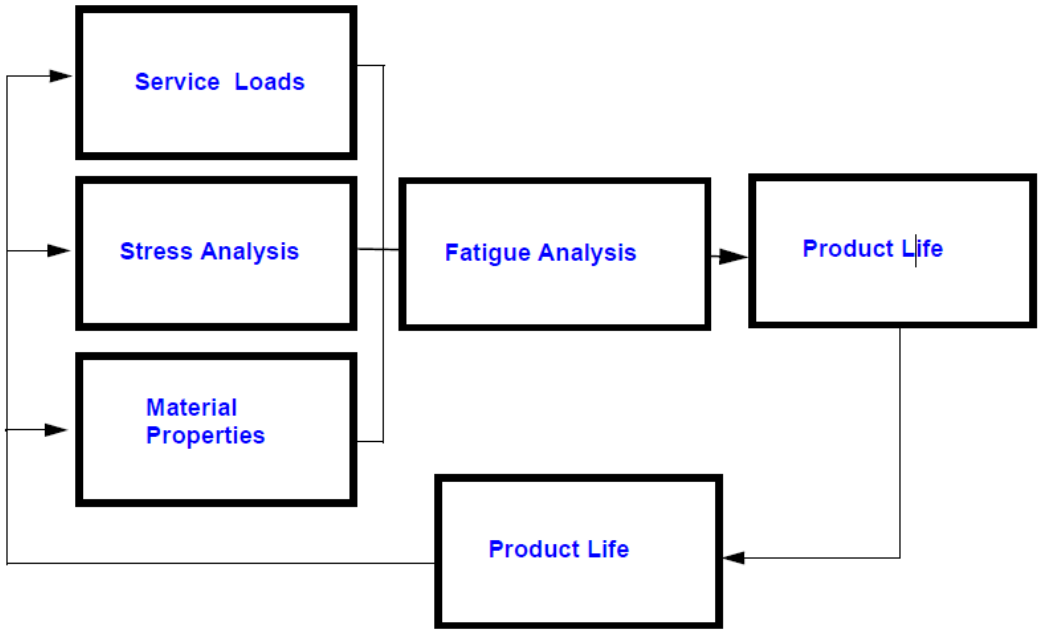

Figure 2.3: Design process for optimum product life.

2.2.3 Fail-safe design

When a component, structure or vehicle reaches to its allowable safe life, it must be retired from service. This can be inadequate since all the fleet must be retired before the average calculated life or test life is attained. This practice is very costly and wasteful. Also, testing and analysis cannot predict all service failures. Thus, fail-safe fatigue design criteria were developed by aircraft engineers.

They could not tolerate the added weight required by large safety factors, danger to life created by small safety factors or high cost of safe-life design. Fail-safe design requires that if one part fails, the system does not fail. Fail-safe design recognizes that fatigue cracks may occur, and structures are arranged so that cracks will not lead to failure of the structure before they are detected and repaired. Multiple load paths, load transfer between members, crack stoppers built at intervals into the structure, and inspection are some of the means used to achieve fail-safe design. This philosophy originally applied mainly to airframes (wings, fuselages, control surfaces etc.). It is now used in many other applications as well. Engines are fail-safe only in multiengine planes. A landing gear is not fail-safe, but it is designed for a safe life [12].

2.2.4 Damage-tolerant design

This philosophy is a refinement of the fail-safe philosophy. It assumes that cracks will exist, caused either by processing or by fatigue, and uses fracture mechanics analyses and tests to determine whether such cracks will grow large enough to produce failures before they are detected by periodic inspection. Three key items are needed for successful damage-tolerant design: residual strength, fatigue crack growth behavior, and crack detection involving nondestructive inspection. Of course, environmental conditions, load history, statistical aspects, and safety factors must be incorporated in this methodology [12].

3. SYSTEM DEFINITION

An exhaust system is simply a pipe segment to guide reaction exhaust gases away from a controlled combustion inside an engine. Every internal combustion engine vehicle has one system according to properties and needs. In this study, we consider the turbo charged heavy duty diesel engine exhaust manifold. To obtain reel life working conditions, loadings, pretensions, turbo down pipes and brackets are also integrated to the TMF test rig.

3.1 Exhaust Manifold

The exhaust manifold mounted on the cylinder head of an engine collects the gas exhausted from the engine and combines it into one pipe. The manifold can be made of steel, aluminum, stainless steel, or more commonly cast iron. Figure 3.1 shows three pieces cast iron exhaust manifold. It is belong to six cylinder heavy duty diesel truck engine.

Figure 3.1: 1994-98 Dodge 12-Valve, T3, 3-Piece Cast Exhaust Manifold.

The exhaust manifold plays an important role in the performance of an engine. Particularly, the amount of emissions and fuel efficiency are closely related to the exhaust manifold. The exhaust manifold is under a thermal fatigue loading produced by temperature variations, which leads to a crack nucleation and propagation in the exhaust manifold.

Table 3.1 shows most common used exhaust manifold materials and their specifications. The table summarizes the main types of exhaust manifolds with some sample materials. Still there are material development researches for better quality exhaust manifolds.

Table 3.1 : Exhaust manifold types & materials versus demands [13].

Type	Materials	$T_{max}^{material}$ (°C)	Main Pros & Cons	Demands
Cast	GJS-SiMo-5.0-1.0 GJV-SiMo-4.5-0.6 GJSA-XNiSiCr 35-5-2 GX40CrNiSi25-20	700 - 830 800 - 860 850 -1050 1050 -1100	+ production costs + design flexibility - emissions - weight	Emissions, Power, Weight, Size, Production costs, Acoustics, Dynamic durability, Thermal life
Fabricated	X2 CrTiNb 18 X5 CrNi 18-10 X6 CrNiTi 18-10 X15 CrNiSi 20-12	900 - 950 800 - 850 850 - 920 950 -1000	+ emissions + thermal stability - dynamic loading - complex design	

Exhaust manifolds are classified as cast and fabricated. Cast manifolds can be designed as a separate part but can also be integrated in the cylinder head structure. They are also could be an assembly consisting of many sub-parts. Fabricated manifolds are known in single and dual wall design, where interior and exterior sheet metals are separated by an isolating air gap [13].

Exhaust manifold design has to reflect the individual material characteristics and loading conditions by appropriate stiffness and low operating temperatures in addition to satisfying main objectives of engine development; namely emissions, power characteristics and fuel consumption.

Major players always select test-analysis way to obtain the optimum design. Figure 3.2 shows sample the exhaust manifold which is used at this study. Figure 3.3 presents the gas circulation diagram for TMF test rig.

Before mass production, critical parts must be verified for different aspects and conditions. Exhaust manifold failure is unacceptable for global manufacturers. Companies could complete TMF tests and analysis or make their designs too strong.

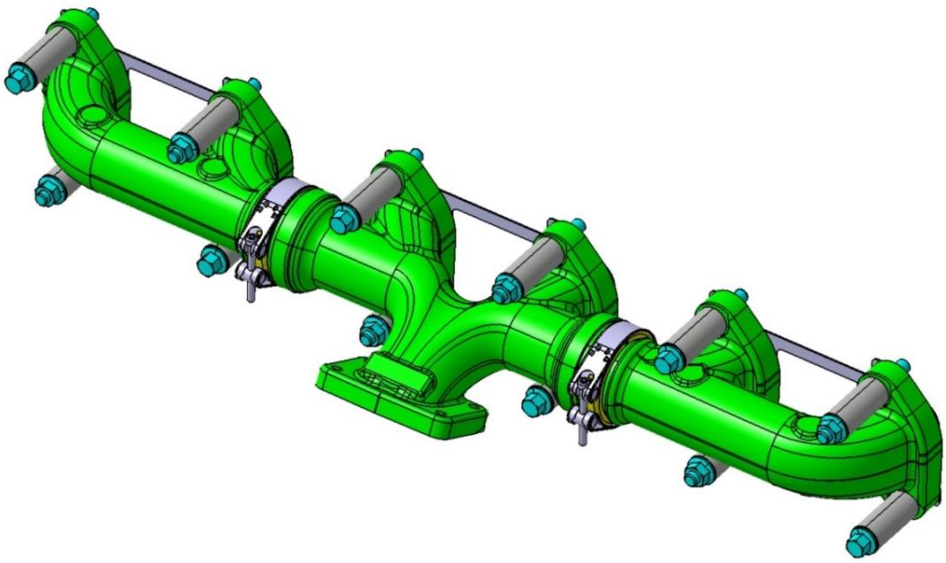

Figure 3.2: Ford Otosan heavy duty diesel engine exhaust manifold.

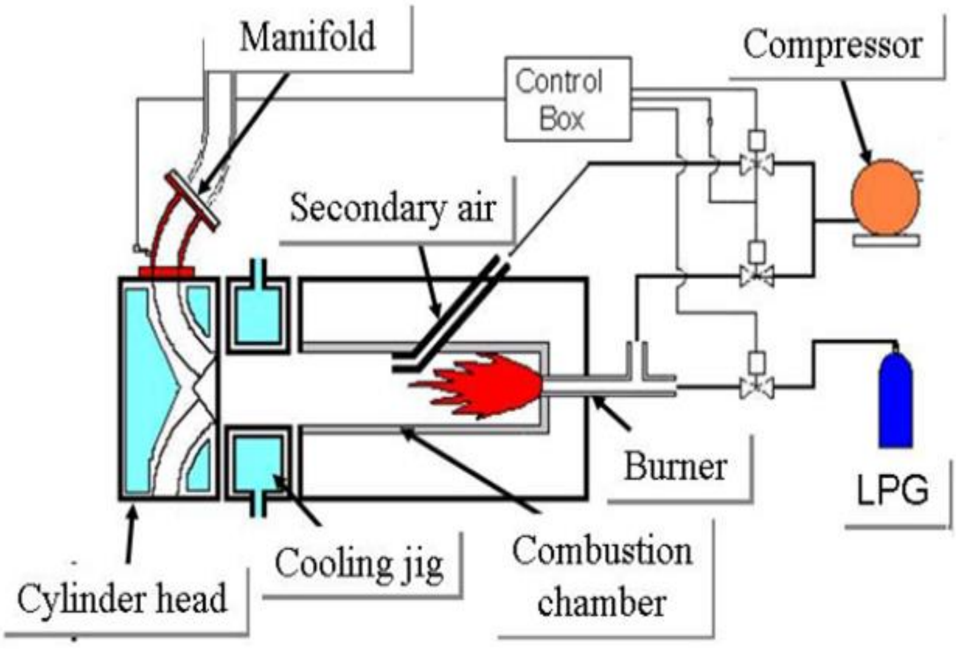

Figure 3.3: Exhaust gas simulation system by Hitachi-Japan.

In most systems, exhaust manifolds, turbo and down pipes are mounted to each other. In the Figure 3.4, engine cylinder head mounted casting exhaust manifold is seen. Especially, with casting exhaust manifolds, it is very common situation. In such a case, extra components make an important effect on the fatigue life properties. Extra components are always produced by casting that are very heavy. To obtain real working conditions, rigidly mounted parts should be tested as a single part.

Figure 3.4 : Exhaust manifold, turbo and down pipe assembly on a V8 engine.

4. TMF TEST RIG DESIGN

The main thermal mechanical loading is caused by cyclic temperature variations coming from the hot/cold cycles induced by the start–stop operation and the transient load variation during engine operation. The calculation of the cyclic temperature field is a complex task involving the use of computational fluid dynamic (CFD), conjugate heat transfer (CHT) and non-linear finite element (FE) analysis tools for different components under consideration. In the mechanical FE analysis the material deformation is described with a visco-plastic material model [14].

In the Figure 4.1, a TMF test rig is shown for cat exhaust manifold. The test rig simulates hos exhaust gas without engine combustion.

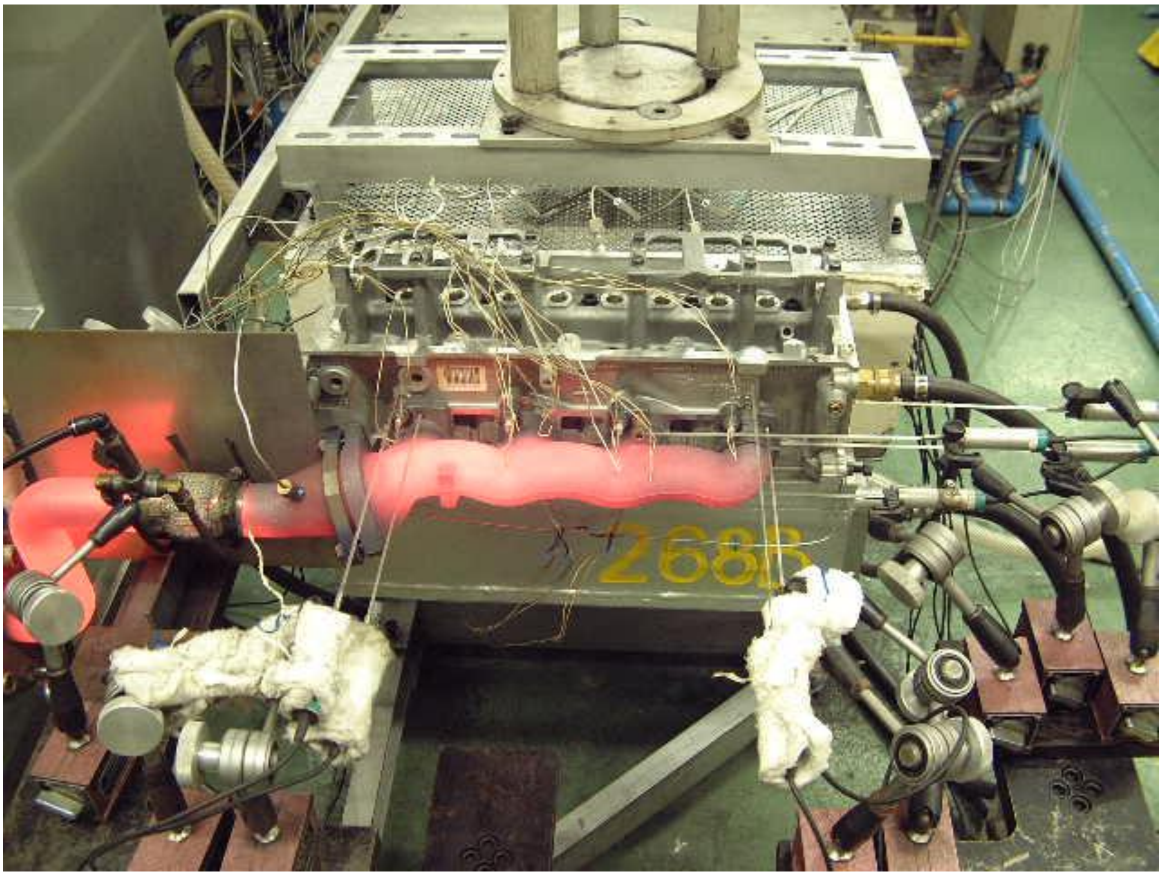

Figure 4.1: Experimental set-up at Hitachi-Japan showing the extensometer and thermocouple locations for an exhaust manifold.

Thermal mechanical fatigue systems simulate the complex effects of thermal cycling combined with mechanical loading, normally experienced by gas turbines and similar equipment during operation. More sophisticated than isothermal fatigue, TMF testing helps to better evaluate the life of many materials and engineering components that are used in high temperature applications. A dynamic heating and cooling system is combined with a high temperature materials testing system to achieve complex mechanical and thermal cycling.

TMF test rig design requires very specific knowledge about modeling target parts or systems. Especially, viscoelastic material modeling is very difficult and hard to be sure about modeling. For very high precision results; FE results, TMF test results and real life working results should be properly close. Even if detailed finite element calculations are made there is no guarantee that a component will not be subjected to damage. So, tests are requirement for verification and obtain reliable FEA methodology.

It is faced with many questions when setting up a TMF test rig. Some types are unique for the single component like Figure 4.1 but some rigs are general purpose like Figure 4.2. Specimens are generally tested in a general purpose rig for having information about the TMF characteristics of the material regardless of geometry.

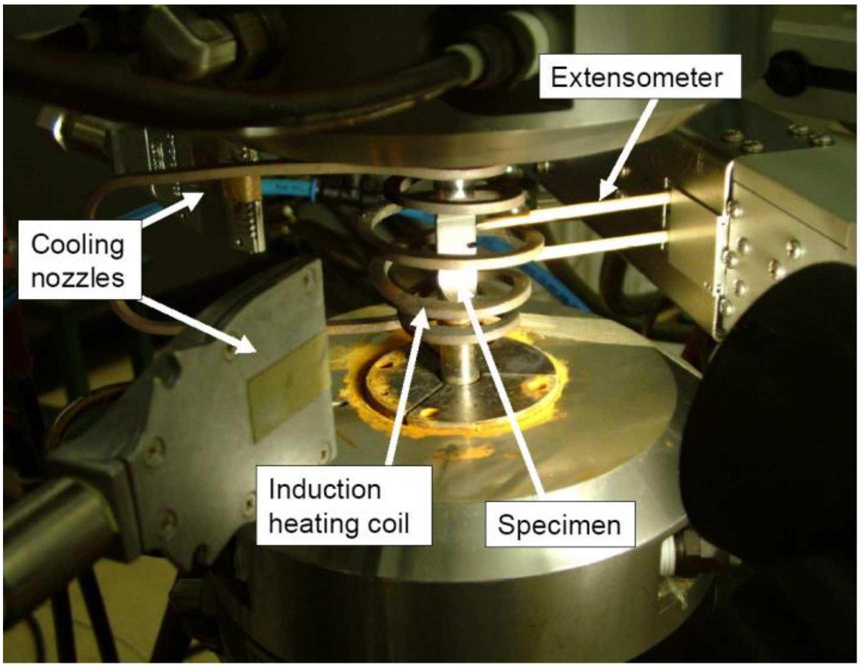

Figure 4.2: Siemens experimental TMF test set-up for a tensile test specimen with heating and cooling systems.

But, most of the time it is wanted to observe effect of geometry on TMF fatigue life. In this study, geometry of the exhaust manifold is wanted to investigate for TMF life behavior so the rig will be specific for the component. Also used some related parts to provide real working conditions. Gas burner bench and engine bench are main concepts of the TMF test rig which are showed in the Figure 4.3.

Figure 4.3: Sango Co. Ltd. thermal stress test (A: gas burner bench, B: engine bench).

4.1 General Concept

A cycle means heating up the exhaust manifold until reaching to the maximum operating temperature and cooling it to ambient temperature. Exhaust manifold has different temperature values at different points. These values are measured from engine dyno tests. For a heavy duty truck, starting the engine and going with high speed then stopping the engine means one cycle. In real life, realization of this is extremely difficult but the worst case scenario must be considered in the design-analysis process. If a truck engine faces this extreme loading condition once in every 3 days, it makes approximately 120 cycles per year. To guarantee twelve years product life of twelve years, specimens should still be in operation beyond after 1500 cycles without any damage. Temperature changes like a symmetrical waves during the TMF test as in the Figure 4.4.

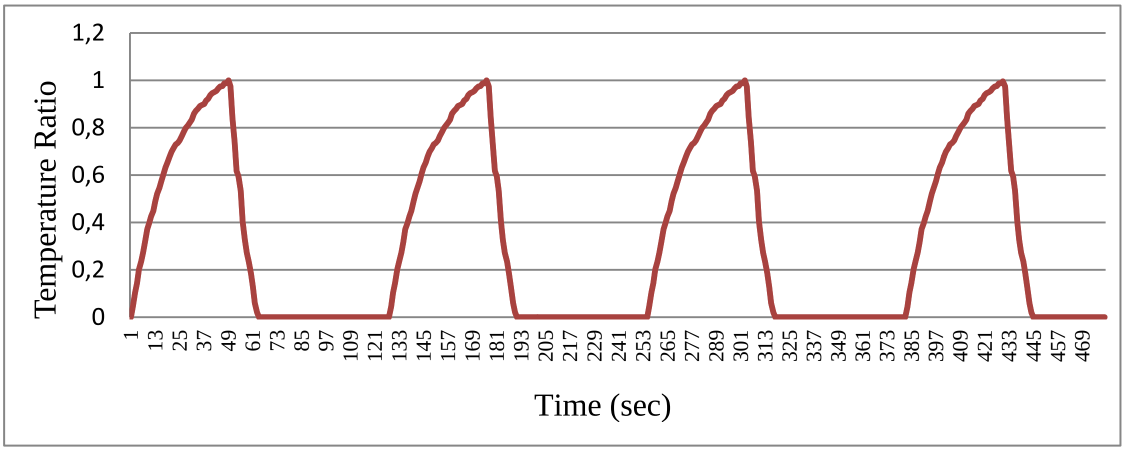

Figure 4.4 : TMF test rig temperature variation.

4.1.1 Vibration shaker

Vibration shaker is one of the essential parts of hot shaking concept design. It is capable of applying special moving map with high precision and short response times. The test rig has two shaking plates for different axes.

The big limitation of the machine is in universal Z axis (perpendicular to the ground) having the shaking mass capacity is 1500 kg. In addition, 300 kg head expander mass is also included in this mass capacity. Consequently, total mass of moving parts cannot be heavier than 1200 kg.

Table 4.1 gives the capacity of the shaker that is shown in Figure 4.5.

Table 4.1: TIRA special vibrational testing machine.

Sine sweep	55000 N
Random	55000 N
Shock	165000 N
Frequency range	5-3000 Hz
Displacement (peak-peak)	76.2 mm

Figure 4.5 : TIRA vibrational testing machine.

4.1.2 Hot gas burner

To simulate hot gases formed in combustion engines, "FAKT hot gas generator HG600" will be used which is shown in Figure 4.6 and its properties are given in Table 4.2. It supplies high temperature and pressure gases with high mass flow rates. Properties of the hot gas burner has direct effect on the TMF test cycle time.

Most of the time, burner number is equal to the cylinder number for exhaust manifolds or engine TMF fatigue test rigs. Nevertheless, the capacity of existing instrumentation is determined to be sufficient for six cylinders; thus single burner is used and a separator is designed with mass flow control valves.

A pressure drop analysis is performed during CFD analysis to ensure pressure capacity of the burner will be adequate for the test.

The hot gas burner could work with natural gas (CNG) and it will be supplied with existing installations. In addition, there is an exhaust installation for discharging the burned gas to the end of the test system.

Table 4.2 : FAKT heatFACtory ® HG400HD technical properties.

heatFAKTory® HG400HD	
Performance	8KW - 400KW
Temperature range	80°C - 1200°C (optional: 1300°C)
Temperature transien (max)	>200K/s
MassFlowRate (MFR)	40 - 1500kg/h 0.011 - 0.417kg/s
Max. high pressure:	3.0bar abs. (optional: 6.0/8.0 bar abs.)
Adjustment range/scale	1:50
Combustible	Natural gas [CNG] (optional: Liquid petroleum gas [LPG])
Energy consumption	~ 0.1m³n/kW (CNG)
Automation	ThermControl-Mini [TCmini]
Communication interface	Ethernet (optional: Profibus, ...)
Dimension [mm]	~ 1200x390x1100
Weight	~ 170kg

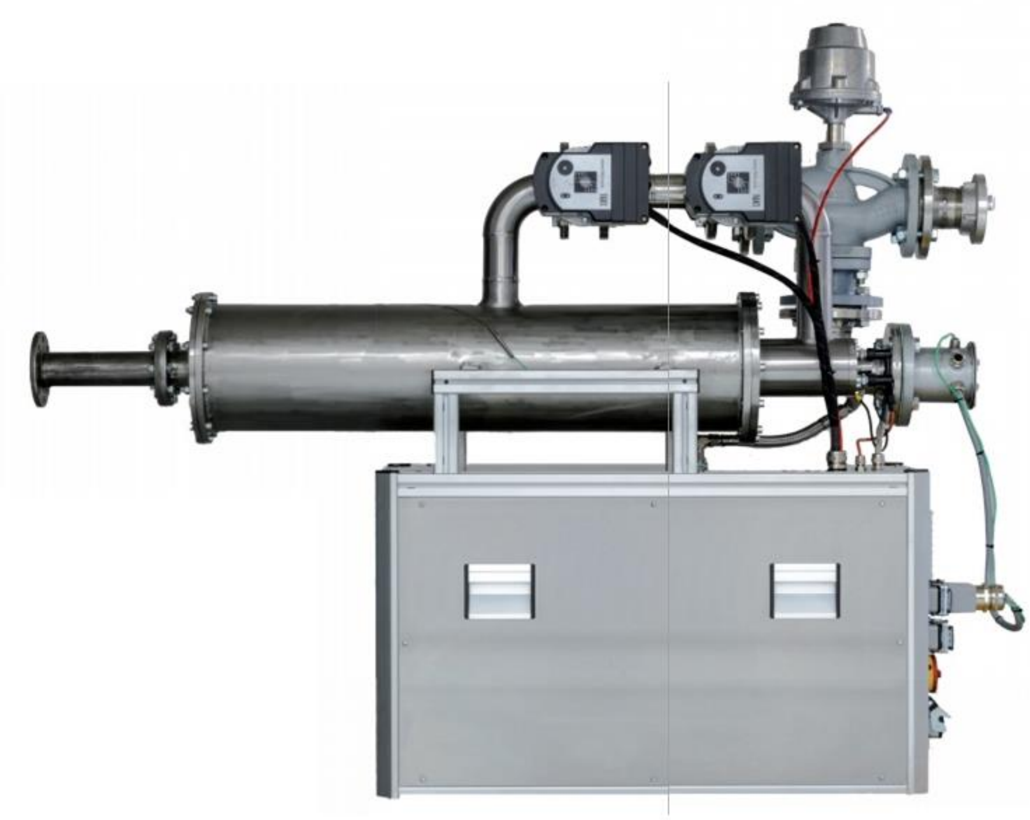

Figure 4.6 : FAKT hot gas generator HG600.

4.2 Exhaust Manifold Test Rig Design

CATIA V5 R22 design program is used during design. Before the design, there are environmental restrictions and constraint of using existing parts. The final design satisfies all necessary requirements and approved by the firm.

At the beginning, engine block and cylinder head were thought to be included in the TMF test rig. In particular, the existence of cooling system in the test rig and no need for new base part were great advantages. But the weight capacity problem did not allowed this configuration. After some benchmark studies, it is decided to design a base plate instead of the cylinder head and assembling the exhaust manifold on it.

Total exhaust TMF test rig design could be seen in the Figure 4.7 with vibration shaker and hot gas burner. Air cleaner is also added to the system for supplying clean air for the turbo. Exhaust down pipe bracket and air cleaner are fixed with a stand because they are vehicle chassis parts and do not make any engine movement. This fixing table and burner table are adjustable for the different vibrational shaker position.

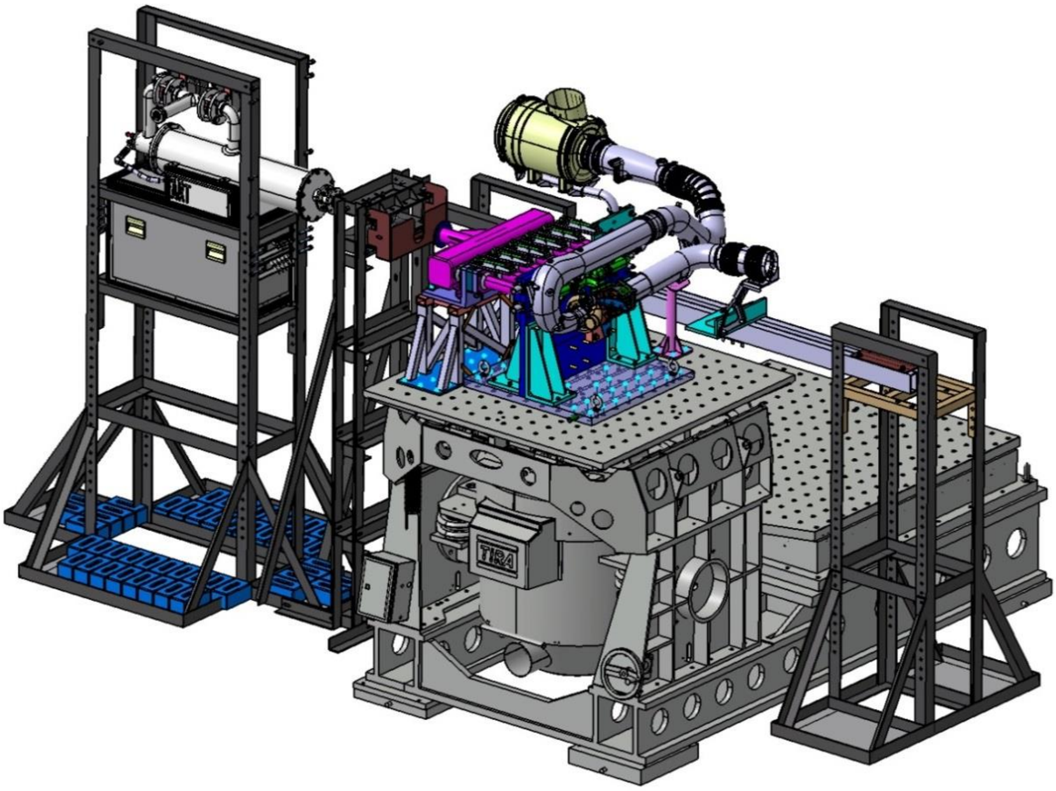

Figure 4.7 : Complete exhaust manifold TMF test rig design.

In the Figure 4.8, designed TMF test rig components are showed over vibrational shaker with closer view. Base plate and vibration shaker connection plate have cooling channel inside. Connection plate material is aluminum, all other parts are steel because they will be exposed to high temperatures during the tests. Hot gas supplied from the burner will be integrated into the system with separator parts. There is a flex part between burner and shaker for damping. Hot gas will be separated into six sections and the flow rate will be controlled by the valves. Across the base plate, exhaust manifold collects six ways to single outlet way like in real working condition. During this setup, the turbo will also work. TMF system will end with an exhaust down pipe through which the burned gas is removed from the environment by the discharge system.

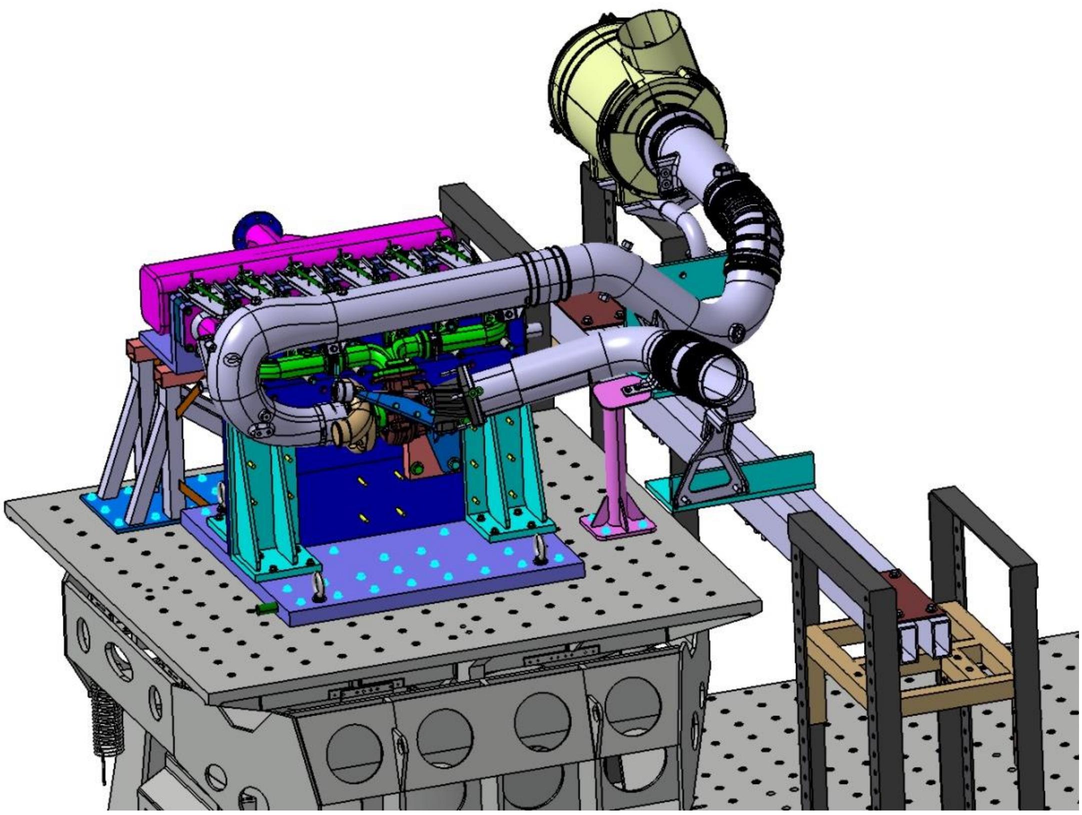

Figure 4.8 : Main parts of exhaust manifold TMF test rig design.

Hot gas temperature will be enough to make exhaust manifold temperature distribution as observed in the real working conditions. The maximum observed temperature on the exhaust manifold is almost 545 ^{0}C. This maximum temperature depends on the fuel type, euro emission level and engine architecture. Main components of the TMF rig is showed in Figure 4.9 with exploded view.

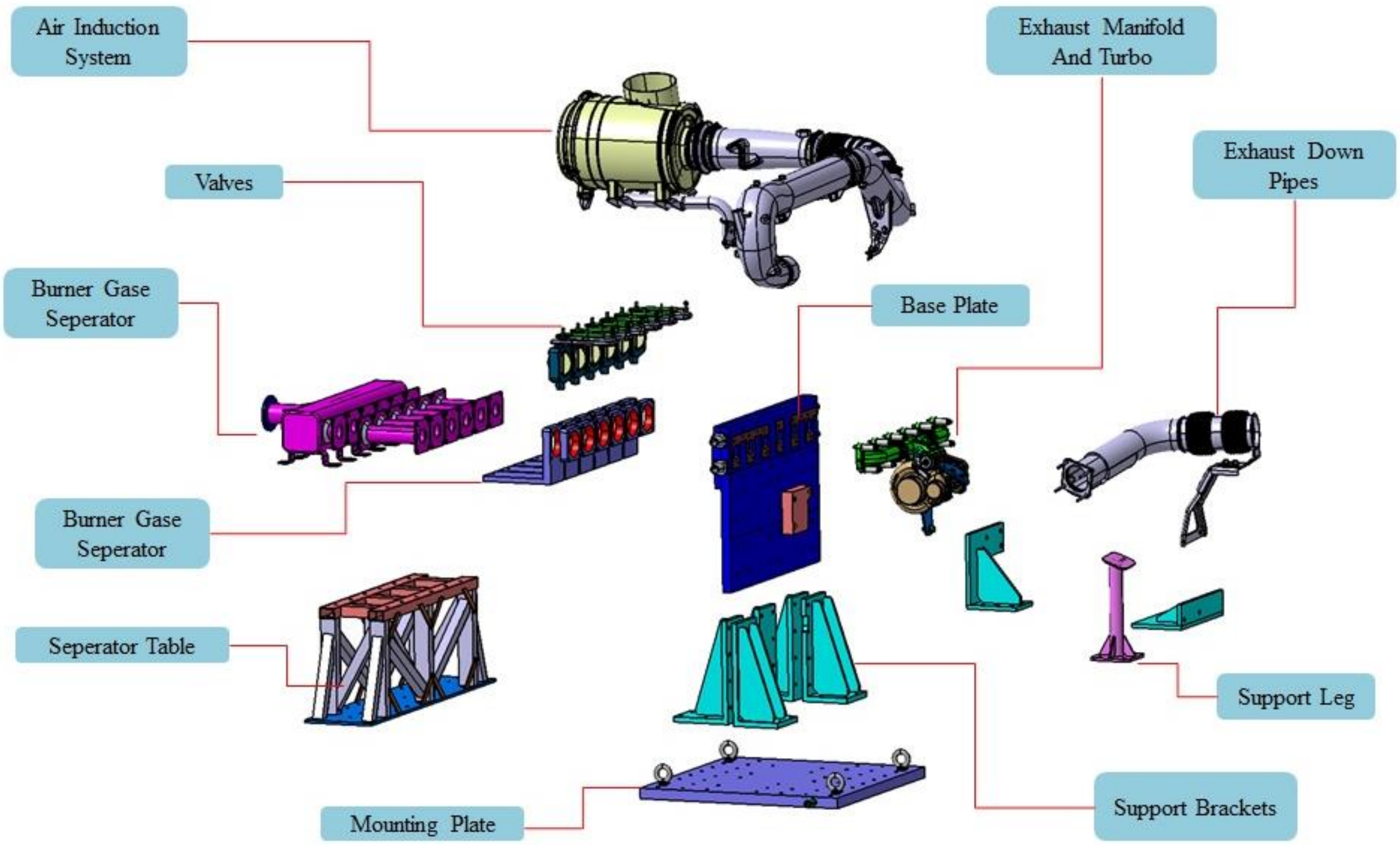

Figure 4.9 : Exploded view of the TMF test rig design core parts.

A special stainless steel burner separator is designed for the almost equal gas flow through the base plate. However, the flow rates are not clear for the exhaust manifold temperature map. Trial and error is the best method according to the testing team; thus six valves are placed on the separator to the control flow rate manually. In Figure 4.10, detailed cut-off section is showed for design details.

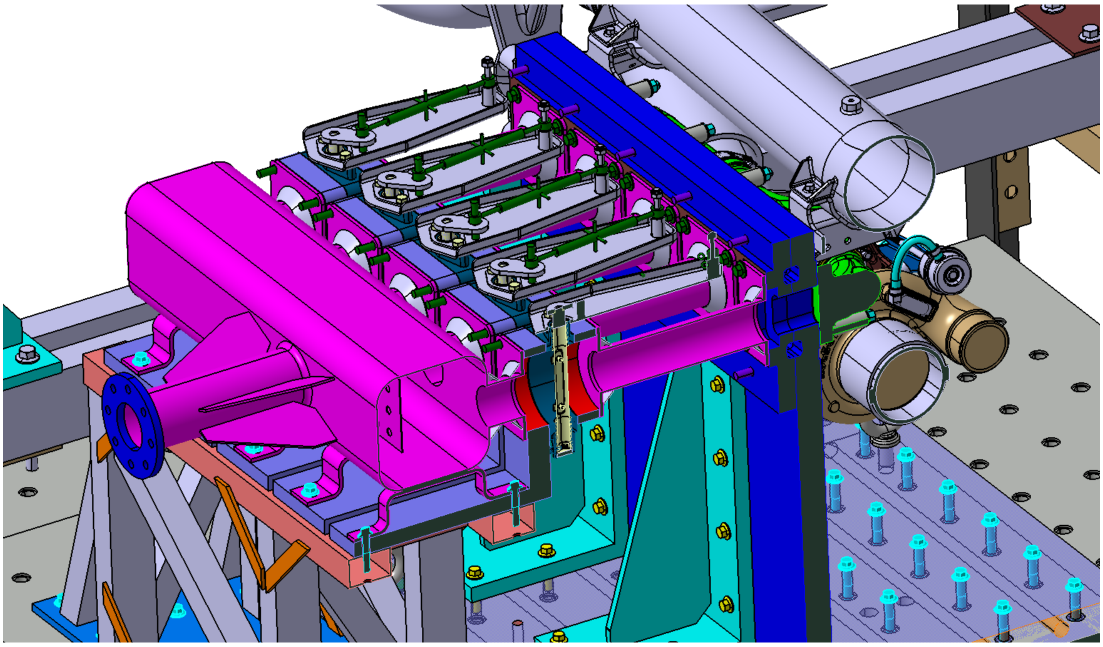

Figure 4.10 : Detailed cut-off view of the TMF rig (Manual valve control).

5. ANALYSIS METHODOLOGY

For thermal mechanical analysis, prediction of metal temperature during heat-up and cool-down cycles are very important. Exhaust manifold heat transfer analysis is a typical multi-physics problem where there is a strong interaction between the fluid and solid domains, so the CFD and FE solvers have to be coupled for these CAE studies [16].

TMF analysis briefly could be separated into three main parts. The first part is heat transfer analysis and the second part is transient nonlinear finite element analysis of exhaust manifold. The last one is to determine the number of fatigue life cycles.

Generally used methodology is long cycle fatigue (LCF) which gives a directional assessment of TMF vulnerability. The equivalent plastic strain (PEEQ) is used here to evaluate the yield condition of the critical parts. In an isotropic hardening plasticity theory, for most materials, the PEEQ is defined as;

$$\sqrt{\frac{2}{3} d\varepsilon^{pl} : d\varepsilon^{pl}} = PEEQ \qquad \textbf{(5.1)}$$

PEEQ value criteria for TMF analysis is not specified here because it is confidential information of the company but they are considered during fatigue life interpretation. For more reliable fatigue life prediction, fatigue analysis programs could be used.

On this study, commercial nCODE DesignLife program is used for fatigue life prediction. Cast manifolds are modeled with tetrahedral elements with a maximum size not exceeding 5 mm. Extra care should be paid to the critical areas of the manifolds, with an average element size 1-2 mm [15].

5.1 Heat Transfer Analysis

The ability to accurately predict metal temperature of exhaust manifold is very important for a robust/durable design of the exhaust manifold. In light of this fact, the first step in the manifold development is the accurate metal temperature prediction of the manifold that requires the coupling of CFD and FEA. This is an iterative approach between CFD and FE solvers and requires the proper data type exchange on the interface between CFD and FE models [16].

The exhaust manifold is modeled in HyperMesh software with dummy plate as seen in the Figure 5.1.

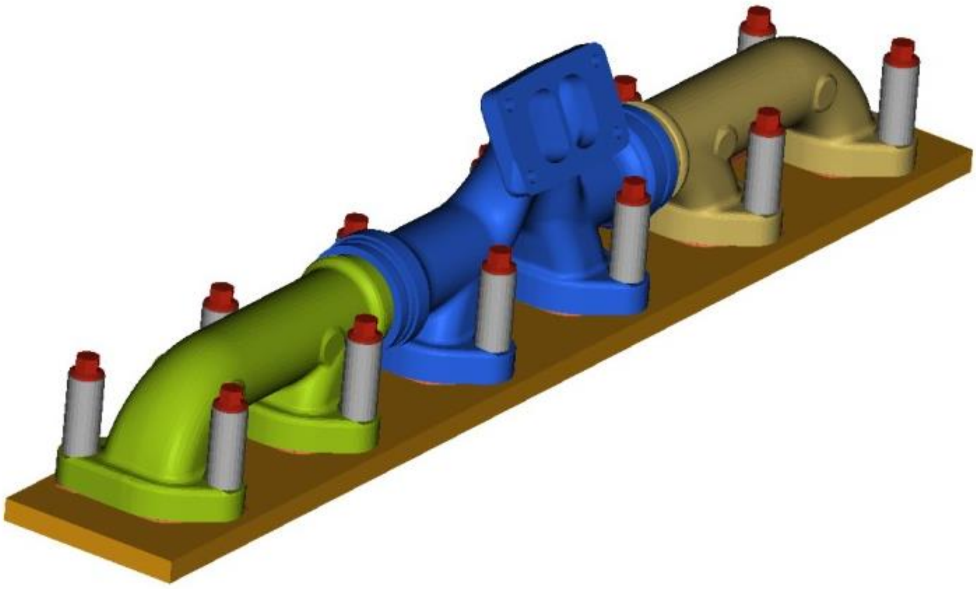

Figure 5.1 : Three pieces cast exhaust manifold model.

5.2 Thermal Mechanical Analysis

There are two different approaches to TMF analysis for exhaust manifold in this study. The first approach is to make inferences about the fatigue life with PEEQ values. Another approach is using a fatigue post-processor FE analysis program like nCODE DesignLife. Actually, the second approach preferred to the first method. There will be a common structural analysis integrated with CFD results.

A transient nonlinear Finite Element Analysis (FEA) is undertaken to simulate the inelastic deformation and predict thermo-mechanical fatigue (TMF) failure. The maximum temperature and gasket sealing are two other design concerns in manifold thermal mechanical fatigue durability.

Critical areas are usually very localized in small zones of high stress and temperature. These include inter-runner ribs, fillets, socket clearances, wall junctions etc. Internal walls that are usually used for flow separation could also lead to critical areas. Since the TMF calculations are based on element inelastic strains in critical areas, it is very important that the elements in critical areas should have good quality. A refined sub-model is recommended for accurate TMF calculations and subsequent iterations. Figure 5.2 shows modeled exhaust manifold with mesh structure.

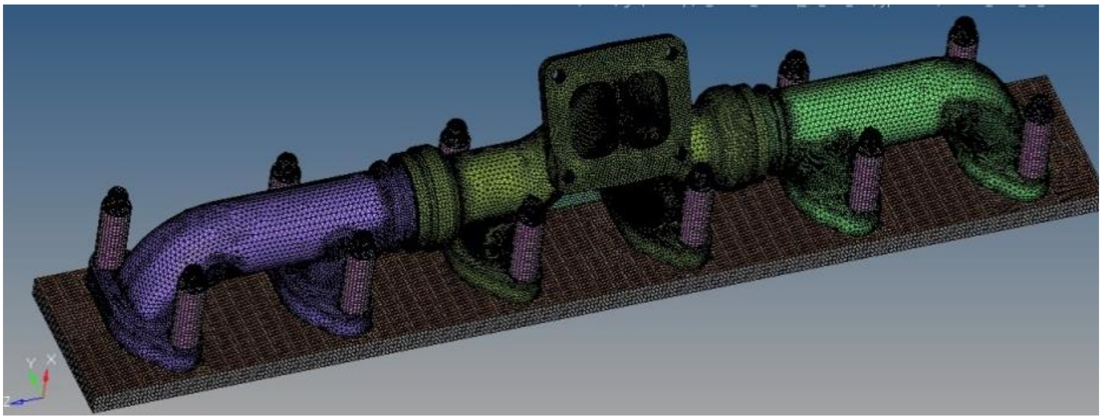

Figure 5.2 : Three pieces cast exhaust manifold model with mesh structure.

The FEA model should be checked for connectivity, duplicate elements, free element edges, warpage, skewness, and Jacobian of elements.

Exhaust manifold structural analysis contains 11 steps. The first three steps are bold pretension steps. Then there are eight sequential heating and cooling steps.

As mentioned earlier, the manifold skin temperatures are very critical for the life of the manifold. Overestimating the temperature could lead to a very conservative life estimate. Thus, skin temperatures should always be checked against Dyno data of the same manifold or similar manifolds whenever possible. Calculations of N* are based on extrapolating the displacement results from 4 cycles, which is difficult to do, and could lead to inaccurate estimates of the number of cycles to contact. This could also significantly affect the TMF estimates. Values of N* should also be checked against tested manifolds.

FEA uses transient heat transfer analysis to simulate the thermal loads on the manifold, and includes the bolts, nuts, bushes, gasket and representative cylinder head. Turbo assembly is also included in the model if necessary. The analysis combines detailed elastic-plastic and creep material models. After bolt tightening step, sufficient number of cycles, i.e., heat up and cool down steps, are applied to the complete model and equivalent creep and plastic strains are calculated [16].

6. TMF TEST RIG ANALYSIS

Before testing the exhaust manifold and other components, TMF test rig design should be proven to failsafe against experimental conditions. Many analyzes were performed to verify the reliability during the design such as modal analysis, CFD analysis and thermal fatigue analysis.

In TMF test rig, stainless steel was used for the parts in contact with the hot gases. Due to the corrosion resistance, formability and weldability characteristics, AISI 304 is selected based on past experiences of the firm. There are cooling channels inside the mounting plate. The dimensions are 800mmx800mmx50mm and its material is selected as Al5083 H111 for good machinability and high strength. ST52 steel is selected for the other parts.

Detailed mechanical properties and chemical analysis results of these materials are showed in the Table 6.1 separately.

Table 6.1 : TMF test rig materials and their properties.

Standard	Quality	Chemical Analysis (%)					Mechanical Properties		
		C (max)	Si	Mn	S (max)	P (max)	UTS , N/mm2	Yield , N/mm^2	Fracture, %
DIN 2391	ST52	0.22	max. 0.55	max. 1.6	0.05	0.05	490.0 - 630.0	min. 355.0	22

Standard	Quality	Chemical Analysis (%)						Mechanical Properties		
		Fe	Mn	Mg	Cr	Al	Hardness (Brinel)	UTS , N/mm2	Yield, N/mm^2	Fracture, %
EN 485-2	5083 H111	0.4	0.4 - 1.0	4.0-4.9	0.05-0.25	Rest	75	270-345	250	15

Standard	Quality	Chemical Analysis (%)							Mechanical Properties		
		C	Si	Mn	Cr	Ni	Fe	Hardness (Brinel)	UTS , N/mm2	Yield , N/mm^2	Fracture, %
AISI 304	AISI 304	0.08	1,0	2	20	11	Rest	150	520	310	30

6.1 TMF Rig Modal Analysis

HyperMesh finite element program is used for the test rig analysis. The first mode goal was 150+ Hz for the system. There are many design iterations and modifications to achieve this target.

2400= Max. Engine Operating Speed

$$3^{rd} \text{ Engine Order} = 2400 \times 3/\,60 = 120 \text{ Hz.} \qquad \textbf{(6.1)}$$

120Hz= Min. required rig frequency

C3D10M tetra secondary 3D meshes are used with 5mm mesh dimensions. Mesh size control was not performed for this analysis because similar part size and analysis were previously made for the mesh size of the control.

From Figure 6.1, the first mode of the rig design is 184 Hz and it is satisfactory. After mounting the other parts, it will be even higher due to more connections to the outside frame. The second mode is 226 Hz and third mode is 260 Hz but they are not important for the scope of work. According to engine operating speed and analysis results, design natural frequency safety factor:

$$184\text{Hz}\,/120\text{Hz} = 1.53 \text{ Safety Factor} \qquad \textbf{(6.2)}$$

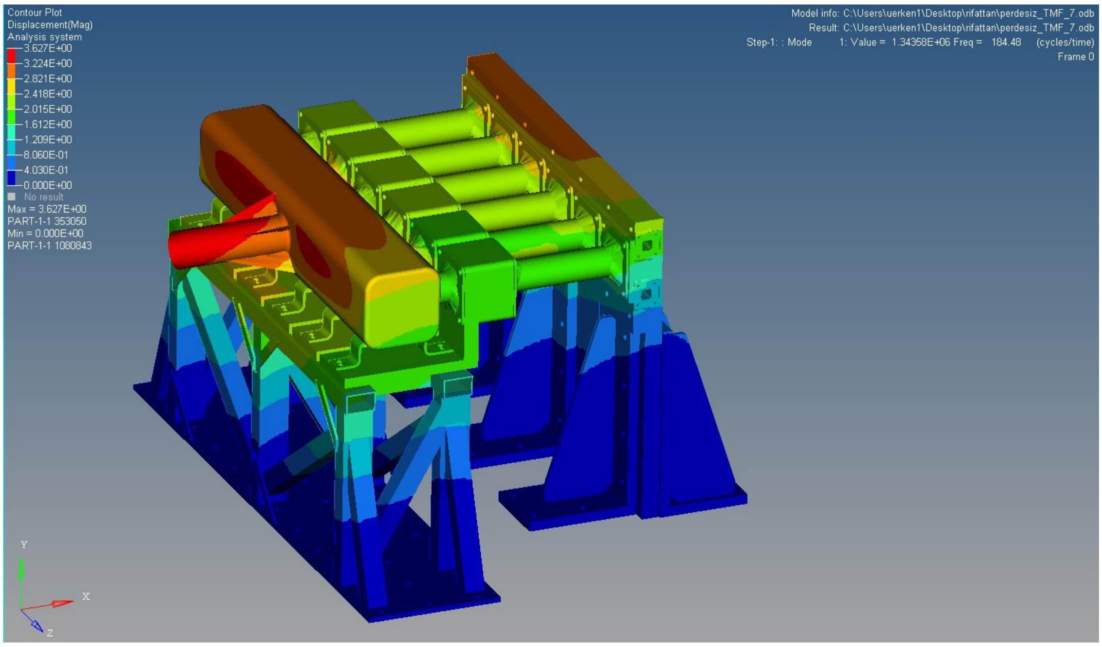

Figure 6.1 : Modal analysis results for TMF rig designed parts.

6.2 TMF Rig CFD Analysis

By the use of Star CCM+ software, CFD analysis is performed to assess the flow balance among runners and inlet flow distribution in the rig with the help of firm's CFD department. There is an optimization process between the design and CFD. After many design iterations, acceptable results are obtained.

CFD analysis parameters are given in Table 6.2. Firstly, CFD analysis are performed in 2-D due to bilateral symmetry of the part. In the Figure 6.2, detail views of the separator part are showed.

Table 6.2 : CFD analysis parameters and settings.

Boundary Conditions	
Inlet	1900 kg/h 500 °C
Oulet	Pref=101325 Pa
Physics Settings	
Physics Model	Two Diomensional
Turbulence Model	K-Epsilon Turbulence Model
Temperature Dependence	Segregated Flow 2nd Order
Wall Treatment	Two Layer All y+
Time Dependence	Steady State
Density Definiton	Ideal Gas
Viscosity	Sutherland's Law
Mesh Settings	
Mesh Model	Trimmer
# of prism layer used	2
Prism Layer Stretching	1.05
Prism Layer Thickness	0.75 mm
# of volume mesh	~215 k
CPU Time (24 CPU)	Avarage 0.5 hours (Star CCM+ 10.02.010)

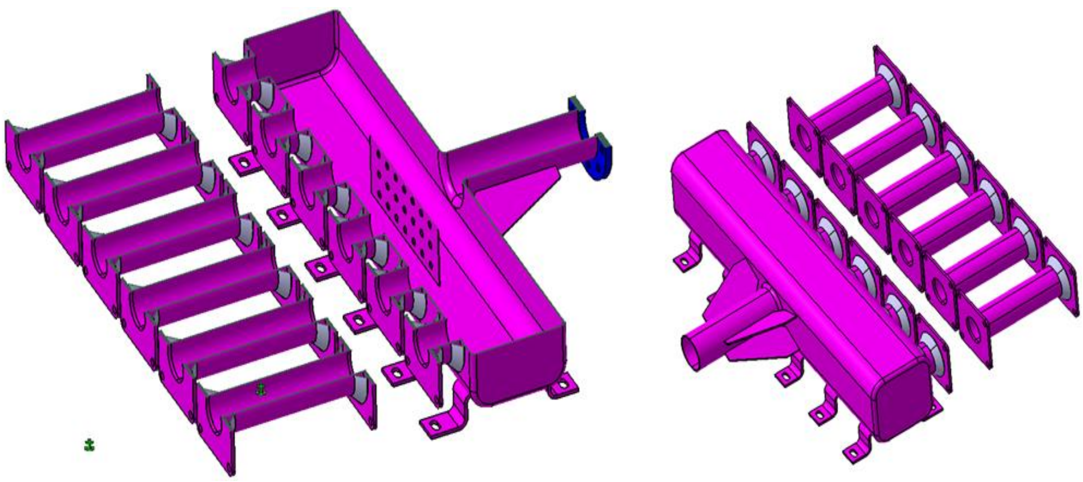

Figure 6.2 : Critical hot gas separator part.

CFD analysis model is showed in the Figure 6.3. In the Figure 6.4, 2-D analysis resutlts are showed.

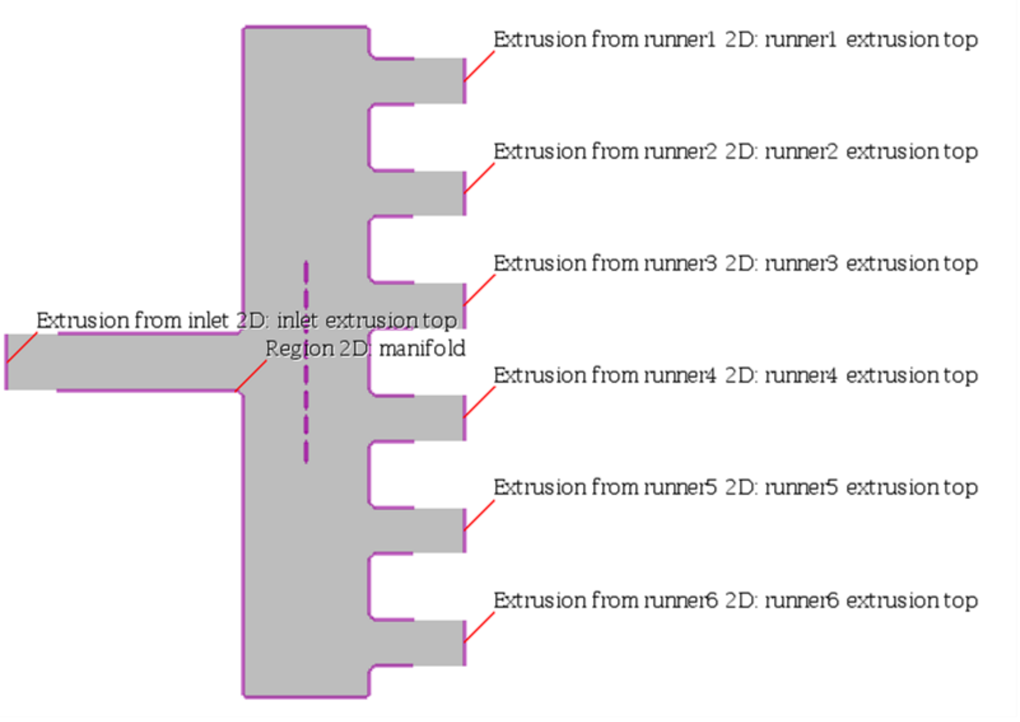

Figure 6.3 : 2-D CFD model of the seperator part.

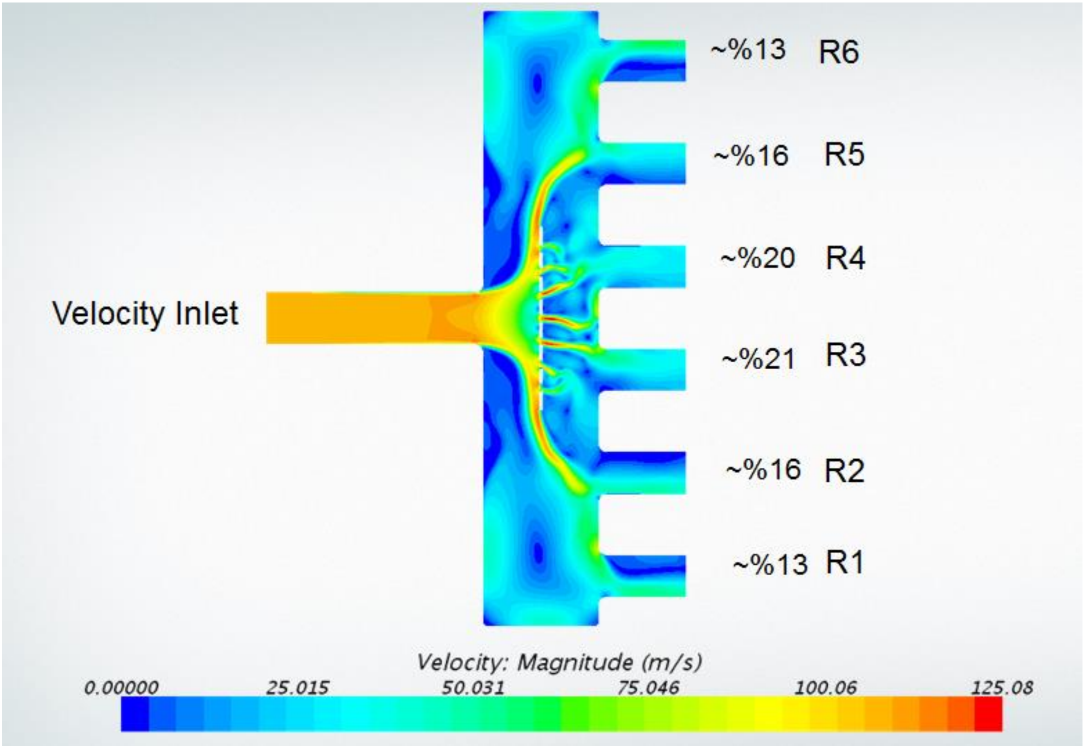

Figure 6.4 : 2-D CFD results for the separator part.

2-D CFD results shows that runner flow rates are similar and could be equal with valve control process. There is some undesired low velocity volumes on the mixture reservoir but in order not to complicate manufacturing process, rectangular prism geometry preferred.

As seen in the Figıre 6.5, 3-D CFD analysis is also performed for the design confirmation and its results are found to be closer for each runner. The middle plate with small holes is very effective in flow distribution.

On the other hand, total pressure drop is measured as 6.64 kPa from 3-D CFD results. (6.64 kPa =0.0664 bar) In comparison to the working pressure of 2 bar, it is not very important.

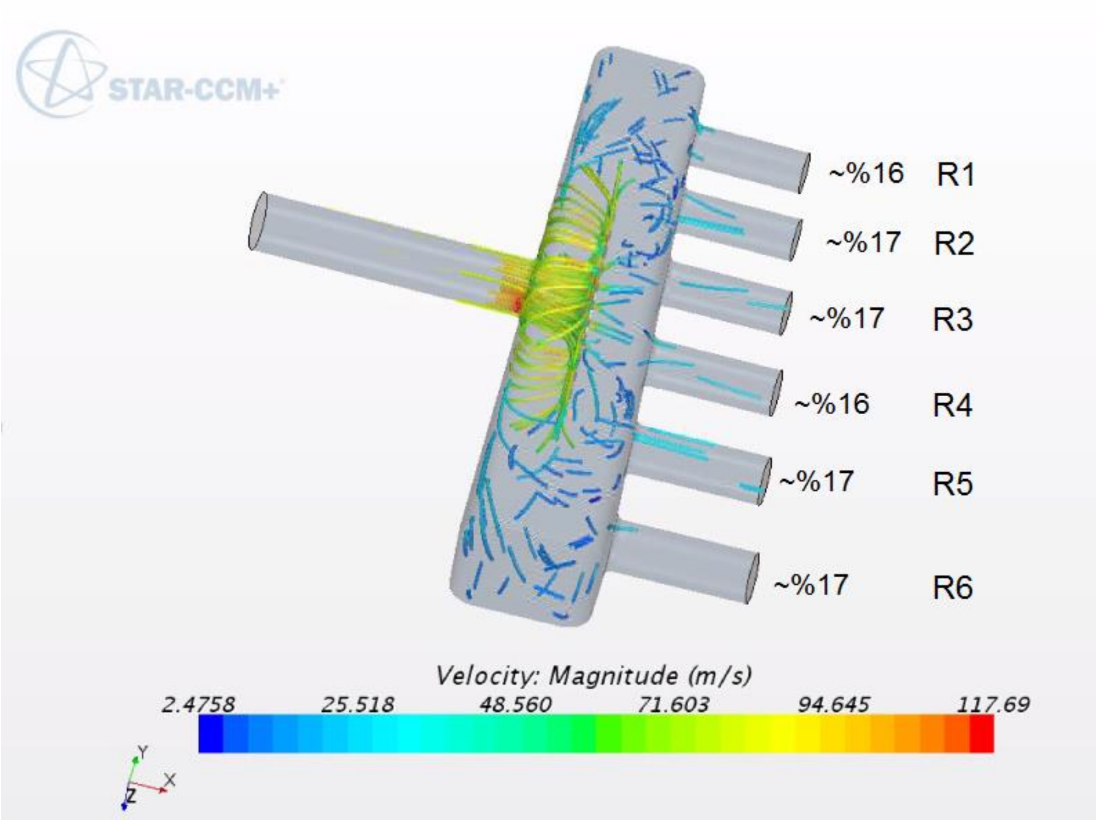

Figure 6.5 : 3-D CFD results for the separator part.

6.3 TMF Rig Structural and Fatigue Analysis

After completion of 1D and 3D CFD analyses, gas temperature and heat-transfer coefficients (HTC) are obtained. This CFD analysis is a type of conjugate analysis, therefore metal temperature distribution is achieved at the same time. The maximum temperature value is observed around the inlet pipe and around the middle perforated plate. Modeled parts are showed in the Figure 6.6.

Following, more accurate model is created for fatigue analysis via HyperMesh software. 2D shell mesh structure is created with S4R element type. This is a general purpose linear 4-sided shell element. S4R is a robust, general-purpose element that is suitable for a wide range of applications.

The parameters which are used to optimize mesh structure are showed in the Table 6.3.

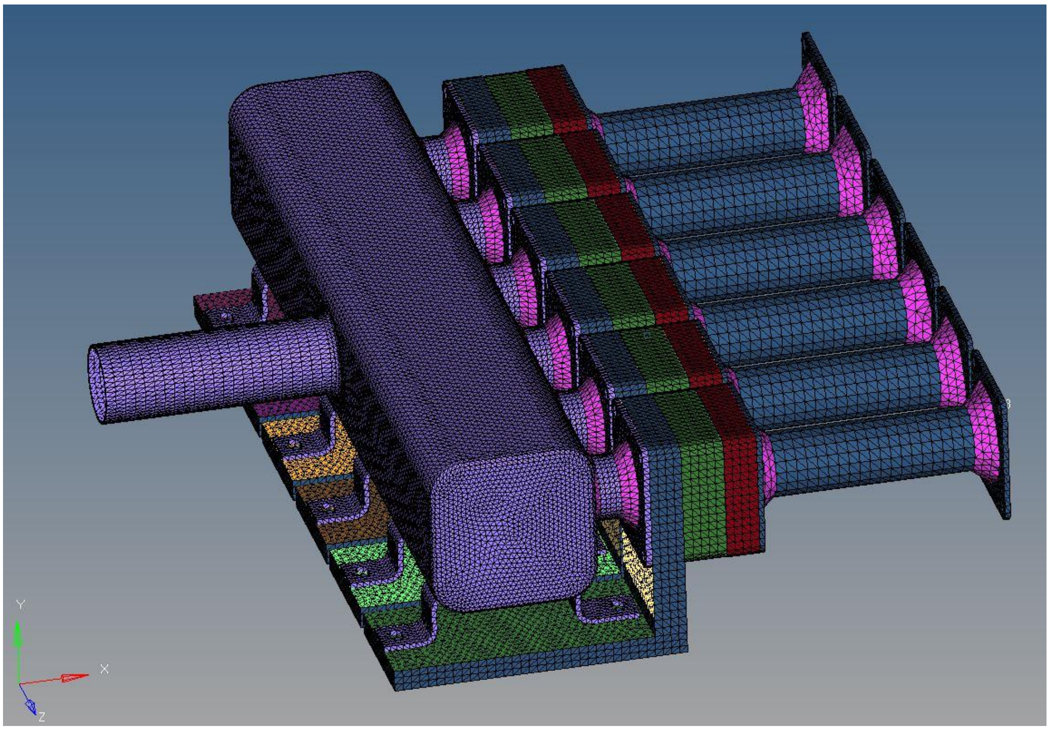

Figure 6.6 : Meshed model for the structural and fatigue analysis.

Table 6.3 : Element quality check parameters for HyperMesh [15].

Entities	2-D (tria)	3-D (tetra)
Warpage	5/40(min)	5/40
Aspect Ratio	5	5
Skew	60	60
Chord. Dev.	0.1	
Jacobian	0.5	0.5
Length	-	-
Taper	0.5	-
Min. Angle	45/20	20/5
Max. Angle	120/160	120/160
Tetra Collapse	-	0.1
Volume Skew	-	1
Volume A.R.	-	5

Then, C3D10M element type (10-node second-order tetrahedral element) is used for the rigid mesh structure creation. Examples representation geometry as shown in Figure 6.7. 3mm mesh size for the separator and 5mm mesh size for the other components are used. There was no need for mesh size verification based on previous experiences.

These elements take the advantage of automatic triangular and tetrahedral mesh generators and are robust for large deformation problems and contact [20].

The maximum temperature is around 560 °C, as shown in Figure 6.8 and Figure 6.9. These temperature values are not high enough to generate static damage, but there is the possibility of creating problems during the TMF cycle.

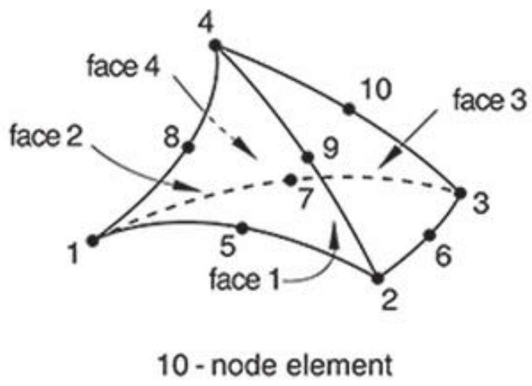

Figure 6.7 : C3D10M Element geometry [20].

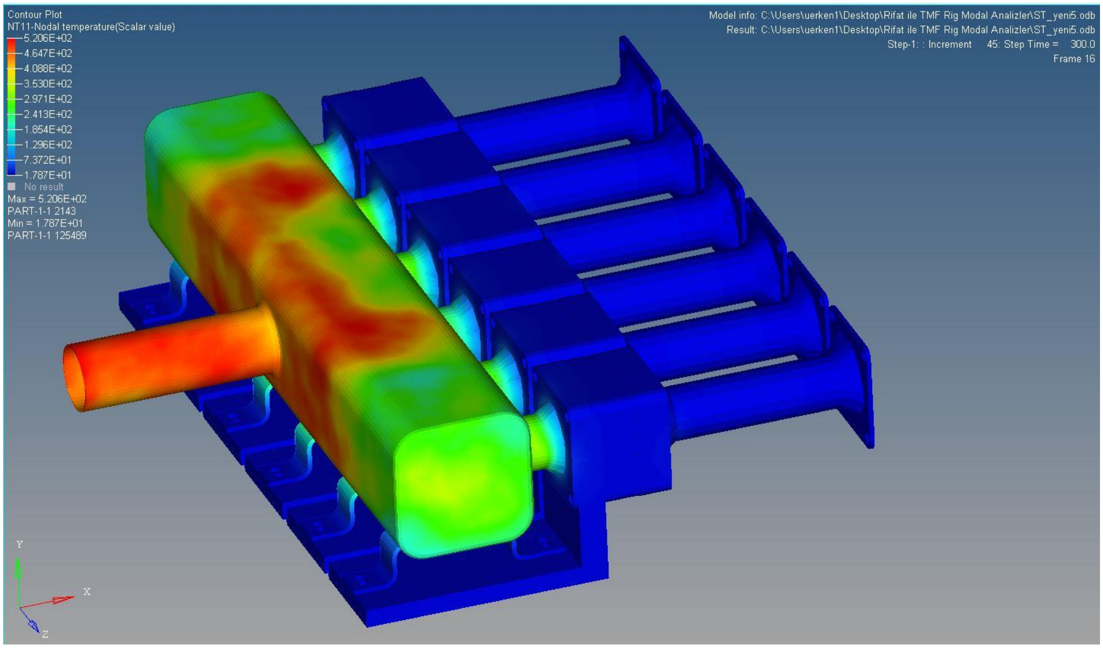

Figure 6.8 : Temperature distribution for the model-1.

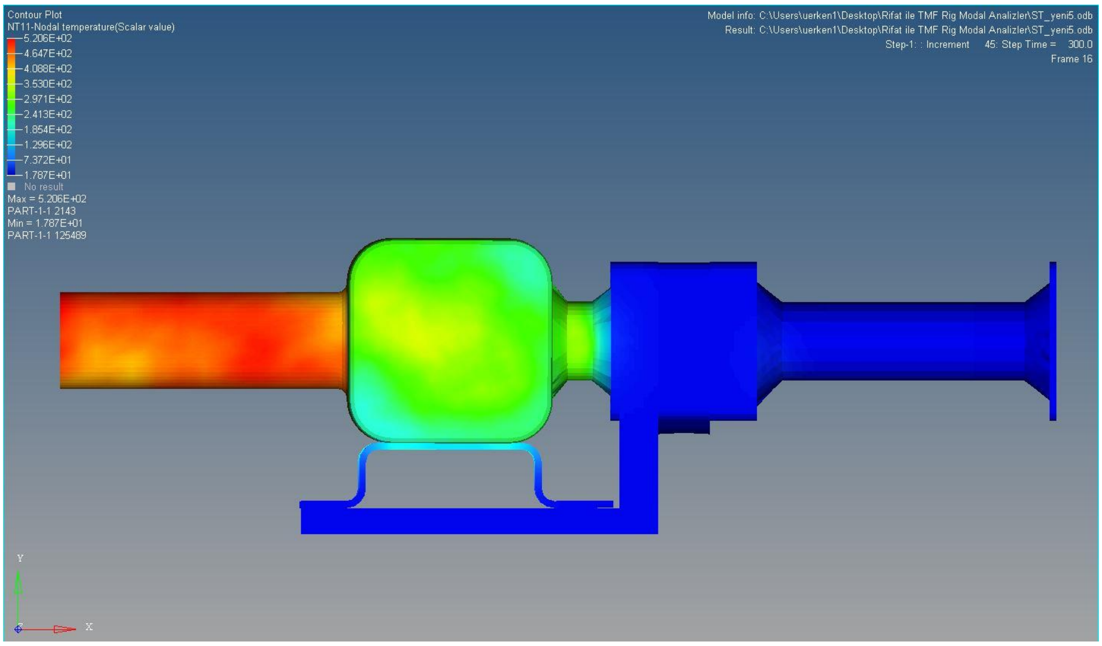

Figure 6.9 : Temperature distribution for the model-2.

Analysis card like below is used for the structure analysis with temperature mapping. This is a single step explicit thermal-mechanical analysis. The heating time is taken as 300 seconds which is the same as physical test heating process on the TMF rig.

```
***
*INITIAL CONDITIONS, TYPE = TEMPERATURE
NALL,21
*BOUNDARY, OP=NEW
bc,1, 3
*STEP
*VISCO,CETOL=5.0000E-02
 1.0E-2, 300, 1.0E-5, 20.0
 *contact controls, stabilize
*TEMPERATURE,FILE =HT_yeni3, BSTEP = 1, MIDSIDE
*OUTPUT, FIELD, FREQUENCY = 3
*NODE OUTPUT
U,
NT,
*ELEMENT OUTPUT
S,
PEEQ,
CEEQ,
*END STEP
***
```

Displacement values are seen in the Figure 6.10 whose maximum is 4.2mm. Most moving section, inlet pipe, is connected to hot gas burner with metal flex. Note that, slot designs on the connection legs prevent accumulation of stress during thermal expansion.

The PEEQ is the ABAQUS parameter name for the equivalent plastic strain which is defined in section 5. It gives us a brief information about the fatigue behavior of components according to past experiences ,e.g., see Figure 6.11.

According to Ford Otosan's past experiences with this kind of stainless steel welded components, the PEEQ is acceptable in terms of thermal mechanical fatigue.

From Figure 6.11, the max. the PEEQ value is on the critical separation neck section. The PEEQ value was higher before adding extra cross welded stiffener features. The PEEQ value in the Figure 6.11 is an acceptable value but its location not on the hot gas touch region. If later added features are masked, the results will be more useful. After masking, the PEEQ value is lower like seen in the Figure 6.12.

As a result, max. the PEEQ value and other stress values are O.K. that TMF test rig will remain standing against the cycling test conditions.

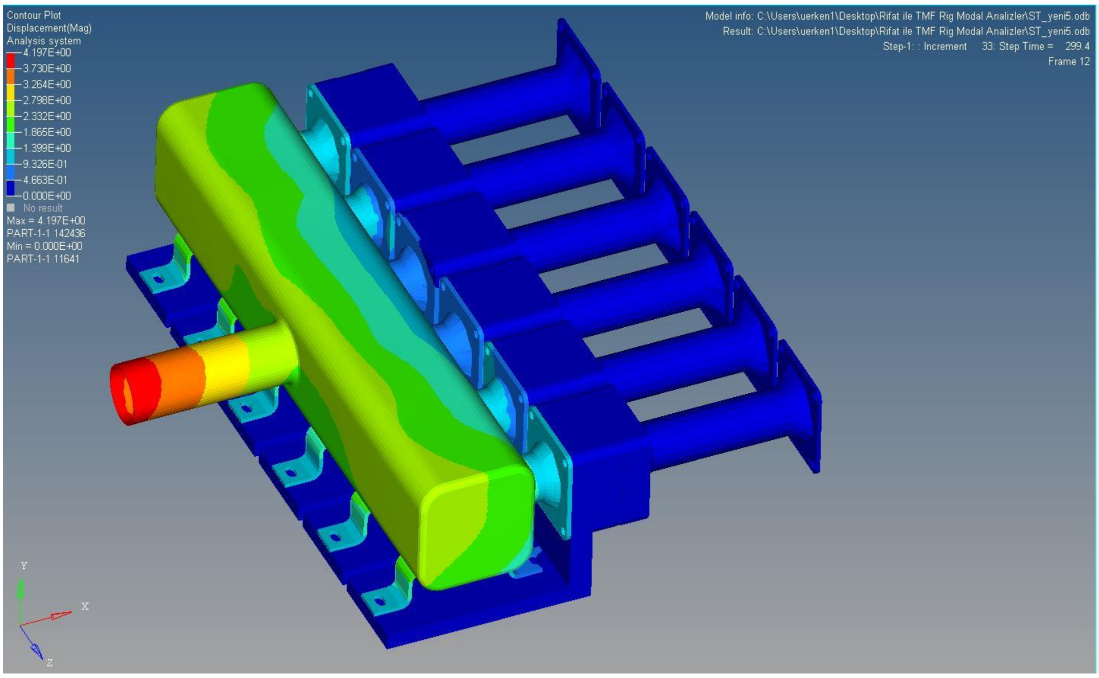

Figure 6.10 : Displacement plot for the model.

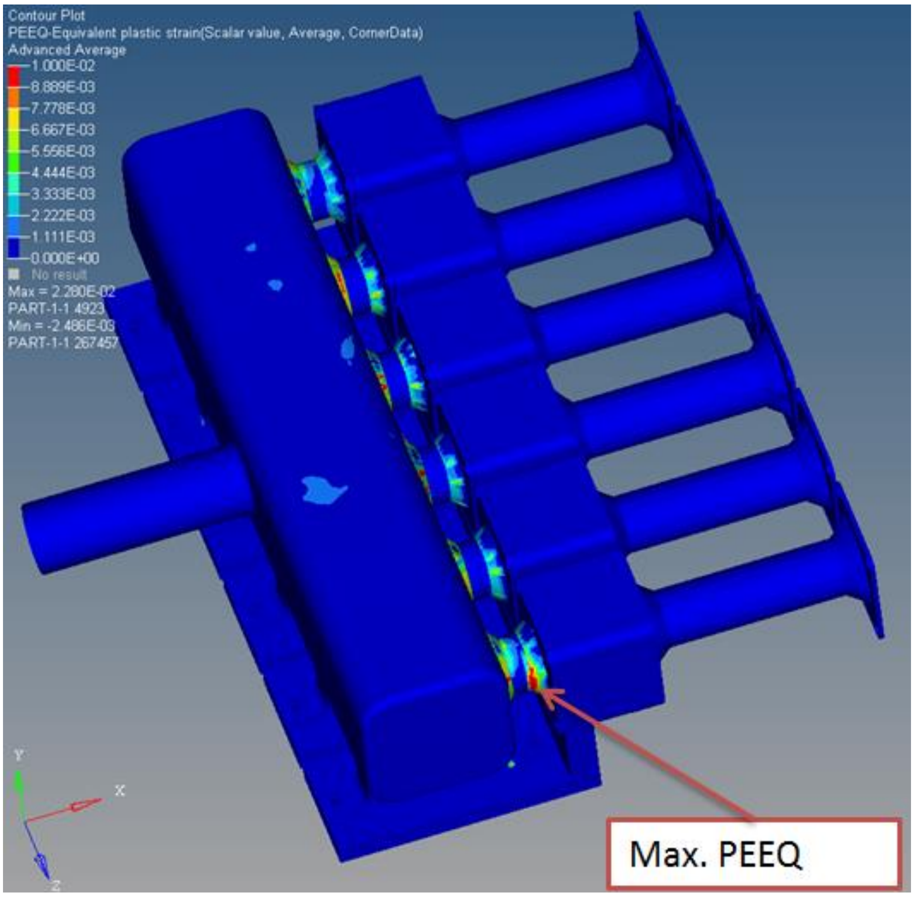

Figure 6.11 : The PEEQ criteria for the TMF rig.

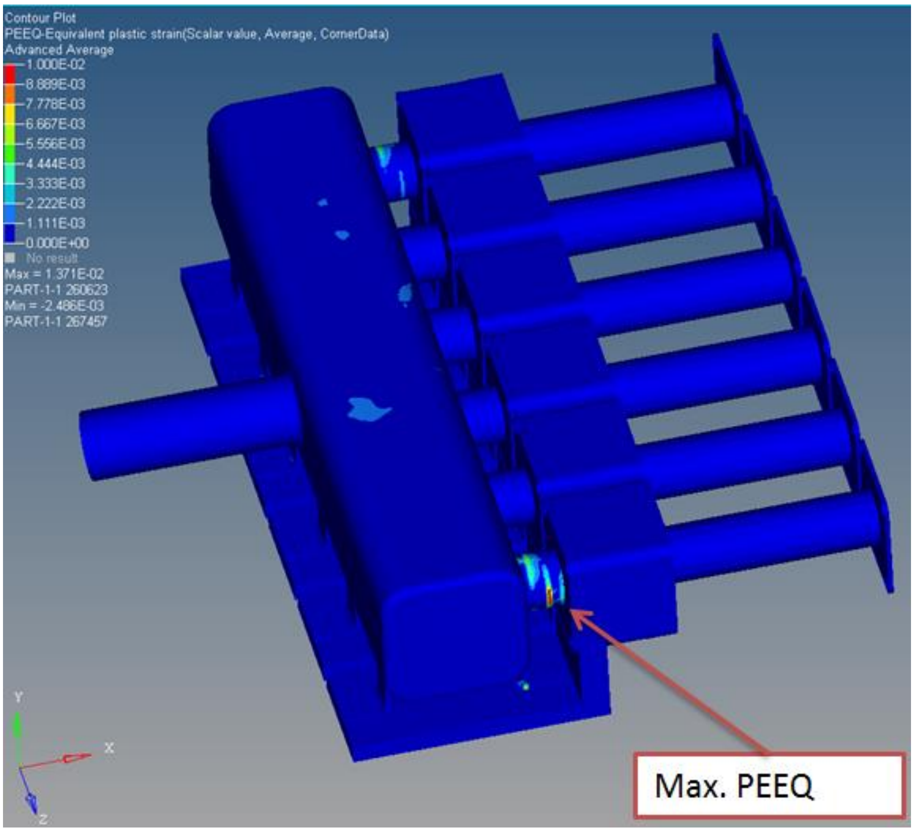

Figure 6.12 : The PEEQ criteria for the TMF rig.

7. EXHAUST MANIFOLD MATERIAL DEFINITION AND MODELING

The maximum predicted metal temperature should not exceed the allowable limit of the material used in the test rig. The maximum metal temperature of cast exhaust manifolds made of HiSiMo material (SAE J2582 Grade 3) should not exceed 840 ^{o}C at any time during real working or test process.

7.1 HiSiMo Cast Iron

High silicon molybdenum (HiSiMo) ductile cast irons (DCI) are frequently used for high temperature engine components, including exhaust manifolds and turbocharger housings. HiSiMo DCI containing 4-6% silicon with greater than 0.3% molybdenum is characterized by good high-temperature strength and oxidation resistance. The high silicon content increases oxidation resistance of DCI through the formation of a silicon-rich surface layer and improves microstructural stability of the ferritic matrix at elevated temperatures [17].

The tensile engineering stress-strain curves are shown up to 20% strain in Figure 7.1. Duplicate specimens were used at all temperatures, and representative curves are reported in Figure 7.1. In the Table 7.1, chemical percentage composition is showed for the HiSiMo. The tensile properties of the HiSiMo used in this study are summarized in Table 7.2 as average values from both tests conducted at each temperature. The Young's modulus, 0.2% offset yield (proof) strength and ultimate tensile strength decrease with increasing temperature. The minimum value of both elongation and reduction in cross-sectional area is seen at 400°C. Elongation at 400°C is found to be just 3% in a 10 mm gauge length. Ductility is recovered above 400°C as demonstrated by an increase in elongation and higher reduction in area[17].

Table 7.1 : Composition of the HiSiMo DCI (wt%).

C	Si	Mn	P	S	Mo	Mg	Fe
3.26	4.28	0.21	0.018	0.010	0.48	0.032	Bal.

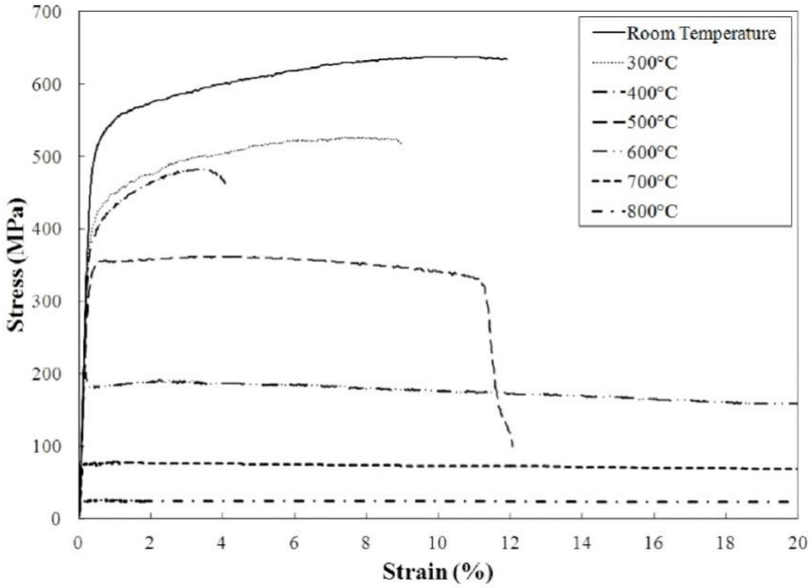

Figure 7.1 : Engineering stress-strain curves for tensile tests conducted at different temperatures at a strain rate of 0.05 per second [17].

Table 7.2 : Summary of tensile properties for the HiSiMo DCI [17].

Temperature (°C)	E (GPa)	0.2% Proof Strength (MPa)	UTS (MPa)	Elong. (%)	Reduc. in Area (%)
RT	168	412	632	14	9
300	159	342	536	12	7
400	154	326	486	3	2
500	146	266	358	11	11
600	139	175	192	31	32
700	118	80	98	35	37
800	86	32	38	50	61

7.2 Material Modeling

In materials where the viscous properties within the plastic range play an important role, it is necessary to apply the elasto-viscoplastic constitutive relations. We can cite the following elasto-viscoplastic models for example: Perzyna, Chaboche, Aubertin, Lehmann-Imatani , Miller, Bodner-Partom, Krempl, Tanimura, Krieg-Swearengen-Jones, Walker, Korhonen-Hannjula-Li, Freed-Virrilli. Their relatively large number shows that they are not universal and can be applied only under certain conditions or for a limited range of materials, as shown in Figure 7.3 and Figure 7.4 This constitutive model is suitable for analysis of isotropic materials (mainly metals at high temperatures) in the range of small inelastic strains. In the Figure 7.2, micrograph of the untested HiSiMo DCI with spherical graphite nodules and regions of intergranular Fe_2MoC eutectic phase are seen. 2% nital etch is used to reveal the grain boundaries.

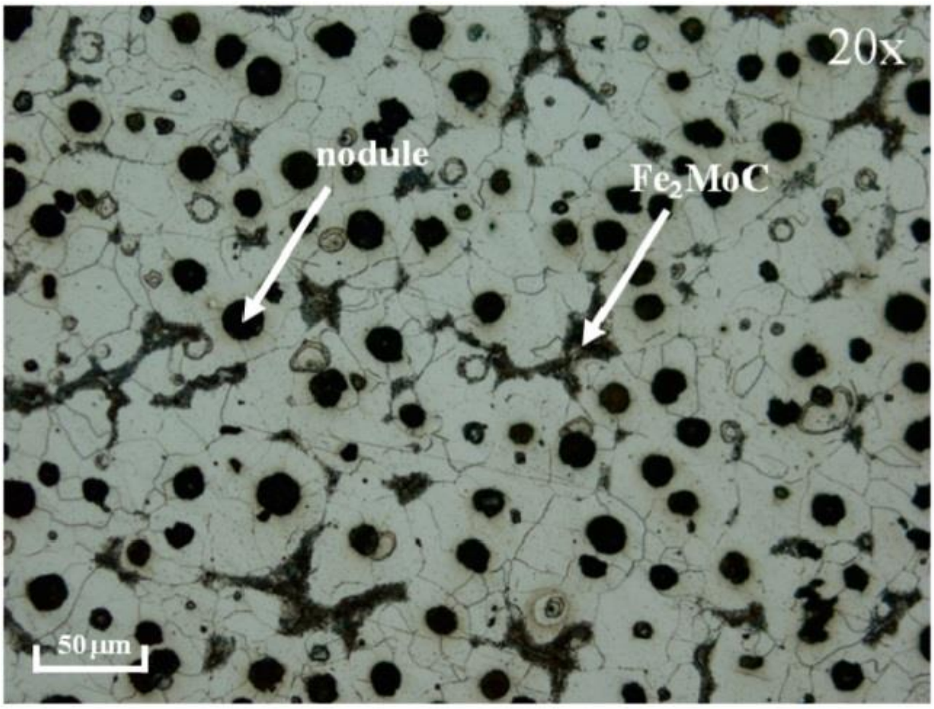

Figure 7.2 : Metallography results for the HiSiMo DCI.

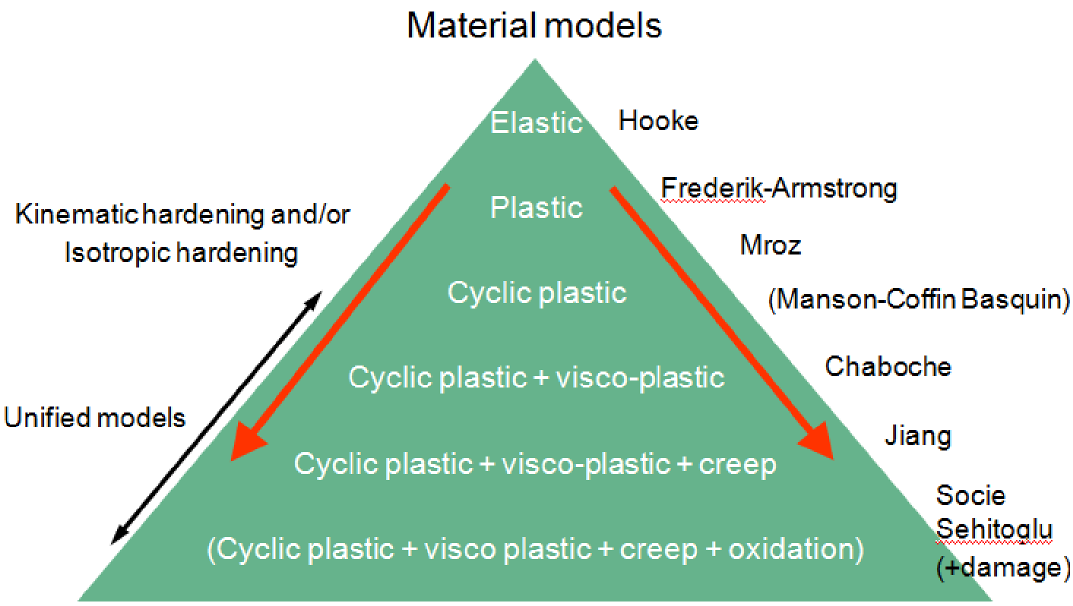

Figure 7.3 : Fatigue material models.

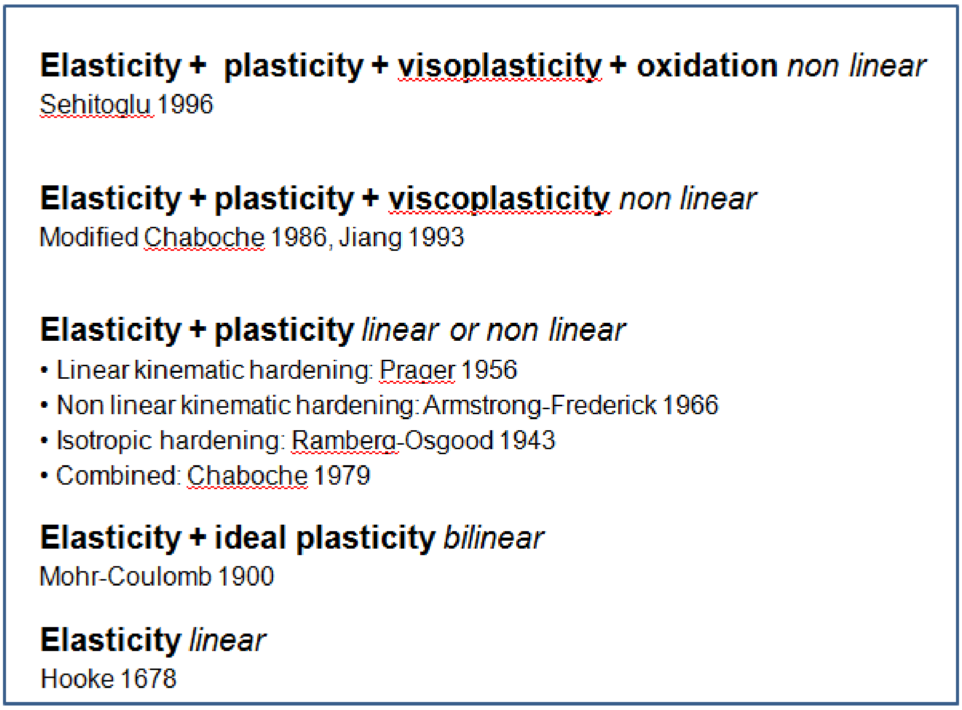

Figure 7.4 : Fatigue material models history [6].

7.3 Manson-Coffin-Basquin Method

Manson and Coffin did highly effective studies about the number of cycles to crack initiation as a function of the amplitude of plastic strain. They were the first people who work on this issue academically. Their works are based on the Basquin equation led to the known equation of the strain–life curve (Figure 7.5) where the total strain amplitude $\varepsilon_{a,t}$ is divided into elastic $\varepsilon_{a,e}$ and plastic $\varepsilon_{a,p}$ components as such:

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad \textbf{(7.1)}$$

The Young's modulus is obtained either by a static tensile material test or from the first hysteresis loop obtained from the fatigue test. Still, four material constants are necessary and they could be determined from several fatigue tests which are performed with cyclic loading, constant amplitude and a load ratio of $R_\varepsilon = -1$. Also specimens are un-notched and identical [19].

By hardening or softening effect are materials subjected to cyclic loading are often unstable, causing stress amplitude variation during the tests. Thus, the stress amplitude must be used according to the stabilized state, which occurs at the half of the number of cycles to crack initiation which was determined at 10% stiffness loss of stiffness over cycles. The Young's modulus, total strain amplitude and the plastic part of the strain amplitude can be derived with stress amplitude.

$$\varepsilon_{a,p} = \varepsilon_{a,t} - \varepsilon_{a,e} = \varepsilon_{a,t} - \frac{\sigma_a}{E} \quad \textbf{(7.2)}$$

To compute the material constant in Equation 7.1 from experimental data the least squares method for fitting the curves can be applied. Linearization of the plastic part of Equation 7.1 leads to

$$Y = \log(\varepsilon'_f) + cX \quad \textbf{(7.3)}$$

where Y = log (ε_a,p) and X = log ($2N_f$). While fitting the line, Equation 7.3, only those points should be taken into account where the value of the plastic strain is higher than the established limit ε_0. This limitation results from the measuring accuracy of the total strain and from the operations of subtraction in Equation 7.2. For steels, the value of $\varepsilon_0 = 0.01\%$ is recommended. Linearization of the elastic part of Equation 7.1 can be done in the same manner;

$$Y = \log\left(\frac{\sigma'_f}{E}\right) + bX \quad \textbf{(7.4)}$$

where Y = log (ea,e), and X = log (2Nf).

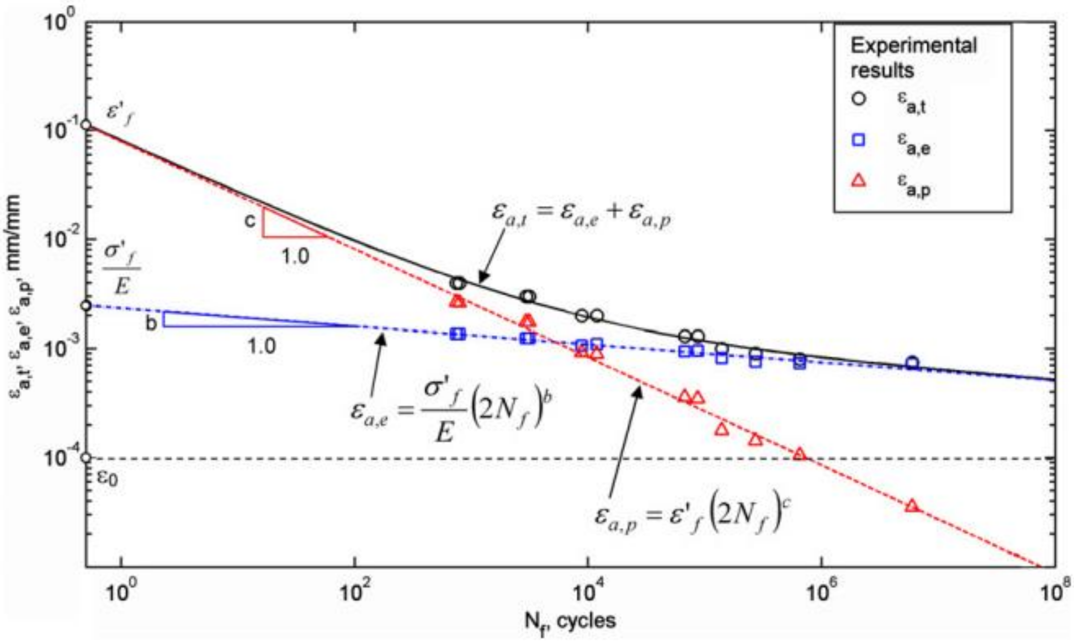

Figure 7.5 : Matematical example of the Manson–Coffin–Basquin curve according to Equation 7.1 [19].

8. EXHAUST MANIFOLD TMF ANALYSIS AND RESULTS

CFD analyses are completed for the model. Then, these results are used for the structural analysis of the exhaust manifold on ABAQUS software. There is a reliable method developed by Ford Motor Company. This method is correlated many times for different TMF analysis case. It contains some bolt pre-tension and initial stress values caused by casting process. Structural analysis is referenced this methodology. As mentioned before, there are three bolt fixing steps and eight heating and cooling steps as a loop. Below, there are basic heating step and output requests.

```
***STEP
cycle 1 heat up 1
*VISCO, CETOL = 0.05
1.0000E-04,     50.0,1.0000E-05,      20.0
*TEMPERATURE, FILE = XYZ.odb, BSTEP = 1, BINC = 1, ESTEP = 1,
EINC = 62, MIDSIDE
*OUTPUT, FIELD, FREQUENCY = 100
*NODE OUTPUT
U,
NT,
*ELEMENT OUTPUT
S,
PEEQ,
CEEQ,
*CONTACT OUTPUT
CSTRESS,
CDISP,
*END STEP
***
```

8.1 Exhaust Manifold Structural Analysis

After performing CFD analysis with commercial STAR CCM+ software, temperature distribution is shown in the Figure 8.1. Max temperature values are observed on the exhaust manifold engine head connection location as might be expected. The maximum. temperature is 545 ^{0}C during the heating step as seen in the Figure 8.1.

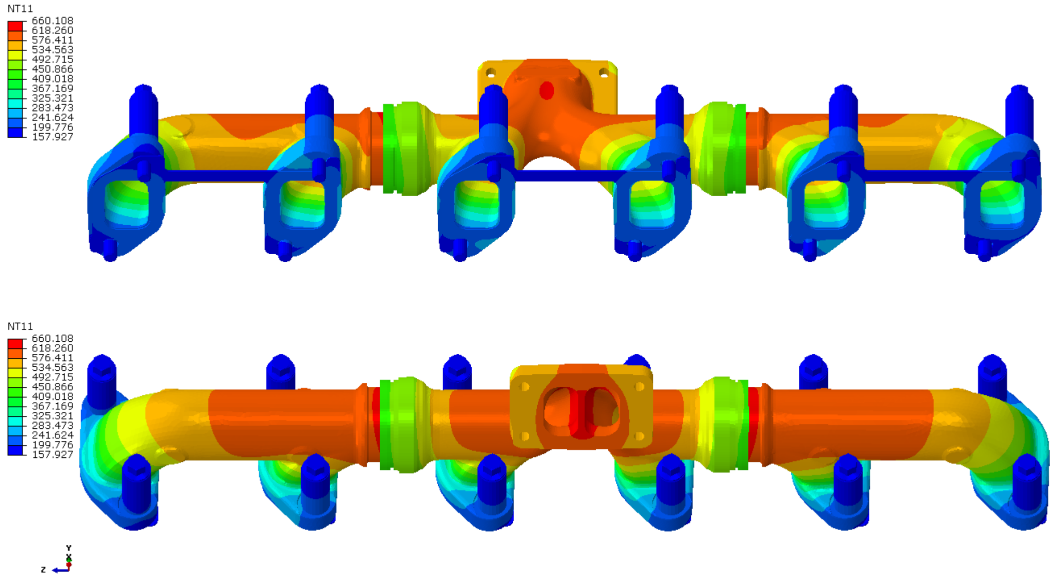

Figure 8.1 : Exhaust manifold temperature distribution at end of the heating step.

During heating and cooling steps, max. Von-Misses Stress values are 208 MPa and 195 MPa, respectively. As seen in the Figure 8.2, locations where stresses accumulate could be seen as contours. Also, deformations with 1x and 100x scale factors are showed in the Figure 8.3.

Beforehand, stresses and deformations are investigated. In the light of these results, nCODE program will give TMF fatigue life cycle estimation HiSiMo Cast Iron material.

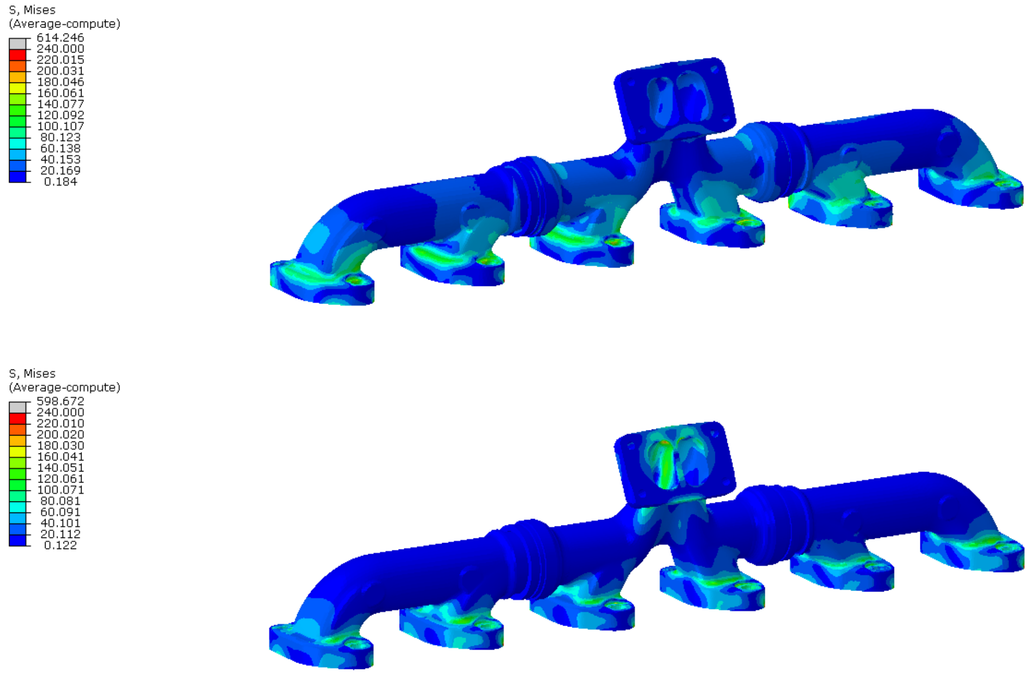

Figure 8.2 : Von-Mises stress distributions for heating up and cooling down steps.

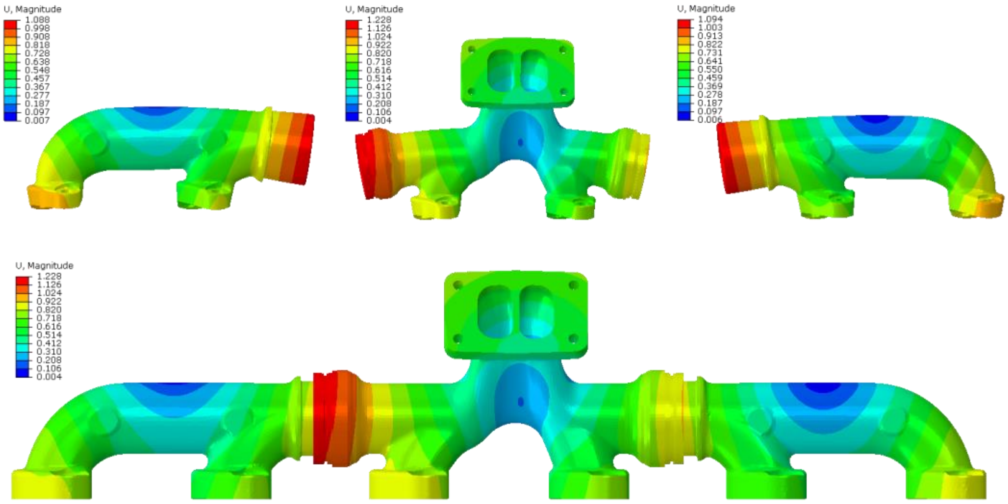

Figure 8.3 : Deformations of exhaust manifold are scaled by 100(above) and 1 (below).

8.2 Exhaust Manifold Fatigue Analysis

As mentioned before, the PEEQ value is very informative for the fatigue behavior. No critical PEEQ values are obtained on the exhaust manifold according to Ford Otosan's PEEQ fatigue criteria. This happens at the end of the latst step as shown in the Figure 8.4. It can be concluded that there will be no fatigue damage on the exhaust manifold on the basis of stress, deformation and PEEQ values.

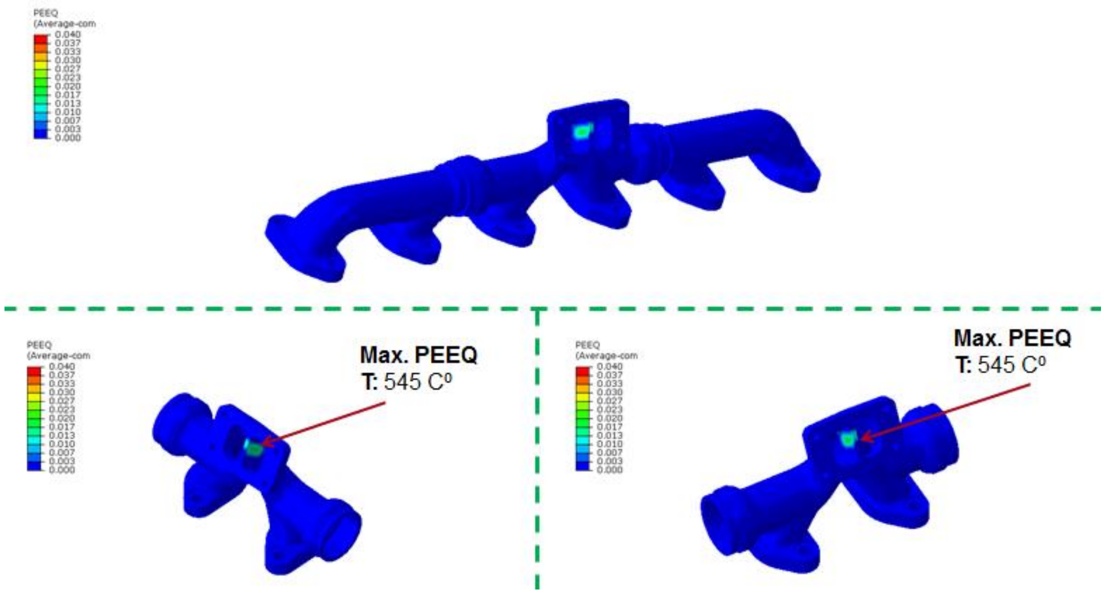

Figure 8.4 : Max. PEEQ values for exhaust manifold

9. FATIGUE ANALYSIS METHODOLOGY FOR LIFE PREDICTION

As already mentioned, sequential heating and cooling cycles and high temperature working conditions create significant strains on the exhaust manifold. In this study, Strain-Life (E-N) approach is used to calculate fatigue life of the components. Analysis model is showed in the Figure 9.1.

The E-N approach typically relates to situations where some of the cyclic loads are relatively large and have significant amounts of plastic deformation associated with them, together with relatively short lives [21].

nCODE DesignLife commercial FEM program is used to find critical low cycle fatigue (LCF) locations and their life cycle predictions in the test conditions.

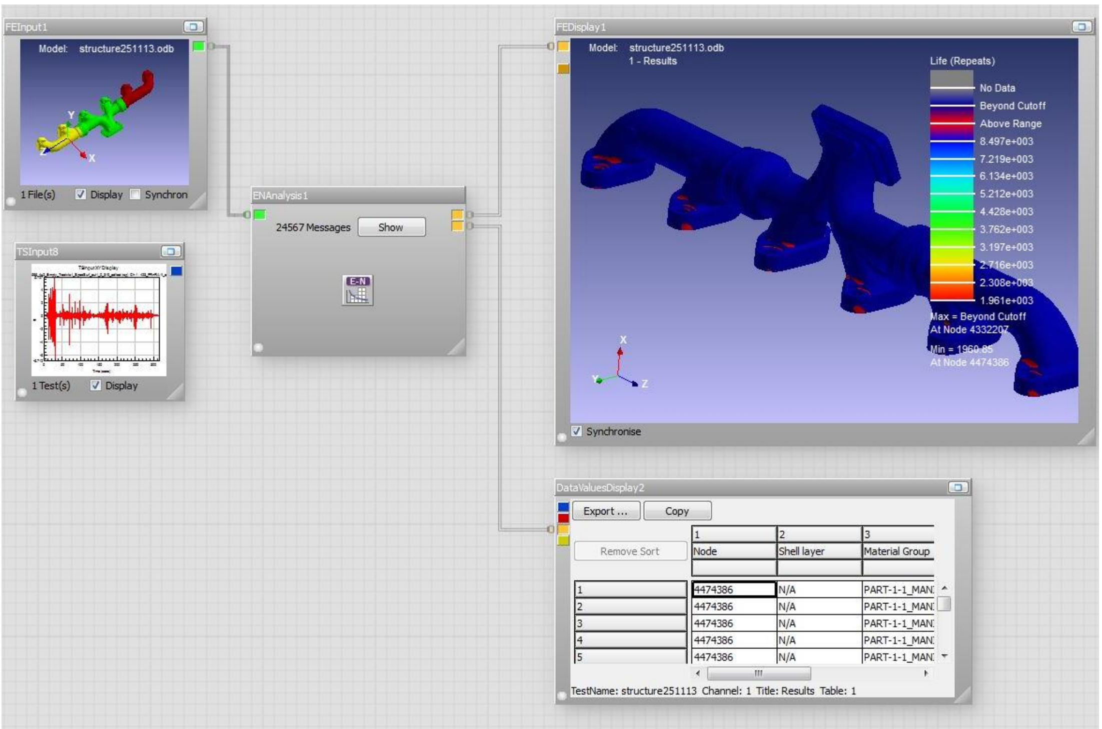

Figure 9.1 : View from nCODE DesignLife interface.

9.1 Modeling With nCODE DesignLife

This method sometimes referred to as the E-N approach and is used for finite fatigue lives in ductile materials where plasticity around stress concentrations is important. One of the most critical issues in the fatigue analysis is performed to identify the material. HiSiMo exhaust manifold material is defined with parameters seen in Table 9.1. These parameters will supply E-N fatigue material curves.

Table 9.1 : HiSiMo nCODE E-N material parameters.

Dataset: HiSiMo

Name	Value	Description
b	-0.087	Fatigue Strength Exponent
c	-0.58	Fatigue Ductility Exponent
E	1.68E5	Elastic Modulus (MPa)
Ef'	0.589297619047619	Fatigue Ductility Coefficient
FSN		Fatemi-Socie parameter
K'	1042.8	Cyclic Strength Coefficient (MPa)
K1C		Fracture Toughness (MPa(m^1/2))
K_monotonic		Work Hardening Coefficient (MPa)
MaterialType	99	Material Type
me	0.3	Elastic Poisson's Ratio
mp	0.5	Plastic Poisson's Ratio
n'	0.15	Cyclic Strain Hardening Exponent
n_monotonic		Work Hardening Exponent
Nc	2E8	Cut-off
Ne		Endurance Limit
S		Wang Brown parameter
SEc	0.01	Standard Error of Log(e) (Cyclic)
SEe	0.01	Standard Error of Log(e) (Elastic)
SEp	0.01	Standard Error of Log(e) (Plastic)
Sf'	948	Fatigue Strength Coefficient (MPa)
UTS	632	Ultimate Tensile Strength (MPa)
YS	412	Yield Strength (MPa)

For the TMF life time analysis, speciel material properties should be used. They are cyclic stress-stain curve and strain life curve as shown in the Figure 9.2 and 9.3 respectively. In the Table 9.2, E-N fatigue life analysis properties and parameters are showed.

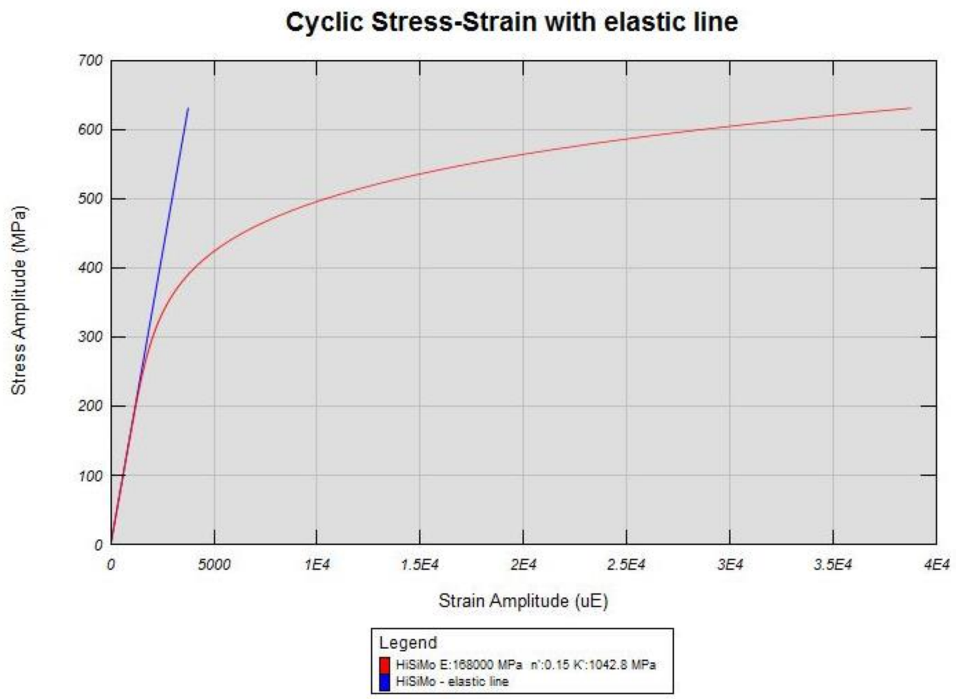

Figure 9.2 : Cyclic Stress-Stain curve with elastic line for HiSiMo material.

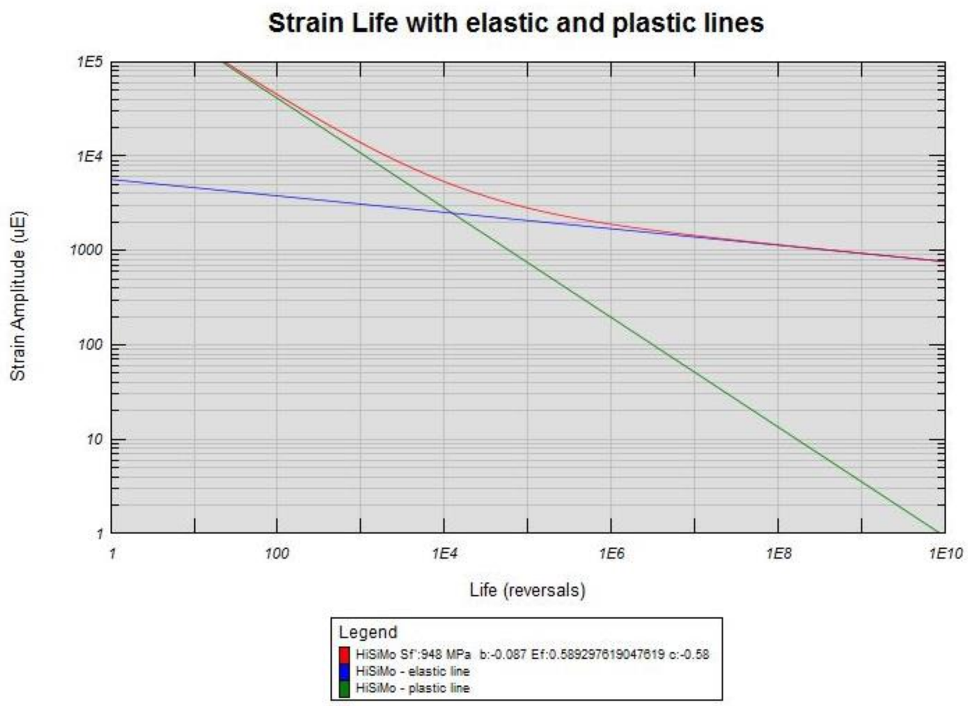

Figure 9.3 : Strain life curve with elastic and plastic lines for HiSiMo material.

Table 9.2 : E-N fatigue life analysis properties.

Name	Value	Description
General		
LoggingLevel	Info	The amount of detail to output to the message window during the run
ResultsUpdateInterval	10	Time interval between processing result output
AnalysisGroup		
AnalysisGroup_GroupNames	*	Groups to process
AnalysisGroup_MaterialAssignmentGroup	SelectionGroup	Sets the grouping type to be used for material mapping
AnalysisGroup_SelectionGroupType	FEInput	Sets the grouping type to be used for extracting results
AnalysisGroup_ShellLayer	TopAndBottom	Shell layer to use
AnalysisGroup_SolutionLocation	AveragedNodeOnElement	Solution location
AnalysisGroup_StressUnits	MPa	The units to use for stress values
Compressed results (for display)		
Compressed results (for display)_ChannelPerEvent	False	Whether to create a channel for each duty cycle event
ENEngine		
ENEngine_CertaintyOfSurvival	50	Required confidence level on damage results
ENEngine_CheckStaticFailure	Warn	The action to take on static failure
ENEngine_CombinationMethod	TypeBCriticalPlaneShearStrain	The method used to combine component stresses/strains
ENEngine_ElasticPlasticCorrection	Neuber	The correction method for elastic plastic transformation in biaxiality
ENEngine_EventProcessing	Independent	How to process separate events in duty cycles
ENEngine_MeanStressCorrection	Morrow	The method used to correct the damage calculation for mean stress
ENEngine_MultiAxialAssessment	Auto	Whether to perform assessment of the multi-axial stress state
ENEngine_OutputEventResults	False	Whether to output results per event or not for duty cycle processing
Job		
Job_NumAnalysisThreads		The number of simultaneous analysis threads to use for this job
Run1		
Run1_Gate	20	The gate value to apply during time history compression
Run1_TimeHistoryCompression	None	Specifies how to compress time history loading

9.2 nCODE DesignLife LCF Results

In Figures 9.4, 9.5 and 9.6, critical fatigue locations could be seen. Their locations are almost the same with the max. PEEQ values (e.g., see Figure 8.4).

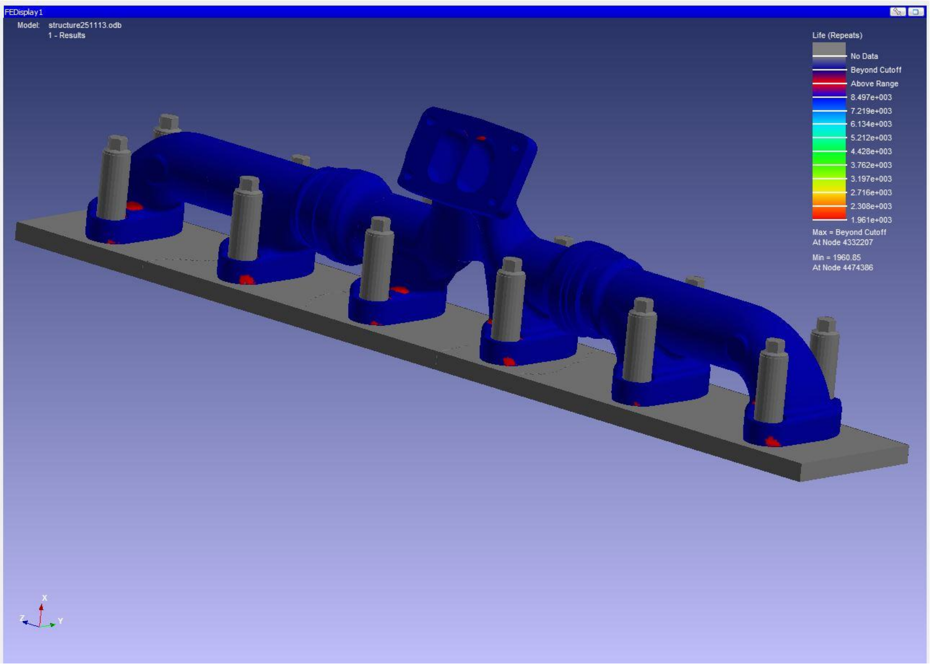

Figure 9.4 : nCODE life repeat results with connection parts.

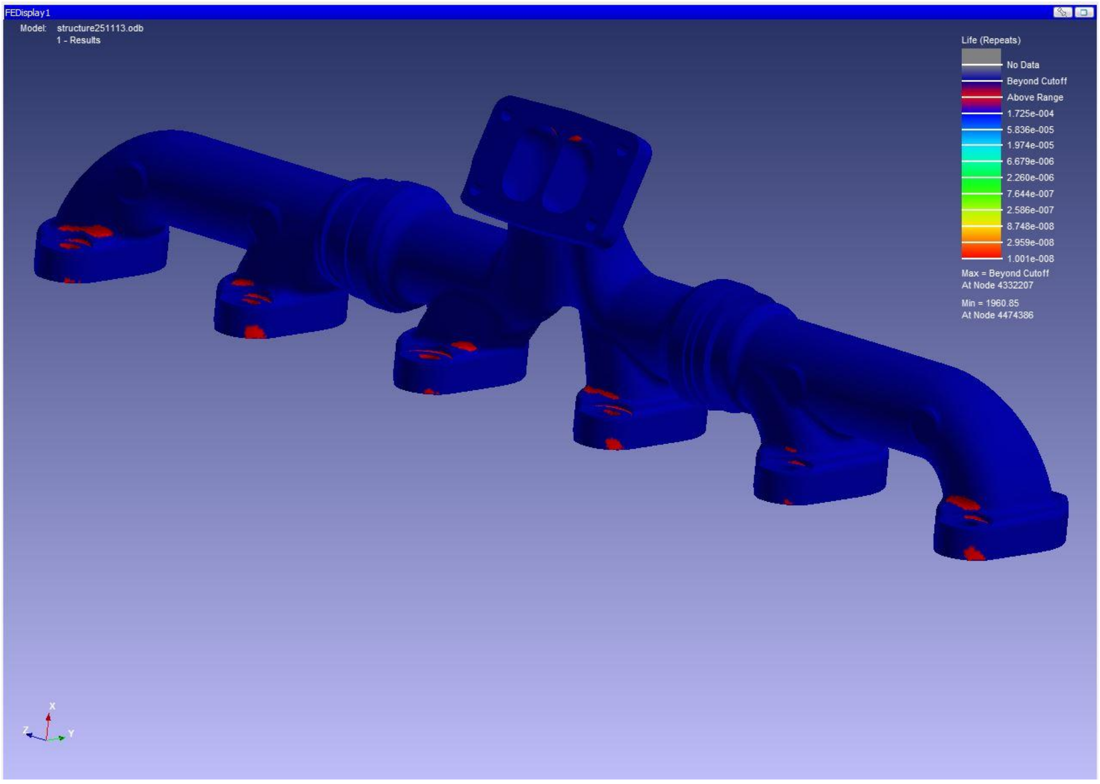

Figure 9.5 : nCODE life repeat results only manifold parts.

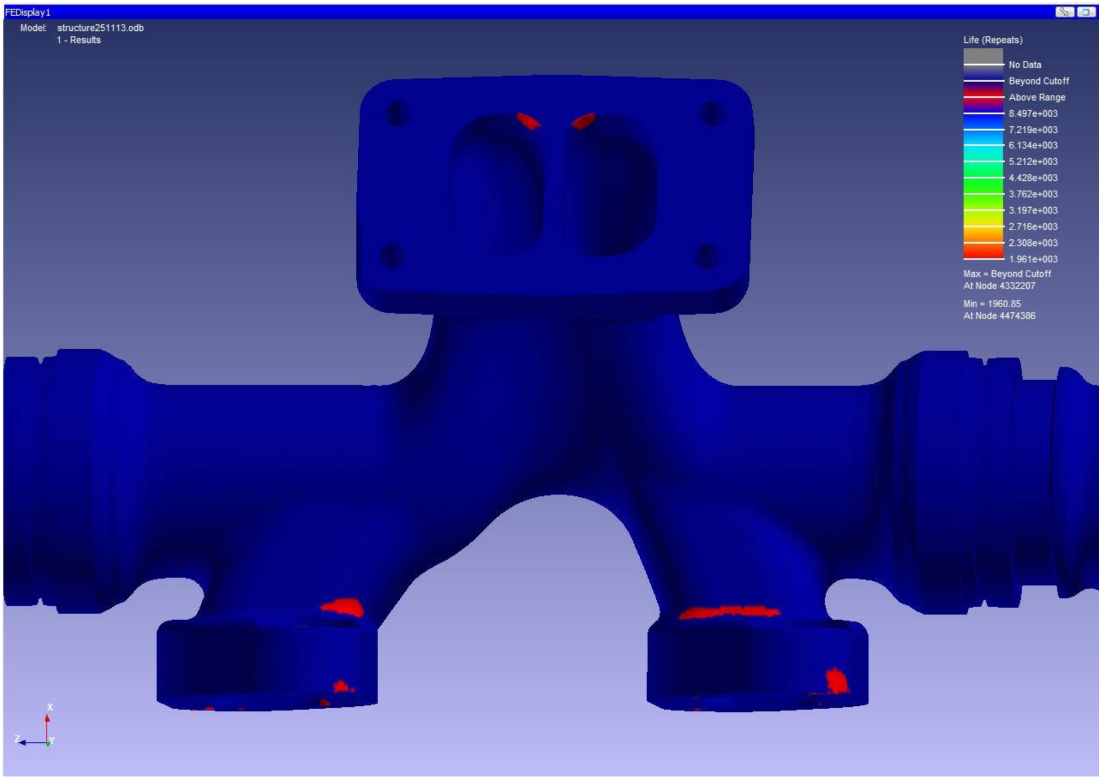

Figure 9.6 : nCODE life repeat results for manifold center part.

Fatigue life cycle count is observed as 1960 with this analysis as seen on the Table 9.3. This value is greater than the worst life cycle count target.

Table 9.3 : For the most critical elements, nCode life cycle analysis results.

DataValuesDisplay2

Export ... Copy

Remove Sort	1 Node	6 Damage	7 Plane angle degrees	8 Mean biaxiality rat	10 Dominant stress d degrees	12 Life Repeats
1	4474386	0.00051	130	0.88	-45.99	1961
2	4474386	0.0005085	140	0.88	-45.99	1967
3	4474386	0.0004968	120	0.88	-45.99	2013
4	4474386	0.0004926	150	0.88	-45.99	2030
5	4474386	0.0004711	110	0.88	-45.99	2123
6	4474386	0.0004649	160	0.88	-45.99	2151
7	4474386	0.0004372	100	0.88	-45.99	2287
8	4474386	0.00043	170	0.88	-45.99	2326
9	4474386	0.0004001	90	0.88	-45.99	2499
10	4474386	0.0003928	0	0.88	-45.99	2546
11	3972485	0.0003652	150	0.8365	-34.39	2739
12	4474386	0.0003647	80	0.88	-45.99	2742
13	3972485	0.0003642	140	0.8365	-34.39	2746
14	4474386	0.0003582	10	0.88	-45.99	2792
15	3972485	0.0003513	160	0.8365	-34.39	2847
16	3972485	0.0003487	130	0.8365	-34.39	2868
17	4474386	0.0003348	70	0.88	-45.99	2986
18	4474386	0.0003299	20	0.88	-45.99	3032
19	4319343	0.0003276	150	0.8322	-32.84	3052
20	3972485	0.0003253	170	0.8365	-34.39	3074
21	4319343	0.0003246	140	0.8322	-32.84	3081
22	3972485	0.0003215	120	0.8365	-34.39	3110
23	4319343	0.0003168	160	0.8322	-32.84	3157
24	4474386	0.0003133	60	0.88	-45.99	3192
25	4474386	0.0003102	30	0.88	-45.99	3224
26	4319343	0.0003083	130	0.8322	-32.84	3244
27	4474386	0.0003017	50	0.88	-45.99	3315
28	4474386	0.0003006	40	0.88	-45.99	3327
29	4319343	0.0002941	170	0.8322	-32.84	3400
30	3972485	0.0002919	0	0.8365	-34.39	3426
31	3972485	0.0002876	110	0.8365	-34.39	3477
32	4319343	0.0002817	120	0.8322	-32.84	3549
33	4474393	0.0002772	10	0.7611	7.202	3608
34	4474393	0.0002734	0	0.7611	7.202	3658
35	4474393	0.000264	20	0.7611	7.202	3788
36	4319343	0.0002639	0	0.8322	-32.84	3789
37	3972485	0.0002564	10	0.8365	-34.39	3901
38	4474393	0.0002535	170	0.7611	7.202	3945
39	3972485	0.0002521	100	0.8365	-34.39	3966
40	4319343	0.0002498	110	0.8322	-32.84	4003

10. THERMAL MECHANICAL FATIGUE TEST RESULTS

Thermal mechanical test is performed at the Ford Otosan Sanayi A.Ş. test facilities as seen in Figure 10.1 which is a full engine test.

This fatigue test continues for total 250 hours with completely the same cycle characteristics. One cycle takes almost 10 minutes. A sample cycle conditions are showed in the Figure 10.2. Engine speed, torque and exhaust temperature are the critical parameters for the TMF test.

$$60 \text{ min} / 10 \text{ min} = 6 \text{ cycle/per hour} \tag{10.1}$$

$$250 \text{ hours} \times 6 \text{ cycle/per hour} = 1500 \text{ Total Cycle} \tag{10.2}$$

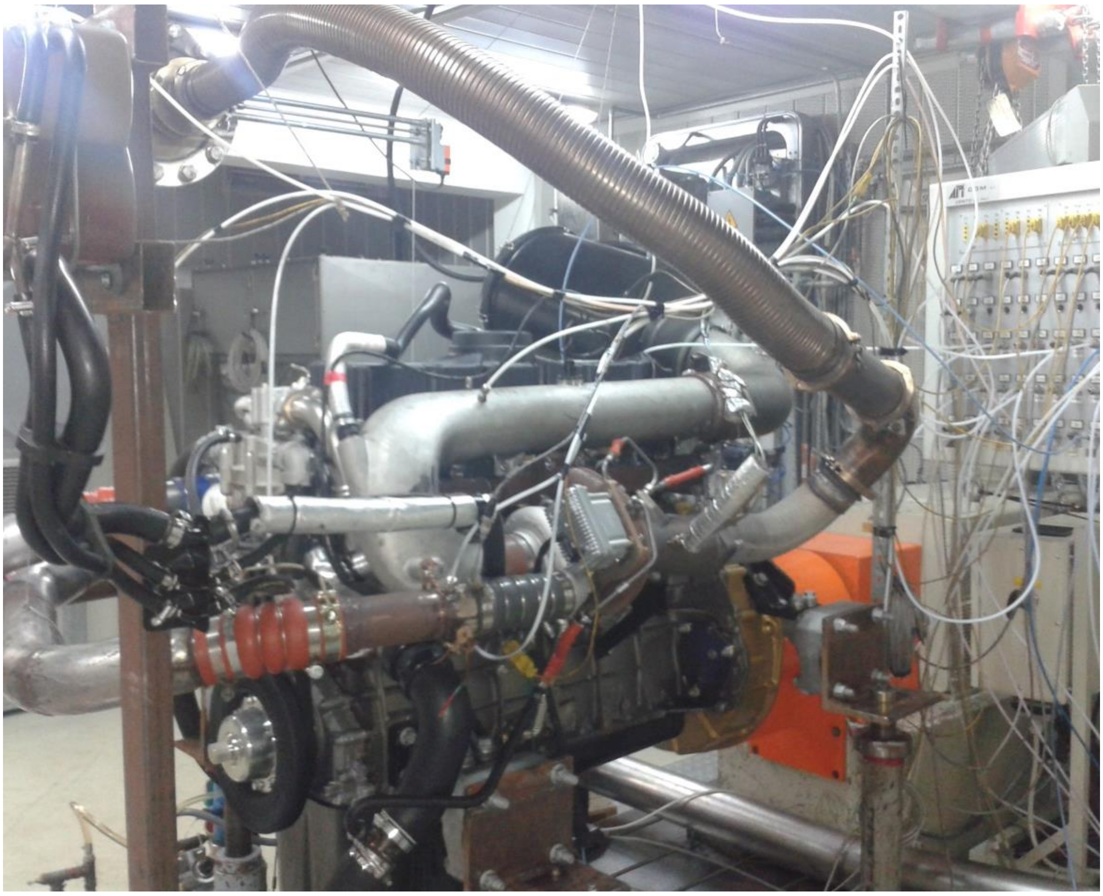

Figure 10.1: Ford Otosan thermal mechanical fatigue test for exhaust manifold and turbo system.

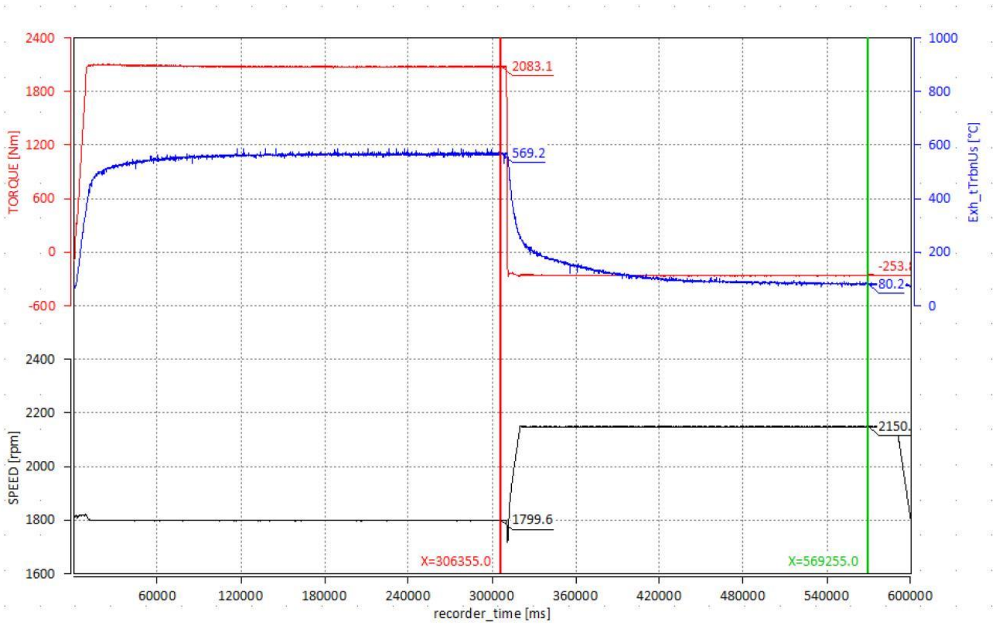

Figure 10.2 : Single cycle for the thermal mechanical test.

To observe cracks on the manifold, penetration is performed on the exhaust manifold as seen in the Figure 10.3. and no damage was observed on the exhaust manifold. This is very important to show that the analysis and test results are consistent.

Also after continuing to this test with the same conditions, cracks are observed on the critical locations which is predicted by fatigue analysis with high sensibility (after 2300 cycle). Life cycle is calculated as 1960 cycle via nCODE program.

$$[(2300-1960) / 2300] * 100 = \%15 \text{ Confidence level} \quad \mathbf{(10.3)}$$

This high correlation between the analysis and test shows that analysis methodology are so close to real working conditions with an error of less than 15%.

Figure 10.3 : Exhaust manifold center part after penetration.

11. CONCLUSION AND RECOMMENDATIONS

Currently, proper fatigue design involves synthesis, analysis, and testing. Fatigue testing alone is not a proper fatigue design procedure, since it should be used for product durability determination, not for product development. Analysis alone is also insufficient for fatigue design, since current fatigue life models, including commercial and government computer-aided engineering (CAE) software programs, are not adequate for the safety of critical parts. They are only models and usually cannot take into consideration of all the synergistic aspects involved in fatigue, such as temperature, corrosion, residual stress, and variable amplitude loading. Thus, both analysis and testing are required for the components that should have good fatigue design.

Safety factors are often used in conjunction with or without proper fatigue design. Values that are too high may lead to noncompetitive products in the global market, while values that are too low can contribute to undesired failures. Safety factors are not replacements for proper fatigue design procedures, nor should they be an excuse to offset poor fatigue design procedures [12].

Analysis conditions and test conditions should be similar with the real working conditions. In this study, some simplifications and analogies are made necessarily. Even if the test results could not show the real situation but they give very close results. On TMF life prediction, although there is significant deviation, test results are often sufficient for verification process.

In this study, full engine fatigue test results are used for the analysis and testing correlation. But full engine testing is longer, expensive and very complicated process. Thus, a specific exhaust-turbo TMF test rig is designed. Analysis of the TMF rig also were completed successfully. It is in the manufacturing phase.

After the system is installed, TMF test will be performed again with same parameters to see reliability. This new TMF test rig will provide more flexible and simplified test opportunities with lower cost. Especially, this rig will give the chance to develop exhaust and turbo systems without engine dyno and working engine. With special test equipment to a particular system, test times could be significantly lower by reinforcing the input effects.

After verification of test and analysis results, only analysis results will be sufficient for further design changes or working conditions change.

CFD results are used to find temperature distribution and heat transfer coefficients. Coupled thermal mechanical FEM analysis are completed to find the stress and strain fields. Fatigue damage criteria are employed to predict TMF damage. Test rig for verification is designed. Numerical TMF results are verified by comparisons with experimental data.

The TMF methodology followed in this study is verified by test results that yield an error of less than 15%. Such a correlation is encouraging to predict TMF failures that are difficult to calculate due to variations in test conditions.

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