ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

DETERMINATION OF A METHODOLOGY FOR FAILURE AVOIDANCE OF ADBLUE TANKS

M.Sc. Thesis by

Metin TOPRAK, B.Sc.

Department : Mechanical Engineering

Programme : Automotive

JUNE 2008

ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

DETERMINATION OF A METHODOLOGY FOR FAILURE AVOIDANCE OF ADBLUE TANKS

M.Sc. Thesis by

Metin TOPRAK, B.Sc.

(503061714)

Date of submission : 5 May 2008

Date of defence examination : 13 June 2008

Supervisor (Chairman) : Prof. Dr. Murat EREKE (ITU)

Members of the Examining Committee : Prof. Dr. Ahmet GÜNEY (ITU)

Prof. İrfan YAVAŞLIOL (YTU)

JUNE 2008

<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

ADBLUE TANKLARINDA HASAR ÖNLEME METODOLOJİSİNİN BELİRLENMESİ

YÜKSEK LİSANS TEZİ

Mak. Müh. Metin TOPRAK

(503061714)

Tezin Enstitüye Verildiği Tarih : 5 Mayıs 2008

Tezin Savunulduğu Tarih : 13 Haziran 2008

Tez Danışmanı : Prof. Dr. Murat EREKE (İTÜ)

Diğer Jüri Üyeleri : Prof. Dr. Ahmet GÜNEY (İTÜ)

Prof. İrfan YAVAŞLIOL (YTÜ)

HAZİRAN 2008

ACKNOWLEDGEMENT

I would like to express my gratitude to all those who gave me the opportunity to complete this thesis. I am deeply indebted to my supervisor Prof. Dr. Murat Ereke for his guidance, contribution and suggestion during all phases of my study.

I would also like to thank all my friends and colleagues for their help and support. Furthermore, I have to thank Mercedes-Benz Türk. A.Ş. Development Bus Test Center division, especially Dr. Şevket Kocaaydın, Cem Şentürk, Fatih Öncel, Harun Çoban, Volkan Ay and Kıvanç Agur for supporting me with brilliant ideas and I should also thank to Mustafa Ataş for his patience, understanding and support.

Also, The Scientific and Technological Research Council of Turkey (TUBITAK) supported me by means of Scientist Supporting Programme Scholarship.

Finally, I should say many thanks to my family for all their patience and encouragement at every phase of my studies.

June 2008 Metin TOPRAK

TABLE OF CONTENTS

ABBREVIATIONS

AUS	:	Aqueous Urea Solution
ESAM	:	Electronic Signal Acquisition Module
LLDPE	:	Linear-Low Density Polyethylene
LVDT	:	Linear Variable Displacement Transducer
NO_x	:	Nitrous Oxide
PE	:	Polyethylene
PSD	:	Power Spectral Density

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

a	:	Acceleration
$\mathbf{a_x}$	:	Acceleration in x direction
$\mathbf{a_y}$	:	Acceleration in y direction
$\mathbf{a_z}$	:	Acceleration in z direction
D	:	Total damage
$\mathbf{e_1}$	:	Measured strain for grid 1
$\mathbf{e_2}$	:	Measured strain for grid 2
$\mathbf{e_3}$	:	Measured strain for grid 3
E	:	Elastic modulus
$\mathbf{F_{max}}$	:	Maximum hydrostatic force
g	:	Acceleration of gravity
GF	:	Gauge factor
i	:	Current value
n	:	Number of cycle
$\mathbf{n_i}$	:	Number of cycle at a stress of i
N	:	Number of cycle to failure
$\mathbf{N_i}$	:	Number of cycle to failure at a stress of i
R	:	Resistance of strain gauge
S	:	Stress amplitude
t	:	Time
$\boldsymbol{\varepsilon_{max}}$	:	Maximum principal strain
$\boldsymbol{\varepsilon_{min}}$	:	Minimum principal strain
$\boldsymbol{\sigma_{max}}$	:	Maximum principal stress
$\boldsymbol{\sigma_{max}}$	:	Minimum principal stress
$\boldsymbol{\theta}$	:	Angle between principal axis and grid 1
$\boldsymbol{\upsilon}$	:	Poisson's ratio

DETERMINATION OF A METHODOLOGY FOR FAILURE AVOIDANCE OF ADBLUE TANKS

SUMMARY

This study aims to determine a methodology for failure avoidance of AdBlue tanks through durability tests.

Today, the use of plastic components in vehicles has increased in great number, as a result of plastic material properties such as lightness and corrosion resistance. In conjunction with this, the need for research of plastic components' durability has been arisen.

This study, firstly mentions the durability tests of plastic tanks that are used to store the AdBlue which is used in today's Mercedes-Benz buses, to decrease the exhaust emissions according to the EURO IV regulation. The durability tests of AdBlue tanks have been conducted in Hydropuls (shaker) test rig within the Mercedes-Benz Turk A.S. Development Bus Test Center. Therefore, the equipment of the test rig has been described firstly, followed by the explanation of how a load collective sample is obtained from the collected data on the road, for durability tests in Hydropuls.

In the following step, the measurements recorded throughout the tests, hardware and equations used to obtain the test results are mentioned. In Hydropuls tests, for the damage calculations, strain gauges were applied at high stress locations based on finite element analysis and previous test experiences.

In the final section, the factors affecting the durability of AdBlue tanks such as AdBlue level, test excitation frequency, fixing points and the constructive properties have been analyzed. Furthermore the strain threshold values, which cause the damage most on tanks, were emphasized. Finally, to reduce the AdBlue tank damage to its minimum value, a methodology for failure avoidance was determined.

ADBLUE TANKLARINDA HASAR ÖNLEME METODOLOJİSİNİN BELİRLENMESİ

ÖZET

Bu çalışma AdBlue tankları üzerinde yapılan dayanım testleri aracılığıyla, hasar önleme methodolojisinin belirlenmesini amaçlar.

Plastik parçaların taşıtlarda kullanımı, hafiflik ve korozyon dayanımı gibi etkenler göz önünde bulundurulduğunda geçmiş yıllara oranla günümüzde daha da çok artmıştır. Bu artışla birlikte, kullanılan plastik parçaların dayanımlarının incelenmesi gereği de ortaya çıkmıştır.

Bu çalışmada ilk olarak günümüz Mercedes-Benz otobüslerinde egzoz emisyonlarını EURO IV normlarına uygun hale getirmek için kullanılan AdBlue sıvısının depolanmasında kullanılan plastik tankların dayanım testlerine değinilmiştir. Bu dayanım testleri, Mercedes-Benz Türk A.Ş. bünyesinde geliştirme test merkezinde bulunan Hidropuls (sarsıcı) test ünitesinde gerçekleştirilmiştir. Bu kapsamda ilk olarak Hidropuls testlerinde kullanılan ekipmanlar incelenmiş, sonrasında ise dayanım testlerinde yoldan alınan sinyalin parça üzerine uygulanabilmesi amacıyla örnek bir yükleme kollektifinin elde edilmesi anlatılmıştır.

Bir sonraki adımda, tank üzerinde test esnasında yapılan ölçümler, kullanılan donanım ve ölçüm sonuçlarını elde etmede kullanılacak denklemler anlatılmıştır. Testlerde, tank üzerinden birim uzamayı ölçerek hasar hesabına geçebilmek için, daha önceden hasar yeri bilenen yerlere veya yapılan sonlu elemanlar analizlerinde gerilme yığılmalarının yoğun olduğu bölgelere strain gauge (birim uzama ölçer) uygulaması yapılmıştır.

Çalışmanın son kısmında, testleri gerçekleştirilen AdBlue tanklarında dayanıma etki eden sıvı yüksekliği, test frekansı, bağlantı noktası ve tankın konstrüktif özellikleri gibi etkenlerin dayanım üzerindeki etkisi incelenmiştir. Ayrıca en çok hasar yaratan muhtemel birim uzama eşik değeri ile ilgili bir çalışmaya da yer verilmiştir. Son olarak, tank dayanımını etkileyen parametreler göz önünde bulundurularak, AdBlue tanklarında hasarın azaltılmasını amaçlayan hasar önleme metodolojisi belirlenmiştir.

1. INTRODUCTION

The use of nonmetallic materials in vehicles has grown considerably over the past few years, and the application of plastics in the automotive industry is now wider and more sophisticated than in any other area of engineering. Recently, much of the consumption of plastics has been in manufacture of bodywork with polymers. However, plastics are not only used in manufacturing of bodywork, also many varieties of plastics are used in other components of vehicles. (i.e. fuel & AdBlue tanks)

Plastic materials have come to be used frequently for automotive tanks in recent years owing to their light weight, freedom for forming various shapes and corrosion resistance, among other reasons. An automotive tank is subjected to variable road conditions during its life. In this study, the durability criteria of AdBlue tanks are investigated.

AdBlue is a registered trademark for AUS32 (Aqueous Urea Solution 32%), it is also often referred to as Automotive Urea Solution. AdBlue is a solution consisting of high purity urea dissolved and suspended within de-ionised water. AdBlue is carried in a separate tank to the fuel and never mix with the fuel, as seen in Figure 1.1. It is injected into the exhaust gases as a post combustion process and reduces harmful NOx (Nitrous Oxide) by converting it into Nitrogen and Oxygen.

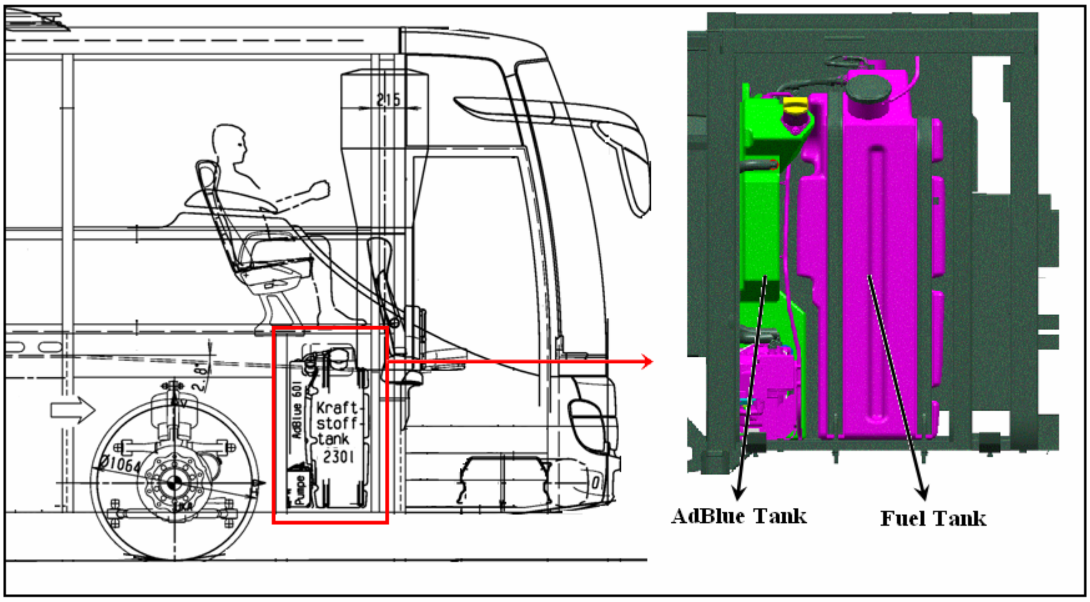

Figure 1.1. The Location of AdBlue Tank in Bus

As seen in Figure 1.1, AdBlue tanks have smaller volumes than fuel tanks because the consumption of AdBlue is approximately at 3 to 5% of the diesel usage. A real picture of an AdBlue tank which is used in Mercedes-Benz buses can be seen in Figure 1.2.

Figure 1.2. AdBlue Tank

Polyethylene (PE) is one of the plastic materials used for AdBlue tanks because of its high corrosion resistance. In this study, tested AdBlue tank material is linear-low density polyethylene (LLDPE).

Figure 1.3 outlines the factors influencing the fatigue life of polyethylene AdBlue tanks with respect to this failure mechanism. Load conditions include stress and frequency, while temperature and AdBlue swelling can be cited as environmental conditions. Factors related to the molecular structure include the molecular weight and its distribution as well as type of branch component and its concentration. Molding conditions that also affect fatigue failure include the resin temperature and cooling condition. Among these various factors, the principal ones examined when evaluating the durability of plastic AdBlue tanks are stress and frequency [2].

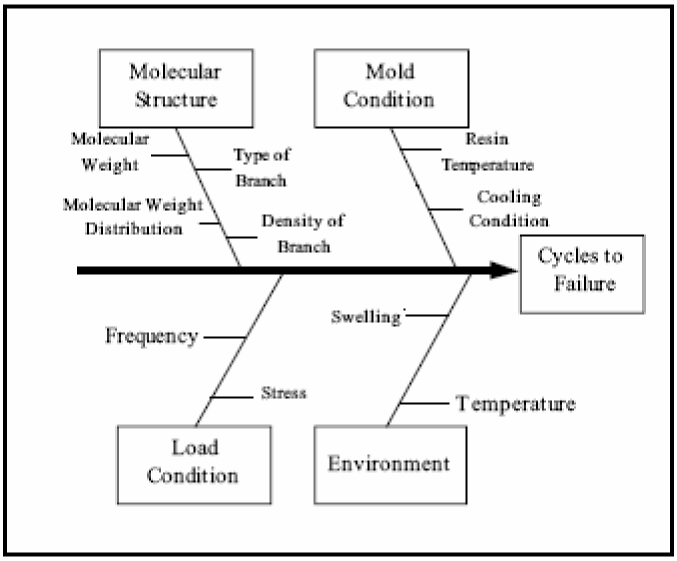

Figure 1.3. Cause and Effect Diagram of Fatigue Failure

The aim of this study is to develop a failure avoidance methodology of AdBlue tanks by using strain-gage rosette measurements. The measurement points have been chosen according to critical locations of finite element calculations. Due to the different constructive properties, plastic AdBlue tanks are tested with respect to the durability point of view. These tanks are tested in Mercedes-Benz Turk A.S. testing facilities by using servo hydraulic actuators (Hydropuls) to exactly simulate road profile in vertical, longitudinal and lateral directions. In the second and third chapters; Hydropuls test equipments, accelerated test method for AdBlue tanks, Hydropuls tests and strain measurements are represented in details. Finally, the last chapter of this study deals with the results of the measurements which were evaluated by means of data counting algorithms and damage analysis of nCode software.

2. ACCELERATED TEST METHOD OF ADBLUE TANKS IN HYDROPULS

The interaction of various intensities of loading and the sequence of high and low loads can have a marked influence on component life, which is not accurately predictable from simple fatigue tests. Fortunately, the current availability of servohydraulic systems make it possible to conduct controlled, realistic fatigue test on both components and assemblies.

The term “accelerating test”, is all too often taken to mean simply increasing the frequency or removing the non-damaging sections of the load application, whereas it should mean the determination of realistic component lives or properties in the shortest amount of elapsed time [1].

Principally, accelerated tests are executed by using servohydraulic test systems. In this study, plastic AdBlue tank tests were done in Hydropuls which is a servohydraulic test unit consists of adequate components for accelerated tests.

2.1 Servohydraulic Test Systems and Components

A servohydraulic test system includes hydraulic actuators, servovalves, feedback transducers, hydraulic distribution and servohydraulic control systems. An example of a servohydraulic test system for a single hydraulic actuator is shown in a simplified form in Figure 2.1 [4].

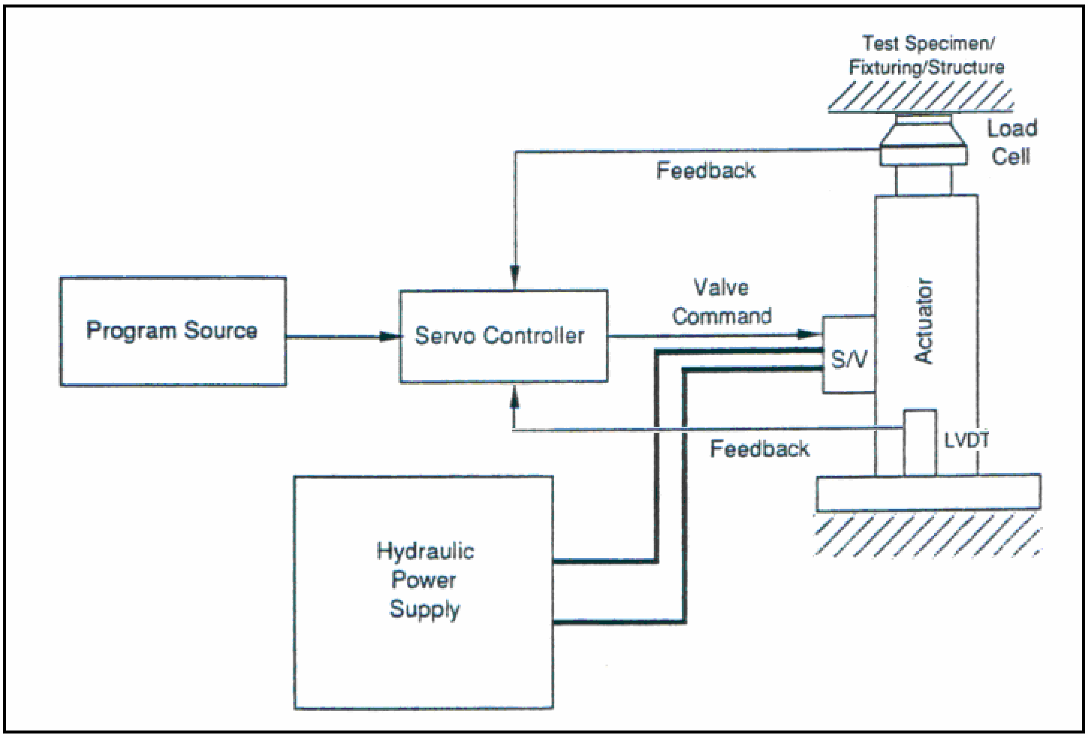

Figure 2.1. Servohydraulic Test System Components

2.1.1 Hydraulic Actuators

In a servohydraulic system, typical actuator is powered by high-pressure hydraulic oil. The direction and amount of oil flow, and therefore the actuator force and position, are controlled by a servovalve. A load cell or LVDT (linear variable displacement transducer), which responds usually to either the force or displacement of the actuator, feeds an electrical signal back to the amplifier, where the instantaneous signal value and the intended signal from program source are compared. Then servovalve corrects the force or position [1]. Typical hydraulic actuator is shown in Figure 2.2.

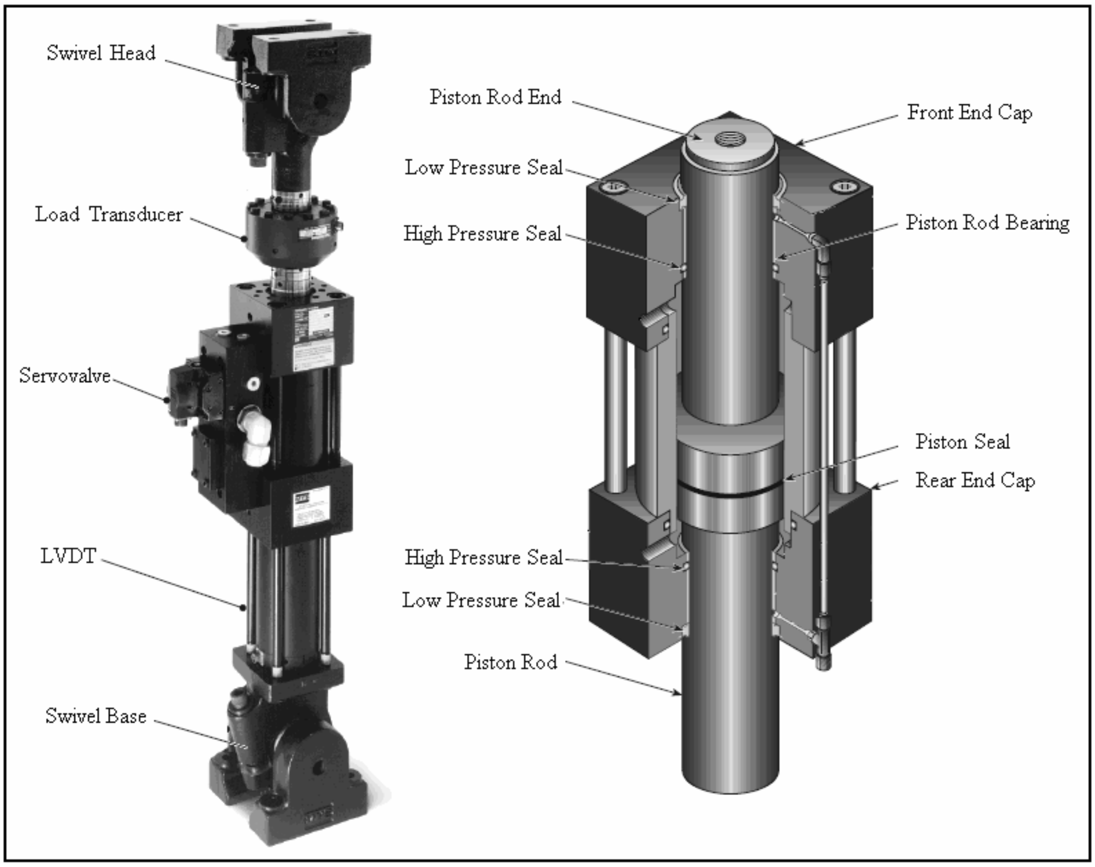

Figure 2.2. Hydraulic Actuator

There are three critical parameters for a hydraulic actuator. These are cylinder length, piston area, piston and rod mass. These parameters determine maximum stroke of the rod, maximum force capability of the actuator and the maximum actuator acceleration respectively [4].

In Hydropuls tests, MTS Series 244 hydraulic actuators which have 15 and 100 kN force ratings, are used.

2.1.2 Servovalves

Servovalve, which is the heart of the servohydraulic test system, controls hydraulic flow to the actuator that moves the actuator piston rod.

A typical servovalve that is used in Hydropuls tests is shown in Figure 2.3.

Figure 2.3. Servovalve

In Figure 2.4 [13], when the current value is zero (i=0) there is no action in actuator. The actuator gets into motion in one direction when the current value is positive (i>0), and the actuator moves inverse direction when the current value is negative (i<0) [4].

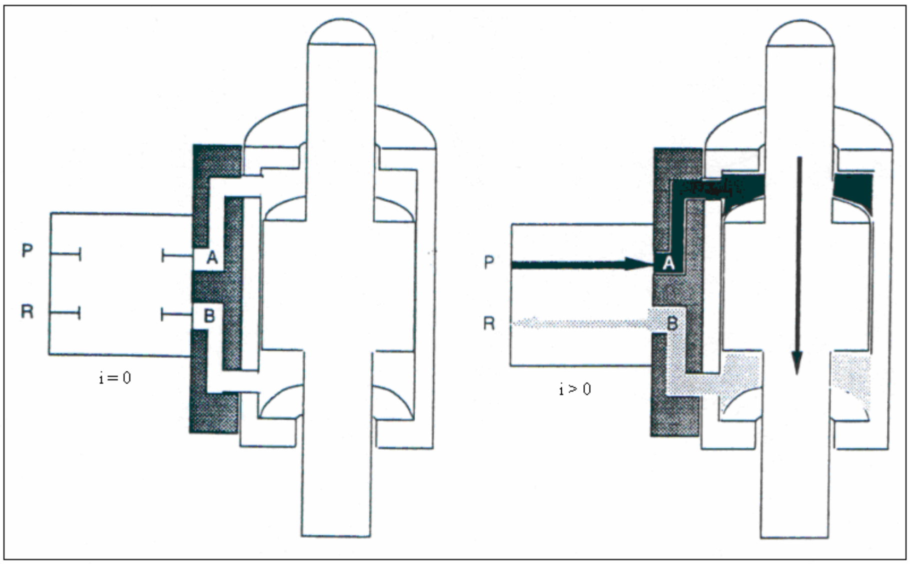

Figure 2.4. Actuator and Servovalve Assembly

In Hydropuls tests, MTS two-stage, four-way 252 Series servovalves are used.

2.1.3 Feedback Transducers

A load or displacement transducer (load-cell or LVDT) provides feedback on whether or not the actuator is moving as intended.

2.1.3.1 Load Cell

A load cell is a typical transducer that is used to convert a force into an electrical signal and mounted on the free end of the piston rod. Through a mechanical arrangement, the strain gauge in the load cell converts the deformation (strain) to electrical signals. A typical example of a strain gauge based load cell which has a 2,5 kN force capacity, is shown in Figure 2.5 [12]. However, load cells are not necessary in Hydropuls tests owing to performing the accelerated tests with displacement control.

Figure 2.5. Strain Gauge Based Load Cell

2.1.3.2 Linear Variable Displacement Transducer (LVDT)

A linear variable displacement transducer (LVDT) provides a piston rod displacement feedback signal to the system control. The LVDT is coaxially mounted within the actuator piston rod and produces an analog signal with excellent linearity. A view of a LVDT is shown in Figure 2.6 [4].

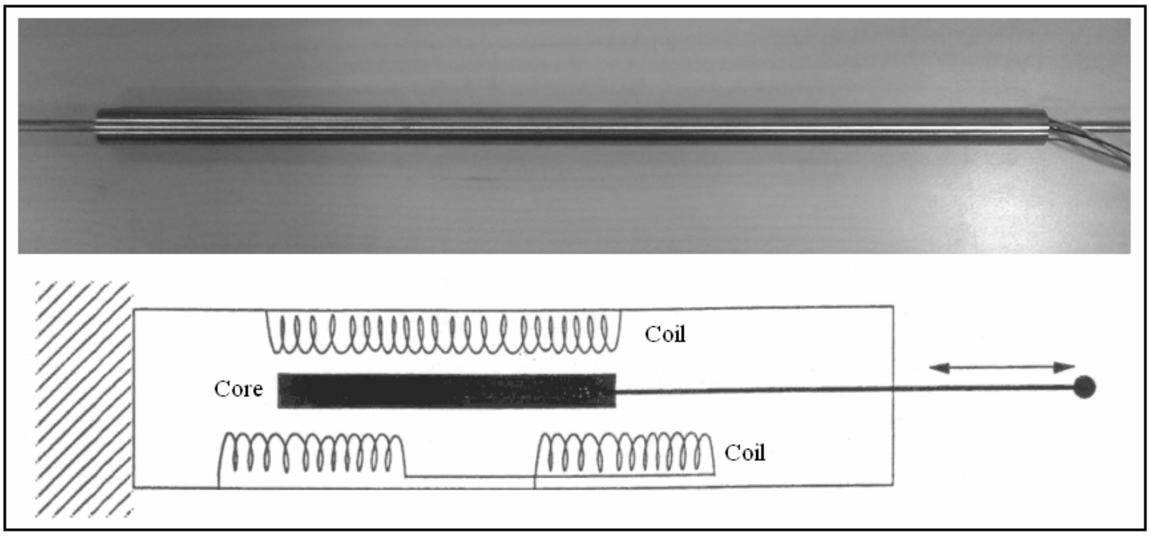

Figure 2.6. Linear Variable Displacement Transducer (LVDT)

When the core moves in one direction, the voltage in one coil is increases and the other decreases. This causes the output voltage to increase from zero to a maximum. The phase of the voltage indicates the direction of the displacement.

2.1.4 Hydraulic Distribution System

A hydraulic distribution system, which consists of hydraulic power unit and hydraulic service manifold, is shown in Figure 2.7.

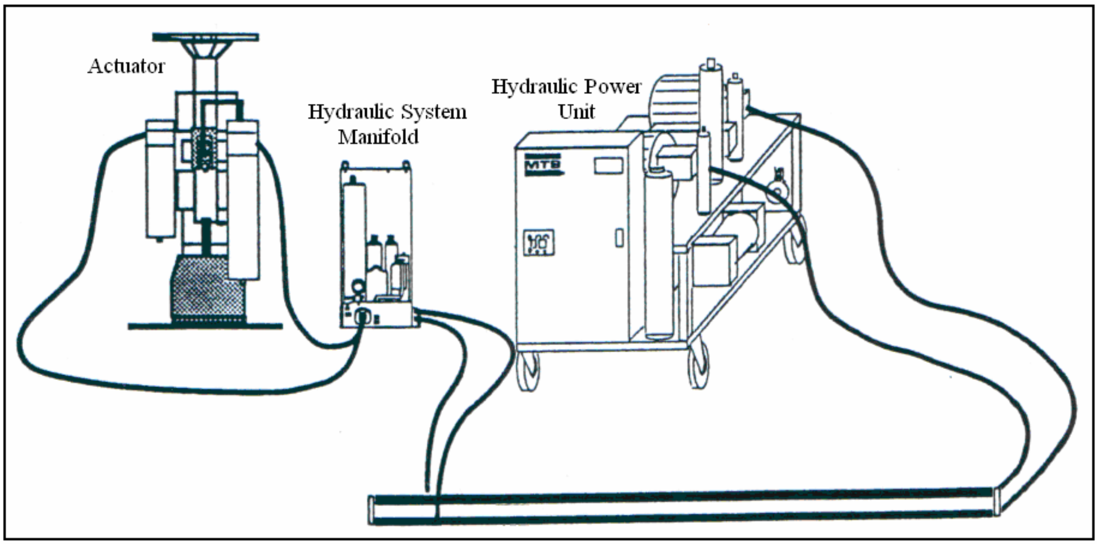

Figure 2.7. Hydraulic Distribution System

2.1.4.1 Hydraulic Power Unit

A hydraulic power unit provides pressurized flow to hydraulic motors, cylinders, and other hydraulic component. Power unit contains a fluid reservoir, multiple pump stages and coolers to keep fluid at a safe working temperature. In Hydropuls tests, two different hydraulic power units which have 90 and 110 kW power capacities are used.

2.1.4.2 Hydraulic Service Manifold

A hydraulic service manifold is a hydraulic pressure and flow regulation device that controls pressure of a test station independent from the main hydraulic power unit, as seen in Figure 2.8. Installing a hydraulic manifold between the power unit and servovalve, allows the operator to turn each hydraulic circuit on and off and set the pressure level. In Hydropuls tests, MTS Series 293 hydraulic service manifold is used.

Figure 2.8. Hydraulic Service Manifold

2.1.5 Servohydraulic Test System Control

The configuration of the system components is shown in Figure 2.9. This kind of configuration provides a means of comparing a command (programmer output) signal with a feedback (transducer output) signal to generate a signal that controls the servovalve [4].

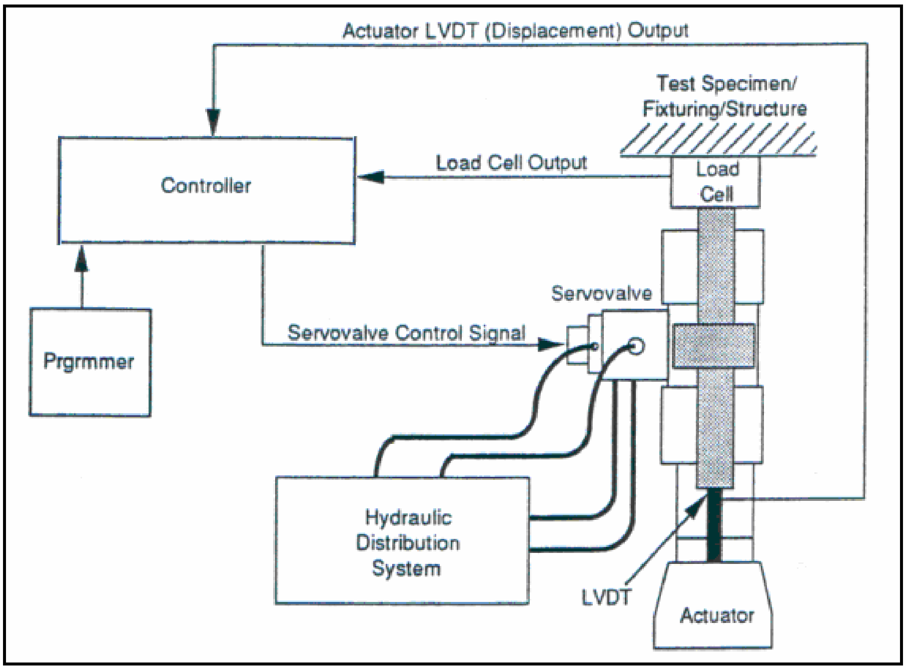

Figure 2.9. Servohydraulic Test System Control

In closed-loop control, command and feedback comparison and controlling servovalve is totally a function of the control circuitry and occurs without operator interaction [4].

As stated before, all AdBlue tank tests are performed by using Hydropuls test rig which consists of all these components.

2.2 From Road Data to Time Optimized Block Programme Test

Accelerated durability testing is suitable for a component, sub-assembly or a whole vehicle. Test must replicate the same failure mechanisms as seen in the real world and should be representative of the real loading environment. Also, tests should be accelerated where possible to reduce time scales and costs [5]. There are three principal test methods of shortening test time without obtaining dubious results [1].

The first applies to constant-amplitude testing. In this type of testing, it may be possible to increase the frequency of the cycle loading, bearing in mind the possible effect of hysteresis.

The second method, compressed time testing, applies to programmed loading, where it should be possible to avoid the use of, or remove the non-damaging sections of the load-time history.

The third method is to run test rigs day and night for 24 hours per day. By doing this many laboratories can achieve 168 hours of testing per week instead of 40 hours. Of course, continuous operation requires good, automatic and cutout systems [1].

In this study, the second method was used to perform accelerated tests in Hydropuls. A flow chart of the compressed time testing process is shown in Figure 2.10. In this process, the data which collected at the proving ground was edited and finally the test data obtained. In data processing, nCode ICE-flow GlyphWorks software was used.

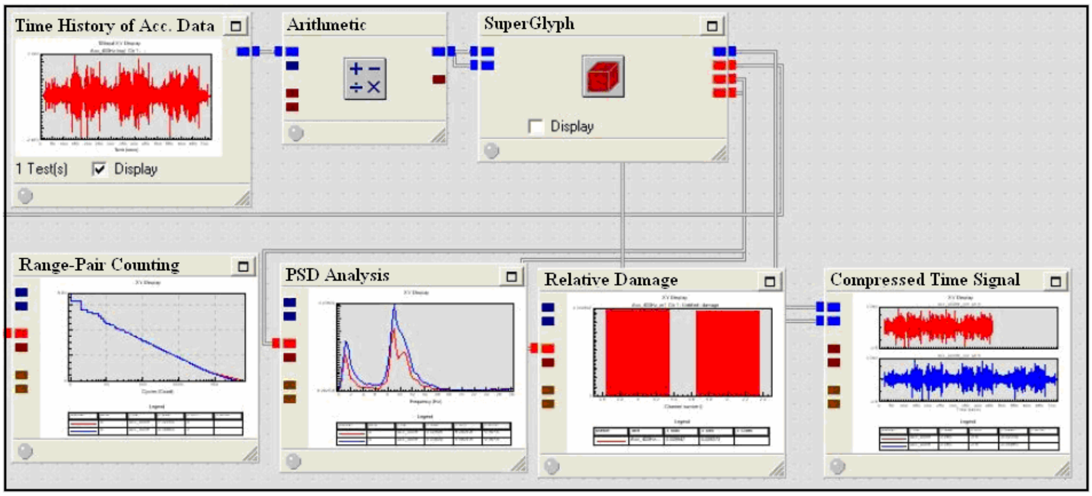

Figure 2.10. Compressed Time Testing Process

Plastic AdBlue tank tests are performed by executing the following steps respectively.

2.2.1 Data Acquisition at Proving Ground

Data acquisition at proving ground is the sampling of the real world to generate data that can be manipulated by a computer. The proving ground consists of various road conditions that simulate real road types, as shown Figure 2.11.

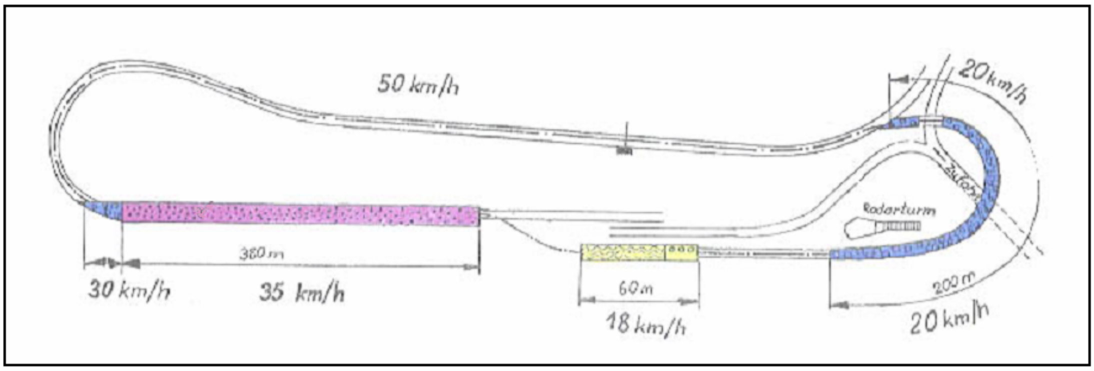

Figure 2.11. Proving Ground

While collecting data at proving ground, a wide variety of transducers are used to measure performance parameters for vehicles. Examples include mechanical, optical, electrical, or magnetic sensors such as accelerometers, strain gauges and thermocouples. Outputs are recorded by a computer. These data are also the basis for the testing of operational strength and fatigue calculation.

In Figure 2.12 shows the acceleration data which has a 400 Hz sample rate, collected at proving ground with accelerometers in vertical direction.

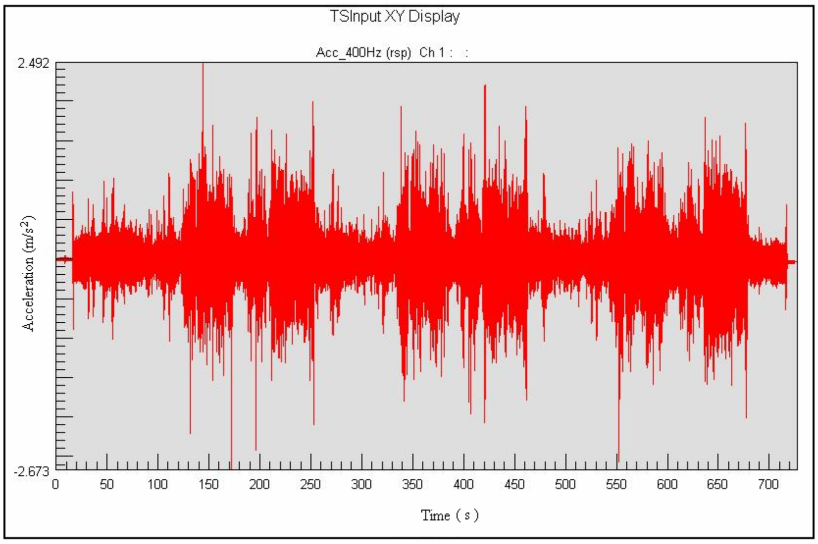

Figure 2.12. Time History of Collected Acceleration Data

This collected data in vertical direction was shifted to the desired maximum vertical acceleration value which is 3.5g, shown in Figure 2.13 as blue signal. Same calculations were made to other directions. Thus, maximum acceleration values were obtained as 1,5 and 2g for foreaft and lateral directions respectively.

2.2.2 Data Editing

In this process, nCode ICE-flow GlyphWorks software identifies regions in a collected data where the signal exceeds defined limits and filters signal parts which cause no or very less damage to the component without losing damage content compared to the original data [6]. Figure 2.13 shows the data reduction. The collected data which is under 0,35g was eliminated because of the non-damaging effect. The duration of the signal decreased from approximately 750 seconds to 450 seconds.

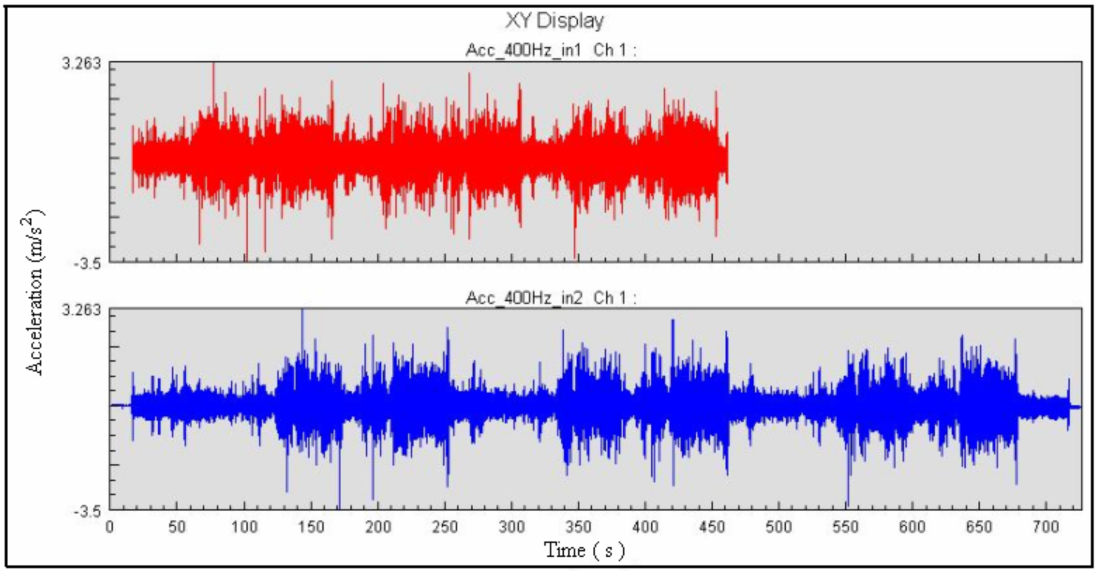

Figure 2.13. Data Reduction

2.2.3 Range Pair Counting

After filtering the non-damaging parts of the signal, the fatigue life of the component can be estimated with the help of counting algorithms. Data counting algorithms are necessary to decrease the duration of the Hydropuls tests and simplify the variety of measured signal. From collected data some information can be obtained. These are amplitude of the signal, maximum, minimum and mean values, frequency, sequence and phase of each wave as seen Figure 2.14 [5].

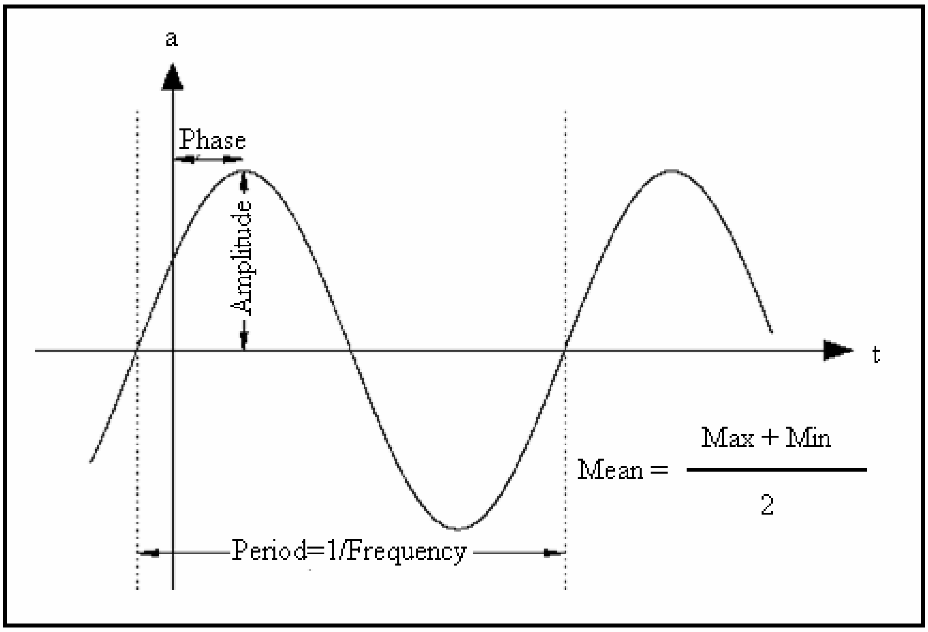

Figure 2.14. Properties of Collected Data

There are two kind of counting algorithm; one or two parametric. One parametric counting algorithm provides the information of the number of cycles and one other value (i.e. amplitude). However with two parametric counting algorithms, two other values can be obtained (i.e. amplitude, mean).

Range pair, one parametric counting algorithm, is not sequential and only complete waves are recognized, as seen in Figure 2.15. Also, it counts the points in pair and suitable for fatigue life estimation with loss of the influence of mean value [3].

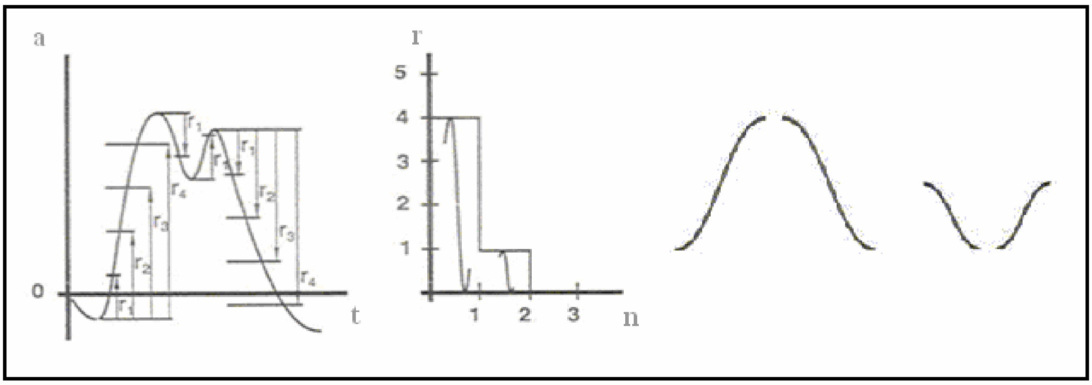

Figure 2.15. Principal of Range Pair Counting and Wave Pairs

In this study, range pair counting was used for time optimized block programmed test, as shown in Figure 2.16.

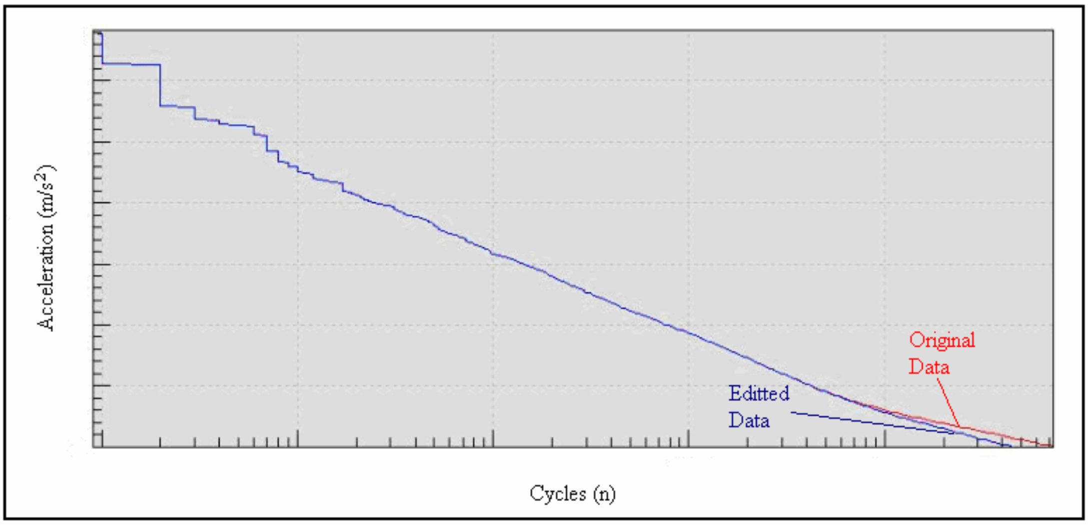

Figure 2.16. Range Pair Counting

2.2.4 Block Programme Loading

2.2.4.1 Loading Patterns

There are three primary, dynamic patterns of loading to be considered in fatigue testing, and these are illustrated in Figure 2.17 [1].

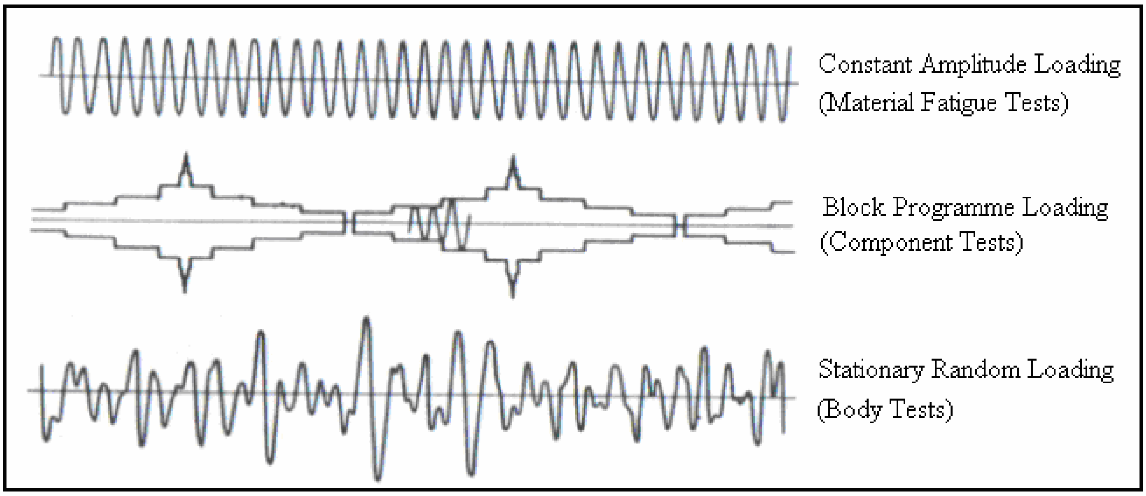

Figure 2.17. Fatigue Loading Patterns

The first pattern is sinusoidal, constant amplitude loading. This is the most common type of loading used in most simple material fatigue tests. The second primary loading pattern is block programme loading which is derived from sinusoidal oscillations but amplitude is varied in discrete blocks of cycles. This type of loading in Figure 2.17 shows a regular pattern of ascending and descending amplitudes and this is the form in which Dr. Gassner originally applied his technique in 1939 [1]. In component tests, this type of loading is generally used so that in this study, the block programme loading was applied in Hydropuls for AdBlue tank tests because of the ease of specification and repeatability.

2.2.4.2 Gassner's Block Programme Loading

The first variable amplitude loading spectrum was introduced by Gassner for aeronautical structures, the historical Eight-Block-Programme Test in Figure 2.18 [7]. The reason of the block programming was that random loading processes could not be yet simulated by existing simple testing machines at that time.

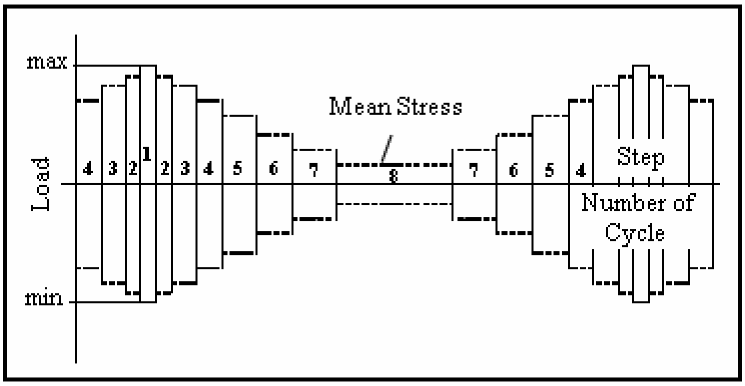

Figure 2.18. Gassner's Block Programme

In plastic AdBlue tank tests, by using range pair counting, a load collective was constructed for x, y and z directions, as shown in Figure 2.19.

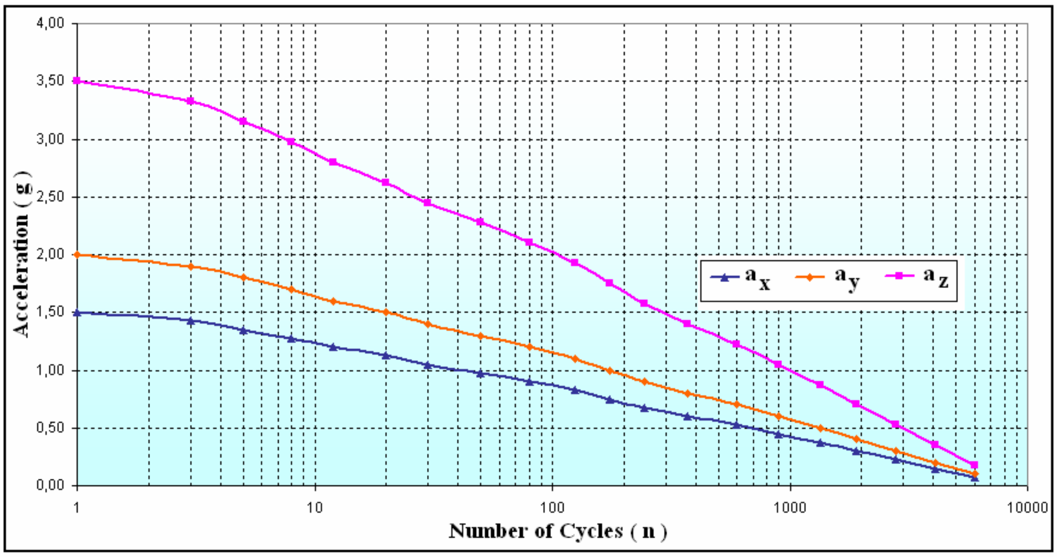

Figure 2.19. Load Collective for x, y and z Directions

After ignoring the non-damaging parts of the data (a < ±0,35g), this load collective was divided into seven steps as done in Figure 2.20 and test spectrum was obtained for z direction. This was also done for x and y directions.

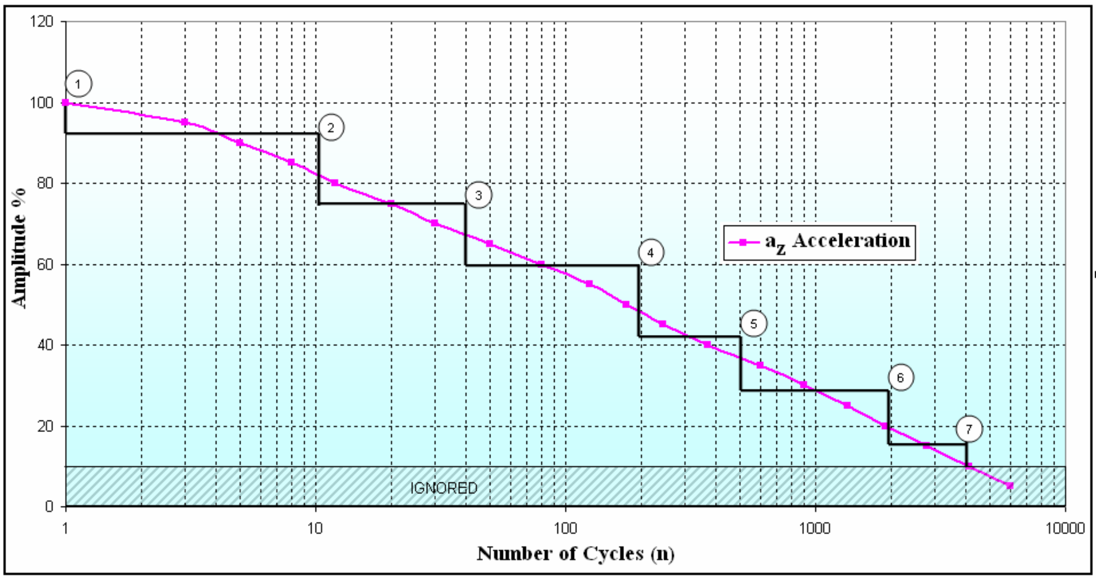

Figure 2.20. Test Spectrum of Plastic AdBlue Tank Testing for z Direction

It is important that the loading steps should be equal in magnitude and that the number of cycles for each step would be arranged to be uniformly distributed about the plotted line as shown in Figure 2.20 [1]. It should be noted that because of the logarithmic presentation, the cycle steps do not appear to be divided equally.

Besides the Hydropuls tests, some computations should be done to calculate the service life of a component and compare the damage effect between test signal and collected data at proving ground.

2.3 Damage Calculation

2.3.1 Cumulative Damage and Life Prediction (Miner's Rule)

Predicting fatigue damage for structural components subjected to variable loading conditions is a complex issue. The first, simplest, and most widely used damage model is the linear damage. This rule is often referred to as Miner's rule (1945) [11].

According to the Miner's rule if a component is subjected to cyclic loading but not regularly repeated loading at the same amplitude, each block of the cycles consumes a determinable amount of the component's life. Each block's effect on the component life is expressed as a fraction and when the summation of the various fractions equals unity, the life of the component is at the end [1].

With the help of Figure 2.21 [4] and Figure 2.22 [7], Miner's rule can be explained easily.

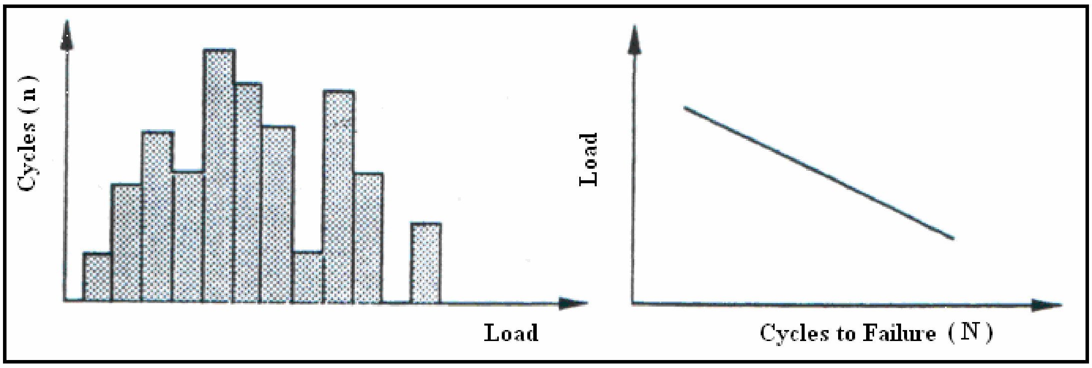

Figure 2.21. List of Cycle Counts and S-N Curve

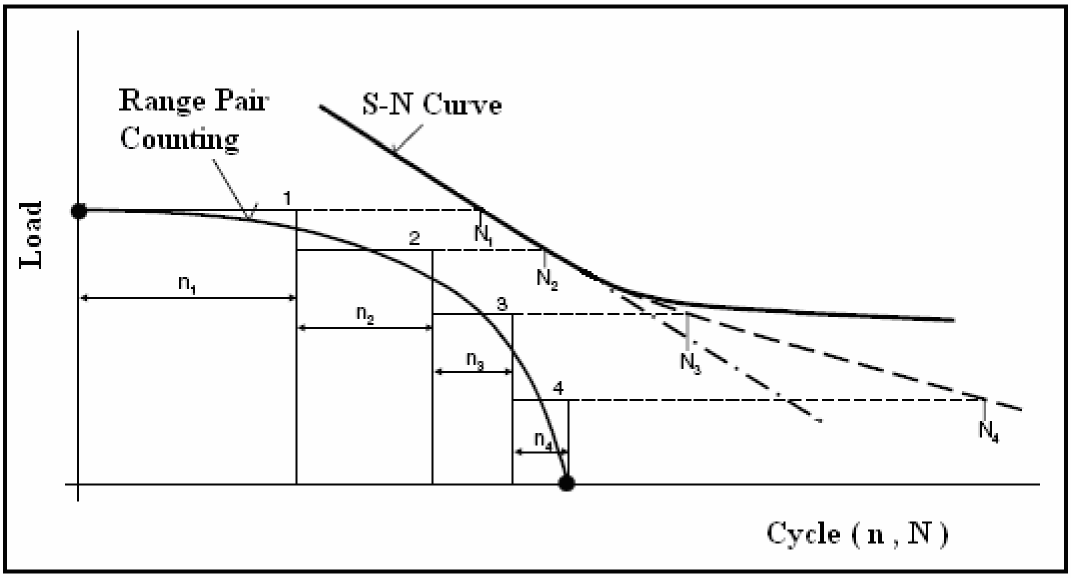

Figure 2.22. S-N Curve and Calculation of Fatigue Life

If the cycle to failure at a stress of i is N_i and the actual cycle in loading history at stress i is n_i, then the damage caused by this loading history is:

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i} \tag{2.1}$$

Failure occurs when D=1 [1]. In Figure 2.22, prolongation of the S-N curve changes with the kind of the material.

2.3.2 Relative Damage

Relative damage provides a simple way of comparing two time series of a single test in a fatigue damage context. It calculates a suitable stress-life (S-N) curve and uses range pair counting and Miner's rule to calculate a damage value for each time series [6]. In Figure 2.23, the comparison of damages between the original time series data and edited data for one block loading is shown graphically. Although the duration of the signal decreased from 750 seconds to 450 seconds, the damage effects are almost same.

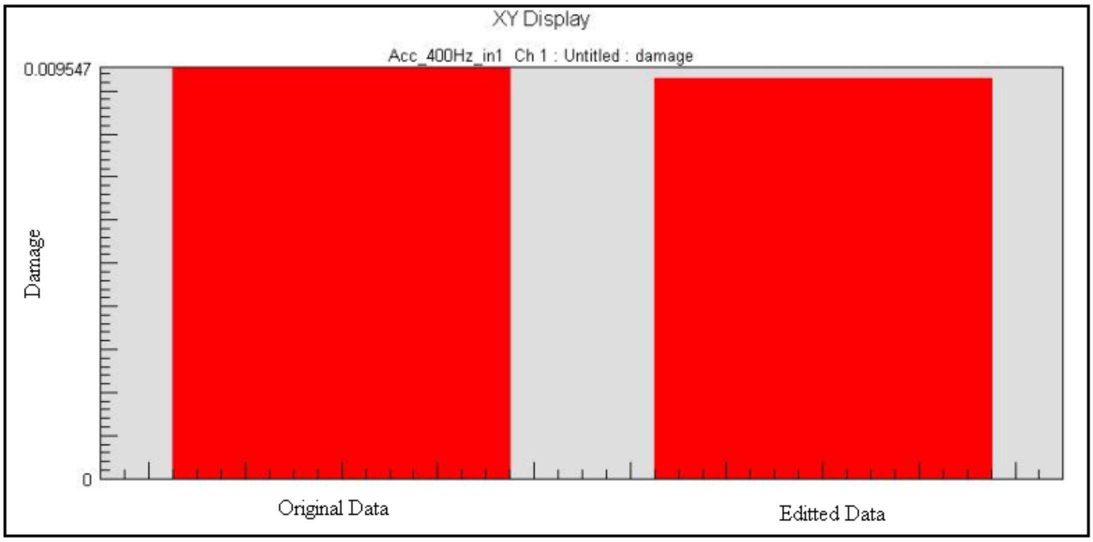

Figure 2.23. Damage Comparison between Original and Edited Time Series Data for One Block Loading

3. HYDROPULS TESTS AND STRAIN MEASUREMENTS

3.1 Test Definition

The aim of the Hydropuls tests is to develop a failure avoidance methodology by using strain-gage rosette measurements for one version of AdBlue Tank which have also four different types.

Throughout the Hydropuls testing, totally 4 types of plastic AdBlue tanks, as seen in Figure 3.1, have been tested either with block and sweep loading in case of full and ¾ volumes [14].

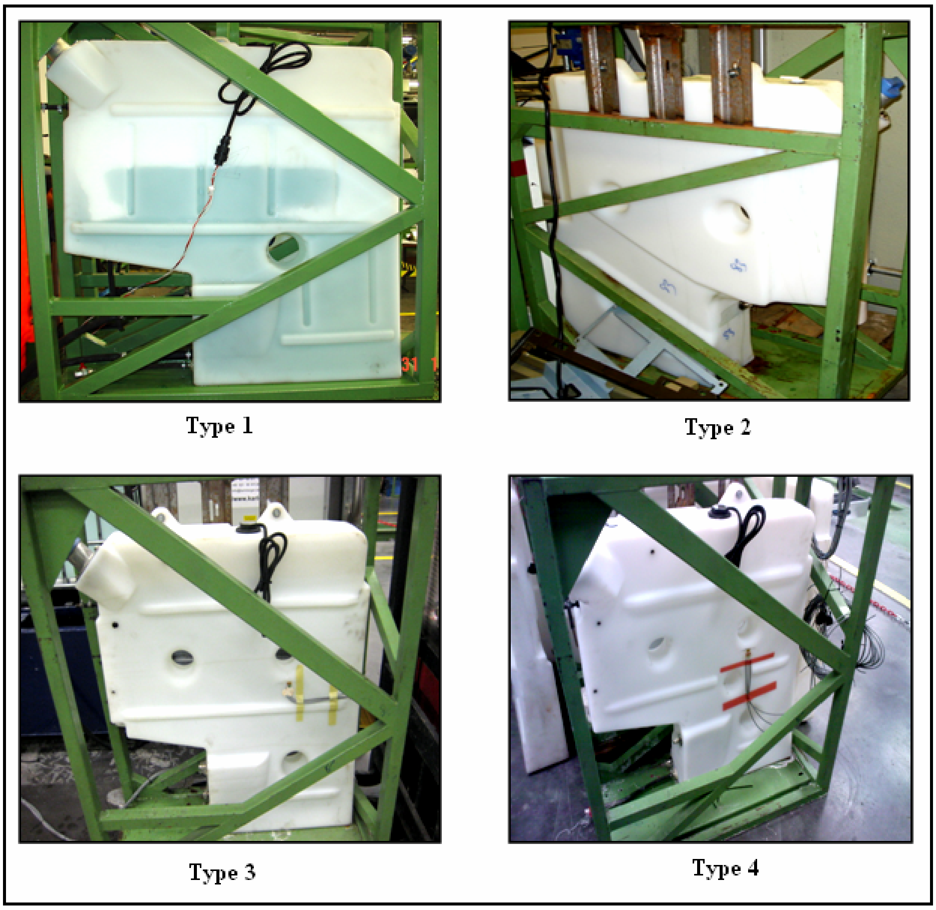

Figure 3.1. Tested Plastic AdBlue Tank Types

These tanks were mounted on a test rig as seen in Figure 3.2. To construct the test signal, block programme has been utilized, as stated before in Section 2.2.4.

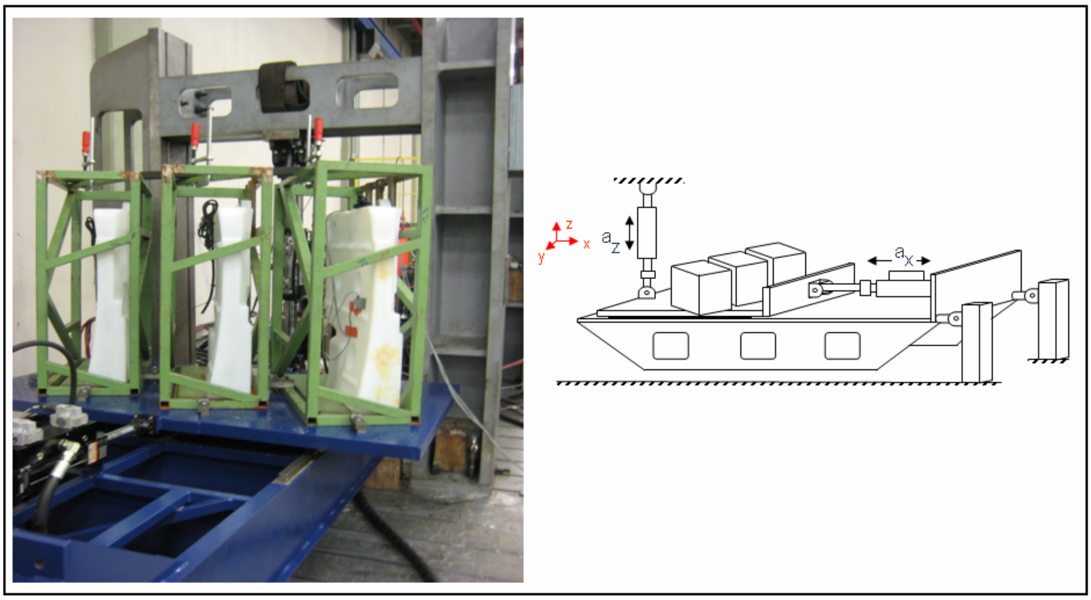

Figure 3.2. Hydropuls Test Rig

The Hydropuls test rig has the following properties;

- Two degree of freedom: in x and z directions.
- Three dimensional testing: third dimension is the resultant of x and y directions.
- Programming technique: Block programming.
- Testing specimens are limited 1,5 m width.
- Hydraulic actuator in z direction: MTS model 244.22, 100kN
- Hydraulic actuator in x direction: MTS model 244.11, 15kN.

The relative damages on stress concentration areas are investigated with respect to one block loading. The frequency responses of plastic AdBlue tanks at different AdBlue levels are also examined with the help of sweep loading. Throughout the testing, strain data was collected from one complete block programme as mentioned in Section 2.2.4 and a sweep loading which varies from 1 to 20 Hz, with 1 mm amplitude and 0,1 Hz/sec increasing ratio was executed. Since the directions of the principal stresses are not known, strain gauges rosettes are required to collect strain data. As seen in Figure 3.3, strain gauges rosettes were applied at high stress locations based on finite element analysis and previous test experiences.

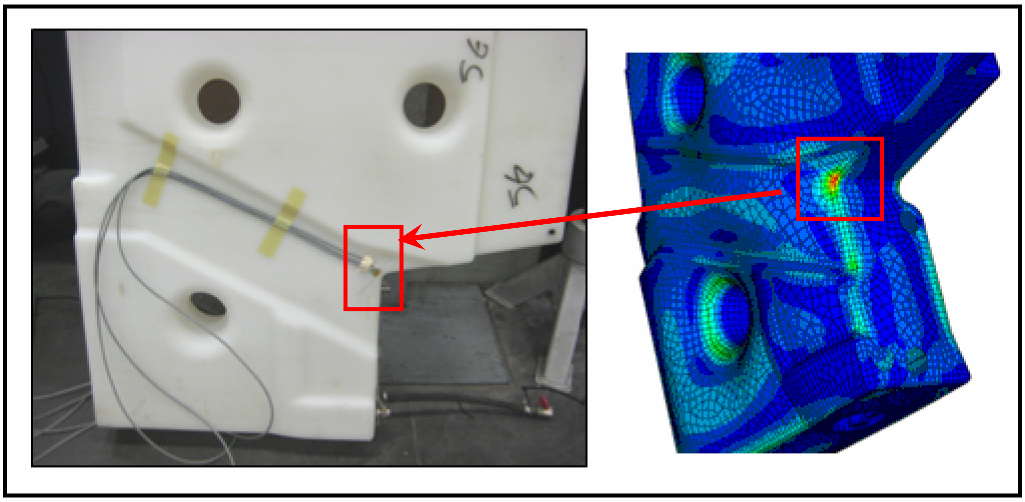

Figure 3.3. Strain Gauge Rosette Location

After one block and sweep loading, the collected strain data was plotted as time series. An example of time history of strain data for both block and sweep loading is shown in Figure 3.4 and Figure 3.5.

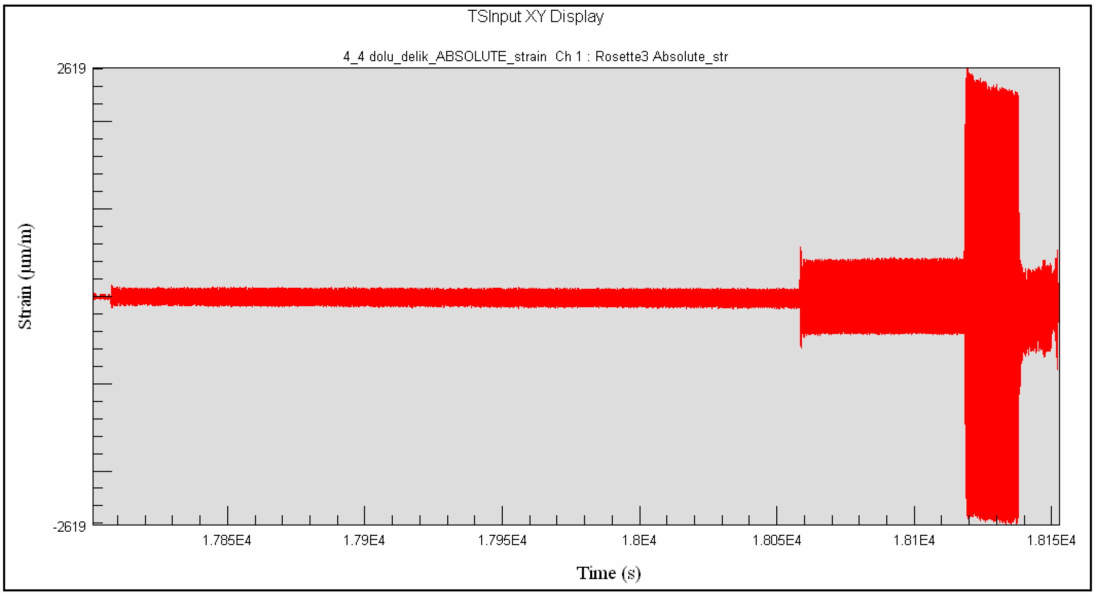

Figure 3.4. Time History of Strain Data for Block Loading

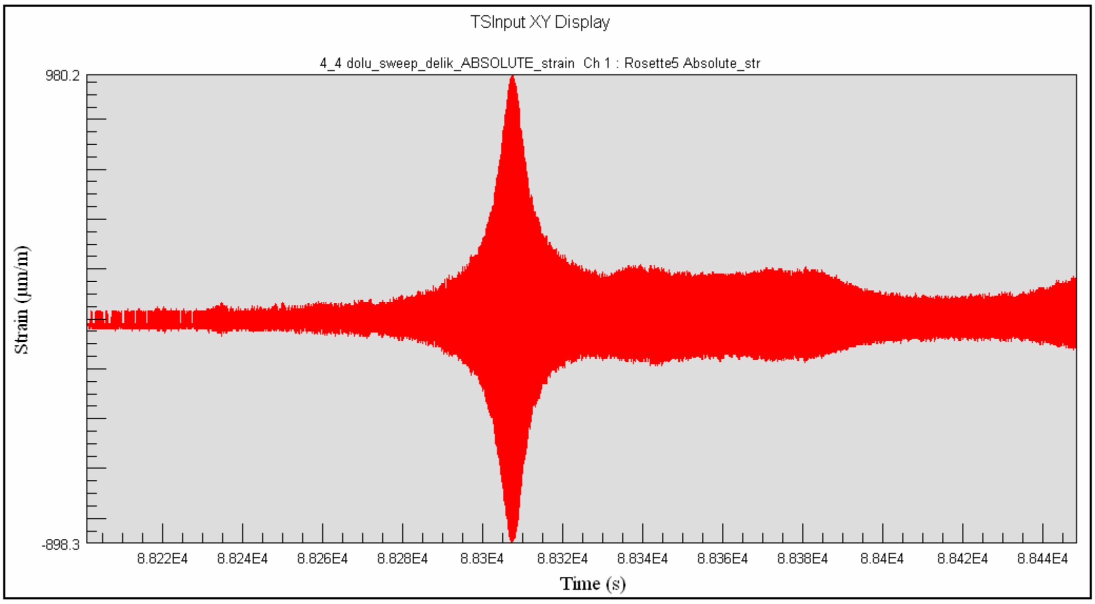

Figure 3.5. Time History of Strain Data for Sweep Loading

The effects and results of these loadings will be discussed in the next Chapter.

3.2 Data Acquisition at Hydropuls Tests

In plastic AdBlue tank tests, strain data was collected by ESAM (Electronic Signal Acquisition Module, as seen in Figure 3.6) which is a measuring system used to wide variety of measurements. ESAM can measure up to eight analog channels and up to four digital channels. Strain gauge rosettes outputs were connected at these analog channels and the collected data was monitored and analyzed on the computer with the help of ESAM software.

Figure 3.6. ESAM Data Traveller

Before data acquisition, strain gauge rosette parameters (rosette type, resistance and gauge factor) and material properties (elastic modulus and Poisson's ratio) should be set correctly in ESAM software.

There are three basic geometry types of strain gage rosettes that are allowed by ESAM, 45°, 60°, and T rosettes. The strain on the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance (R). Gauge factor (GF) of a strain gauge is defined as the ratio of the change in electrical resistance to the change in strain as seen in Equation (3.1) [8].

$$GF = \frac{\Delta R/R}{\varepsilon} \tag{3.1}$$

While collecting strain data on plastic Adblue tanks, 120 Ohms, 45°, type 3/120RY81 HBM strain gauges rosettes were used, as shown in Figure 3.7.

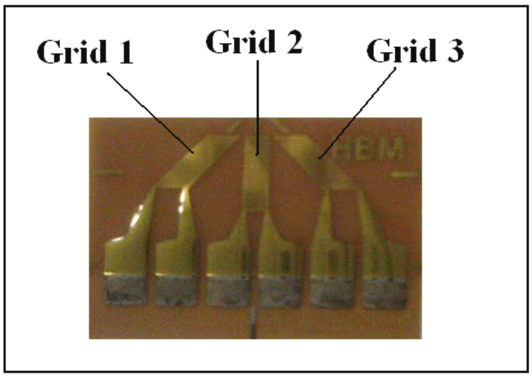

Figure 3.7. Strain Gauge Rosette

3.3 Strain Gauge Rosette Calculations

To obtain correct results, the grids in the rosettes must be numbered in a particular way. Gauge grids must be numbered in the counter clockwise direction. In a 45° rosette, the axis of grid 2 must be 45° away from grid 1's axis; and grid 3 must be 90° away from the grid 1, as seen in Figure 3.7.

3.3.1 Maximum and Minimum Principal Strain & Stress

The planes on which the shear stress is equal to zero is called principal planes and the normal stresses on the principal planes are called principal stresses. Following mathematical relationships are used for calculation of the maximum and minimum principal strain and stress values. e_1, e_2 and e_3 show the measured strains, respectively for grids 1, 2 and 3 [9].

Maximum principal strain:

$$\varepsilon_{max} = \frac{e_1 + e_3}{2} + \frac{1}{\sqrt{2}}.\sqrt{(e_1 - e_2)^2 + (e_2 - e_3)^2} \qquad \textbf{(3.2)}$$

Minimum principal strain:

$$\varepsilon_{min} = \frac{e_1 + e_3}{2} - \frac{1}{\sqrt{2}}.\sqrt{(e_1 - e_2)^2 + (e_2 - e_3)^2} \qquad \textbf{(3.3)}$$

And the angle between grid 1 and principal axis:

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{2e_2 - e_1 - e_3}{e_1 - e_3}\right) \qquad \textbf{(3.4)}$$

Maximum and minimum principal stresses are calculated from the principal strains by using Hooke's law. However, material properties like elastic modulus (E) and Poisson's ratio (ν) must be known for calculations.

Maximum principal stress:

$$\sigma_{max} = \frac{\mathrm{E}}{1\text{-}\nu^2}(\varepsilon_{max} + \nu\,\varepsilon_{min}).10^{-6} \qquad \textbf{(3.5)}$$

Minimum principal stress:

$$\sigma_{min} = \frac{\mathrm{E}}{1\text{-}\nu^2}(\varepsilon_{min} + \nu\,\varepsilon_{max}).10^{-6} \qquad \textbf{(3.6)}$$

In these formulas, it is assumed that ε_{max} and ε_{min} are expressed in µm/m. [9].

3.3.2 Absolute Principal Stress & Strain

Absolute principal value is the value of maximum or minimum principal strain or stress, which has grater absolute value. For example, if the maximum principal strain is 120 µm/m and the minimum principal strain is -110 µm/m, than the absolute principal strain will be 120 µm/m [9].

In the next chapter, the analysis of collected strain data and its damage effect on plastic AdBlue tanks will be evaluated. While doing this, the absolute values of both strain and stress will be used since the absolute value of strain or stress has bigger effect on fatigue life.

4. ANALYSIS AND EVALUATION OF DURABILITY FOR ADBLUE TANKS

To evaluate tanks with respect to the durability point of view, a comparative damage analysis is done by using the strain measurements.

Due to the repeatability of the test results, each block program is adjusted for different volume requirements. To analyze the collected data, durability software tools are utilized. In the evaluation of the results, data counting algorithms and relative damage criteria are used.

Throughout the testing, durability of tanks is evaluated with respect to the following points.

- Estimated critical strain value
- AdBlue level effect
- Test excitation frequency effect
- Fixing points effect
- Constructive properties effect

4.1 Determination of Estimated Critical Strain Value

Figure 4.1 shows an overview of the test result of all four tanks with respect to estimated critical strain value. The x and y axis shows the strain range and damage values respectively. The data acquisition locations are given in Table 4.1.

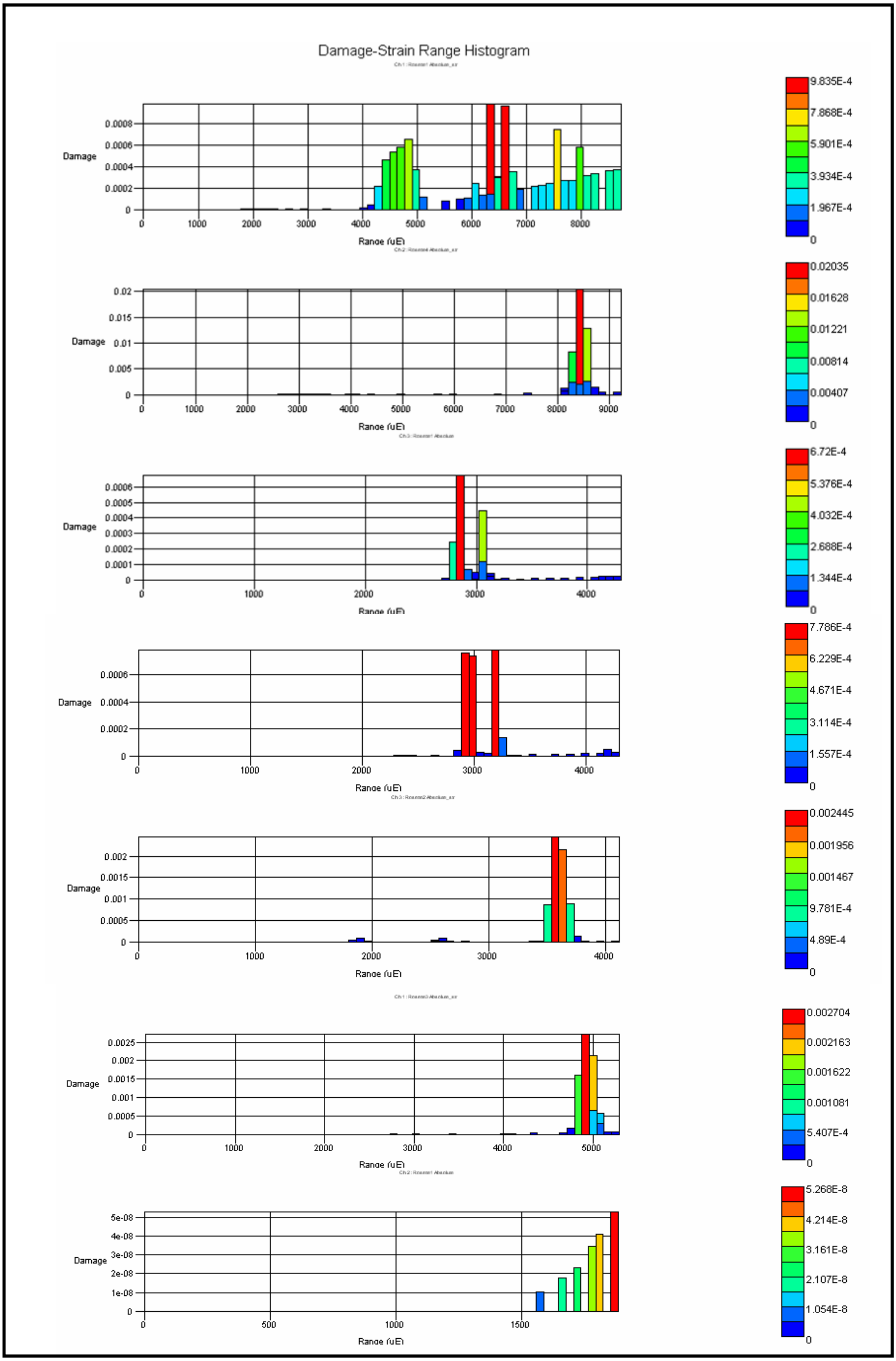

Figure 4.1. Strain Amplitude and Damage Histograms

Table 4.1. Data Acquisition Locations of Block Loading

Channel Number	Data Acquisition Area
1	Type -1 Bottom Hole
2	Type-2 Bottom Corner
3	Type-3 Upper Hole
4	Type-3 Bottom Corner
5	Type-4 Bottom Corner
6	Type-2 Upper Hole
7	Type-4 Upper Hole

General overview is obtained by comparing the strain amplitudes measured from high stress locations. The relative damage (based on Miner's Rule) approach for fatigue damage assessment indicates that a significant amount of damage occurs between 2000-3000 µm/m strain values at high stress locations [14]. Therefore, for this range of strains, a life time calculation should be carried out to see if this area is o.k. or not.

4.2 AdBlue Level Effect

Another critical point which affects AdBlue tank durability is liquid level. During the vehicle driving, the consumption of AdBlue is approximately at 3 to 5% of the diesel usage, thus AdBlue level changes continuously. Thus, an evaluation has been done by using nCode software with the help of damage analysis tool to determine which overall liquid level condition was most damaging to AdBlue tanks. The results of this analysis can be clearly seen in Figure 4.2 and Table 4.2. The full tank is expected to cause more damage due to the larger mass. However, the results show that the fuller than ¾ tanks, the smaller damage scenario for the bottom corner and hole areas [14].

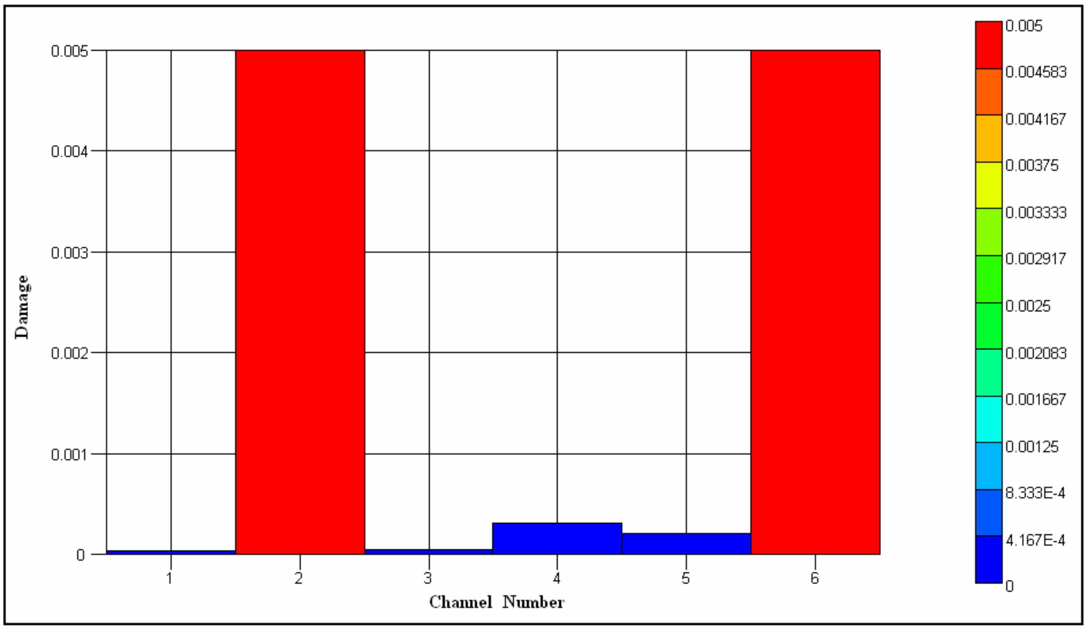

Figure 4.2. Damage Comparison Between Full & ¾ Liquid Levels

Table 4.2. Data Acquisition Locations of Sweep Loading

Channel Number	Data Acquisition Area
1	Type -1 Bottom Hole (full)
2	Type-1 Bottom Hole (¾)
3	Type-3 Upper Hole (full)
4	Type-3 Upper Hole (¾)
5	Type-2 Bottom Corner (full)
6	Type-2 Bottom Corner (¾)

The reason is that when the liquid level decreases, the hydrostatic force acting point is shifting to the corner region due to the geometrical diversity of the tank, which causes more damage for this point, see Figure 4.3. Based on this result, it is assumed that, an AdBlue level of ¾-tank is a critical volume for tested AdBlue tanks.

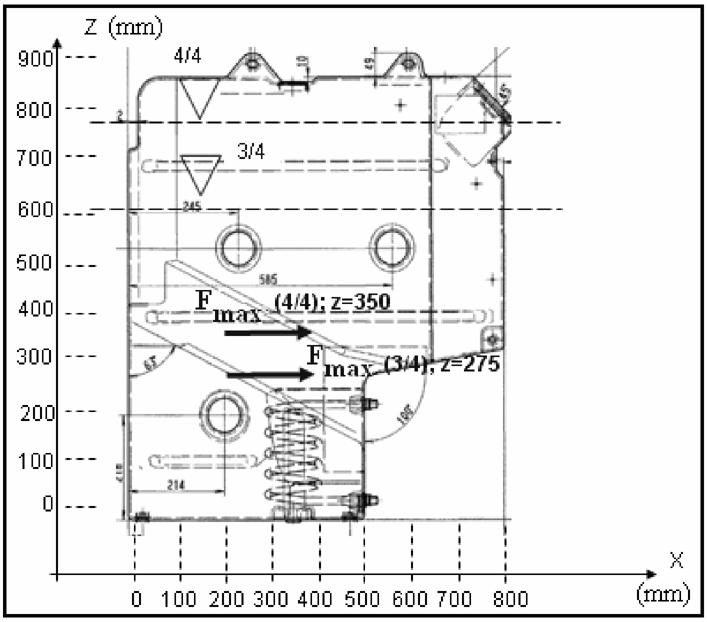

Figure 4.3. Hydrostatic Force Acting Points Due to Different AdBlue Levels

4.3 Test Excitation Frequency Effect

In most service applications, plastic-based materials are likely to be subjected to similar forces to the metallic equivalents. It will be seen, that in general the type of material should not necessarily affect the choice of realistic test loads, but it may influence other details of a test specification, such as loading frequency.

The tanks are exposed to an effective frequency range of 9-12 Hz which is obtained from frequency analysis of the proving ground signal. Frequency analysis data is typically presented in graphical form as a Power Spectral Density (PSD). Essentially a PSD displays the amplitude of each sinusoidal wave of a particular frequency. PSDs are useful for detecting resonance in components [10]. Therefore, to see the exact effect of the test excitation frequency on the measurement points, a comparative frequency spectrum analysis has been done with the help of sweep loading.

In Figure 4.4 the strain PSD analysis (Power Spectral Density) at two critical locations can be seen. The red curve has a peak value around 14 Hz, likewise the peak value of the blue curve is approximately at 16,5 Hz. It can be said that around these values the tanks will be in resonance zone [14].

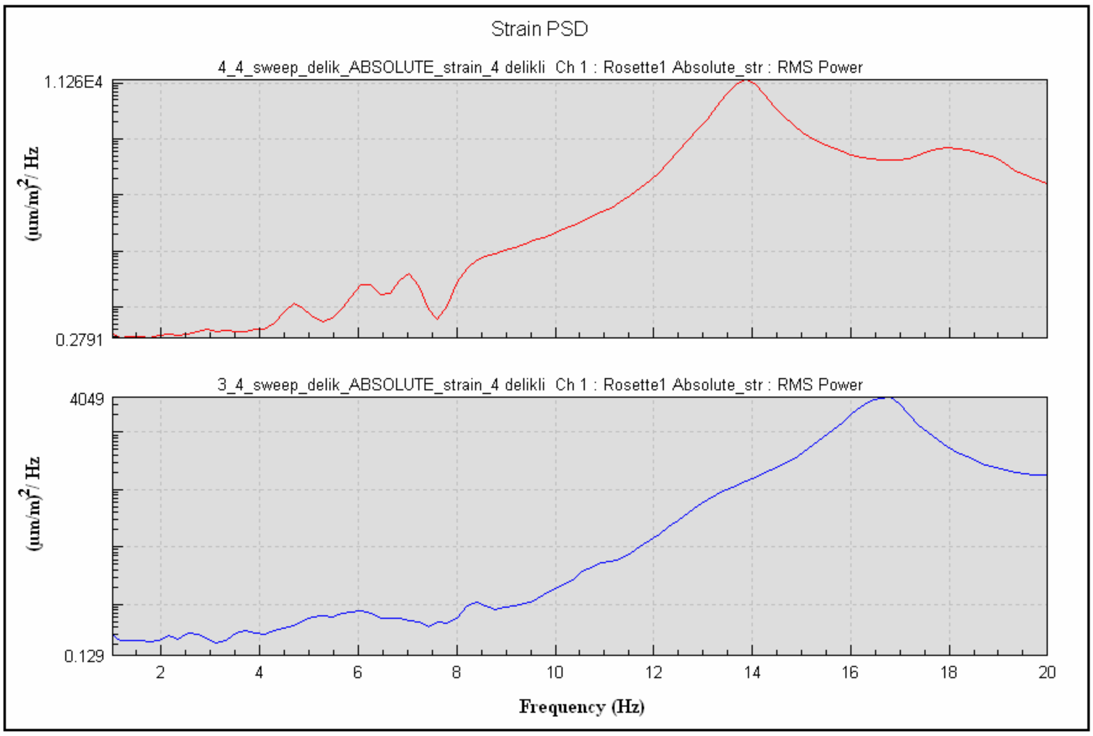

Figure 4.4. Strain PSD of Sweep Data

These frequency analyses have done for the all tank types at two different volumes (full and ¾). These analysis results are given in Figure 4.5 for all tank types. As a result, principally, the estimated natural frequency of side walls of the tanks should be higher than the test frequency range.

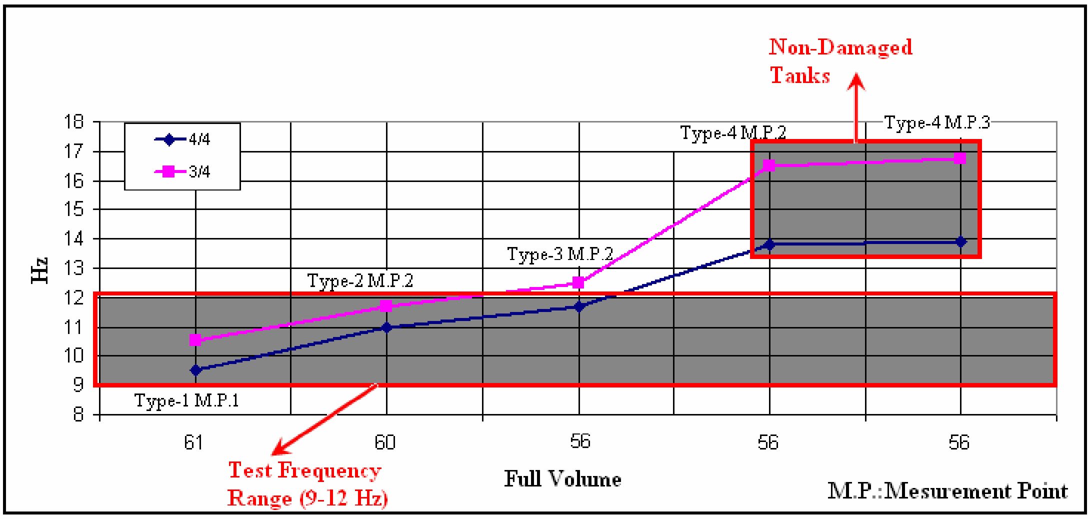

Figure 4.5. Test Excitation Frequency Effect

4.4 Fixing Points Effect

The fixing points create a bending effect over the tanks. This causes the tank wall to expand and contract under stress which also causes more damage than usual. To determine the effect of the fixing points, the tanks which have different fixing points have been tested, as seen in Figure 4.6. By doing this, a type-1 tank was chosen as a default tank and the all changes were applied over this type of tank.

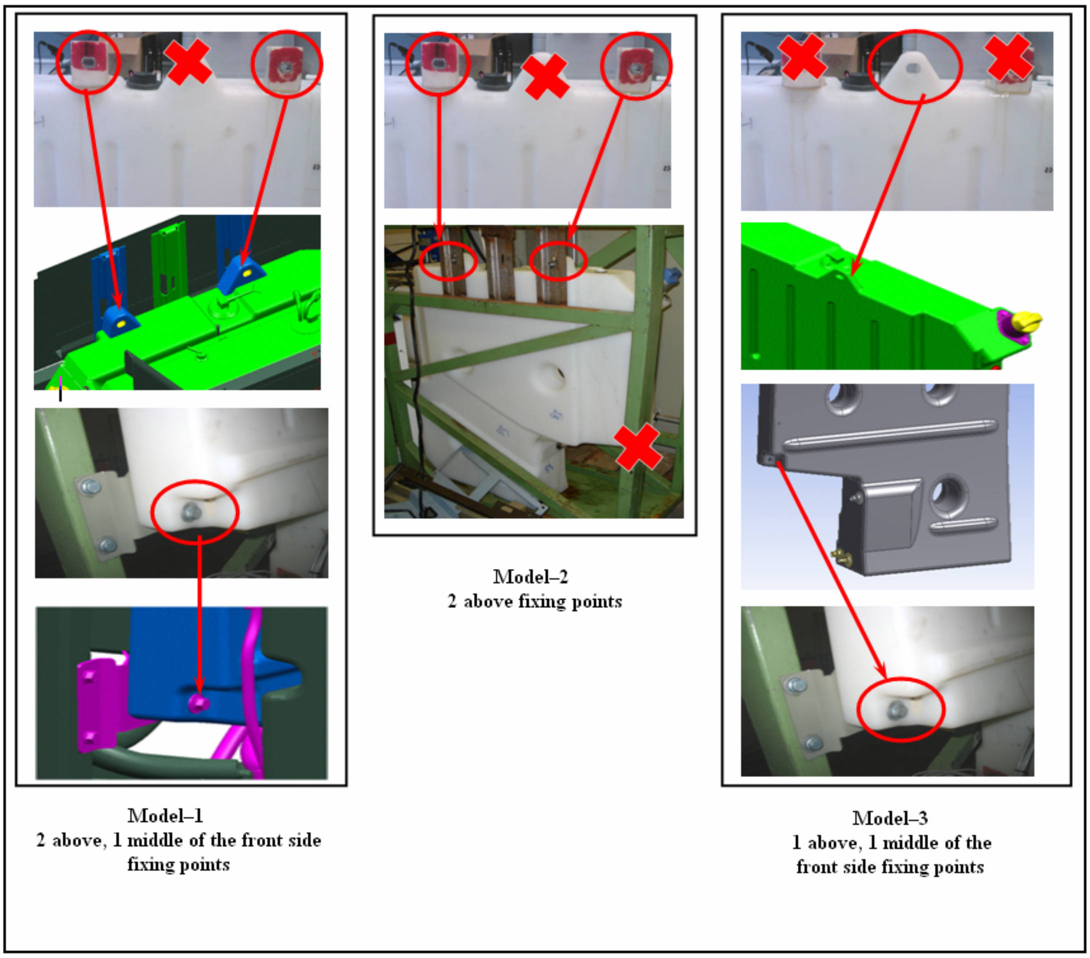

Figure 4.6. Models with Various Fixing Points

Figure 4.7 show the results of comparative damage analysis with respect to using various fixing points. At the end of these tests, it has been observed that increasing the number of fixing points, which makes tanks more rigid, causes more damage. Therefore, it is important to use fixings with the correct flexibility to allow the tank to move freely [14].

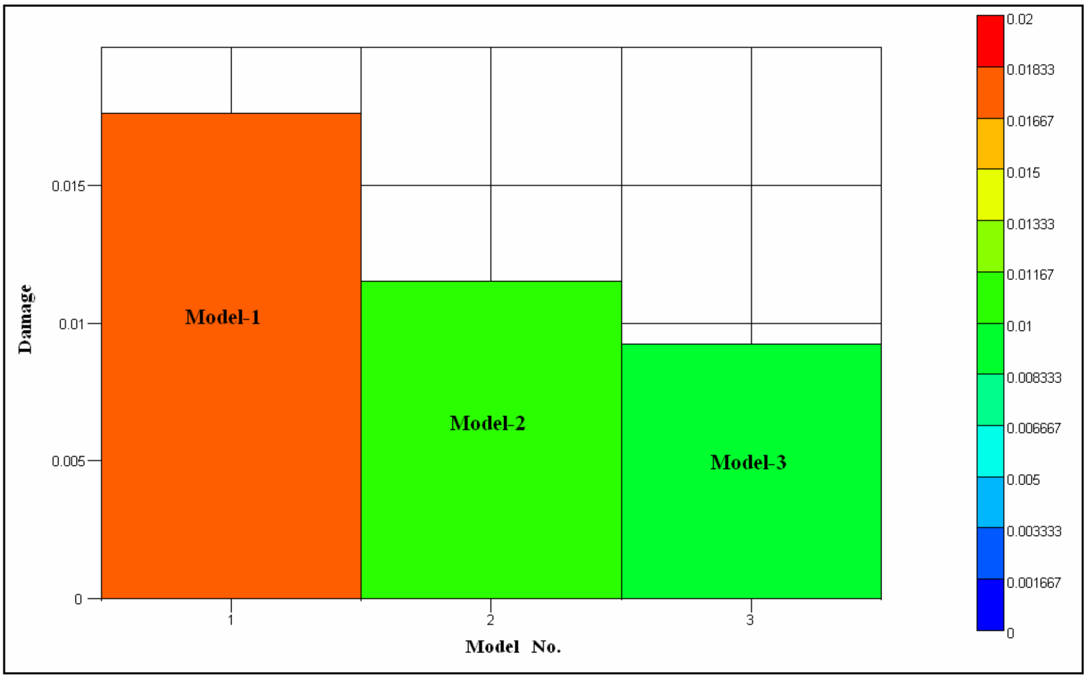

Figure 4.7. Damage Comparison of Failure Areas by Using Various Fixing Points

4.5 Constructive Properties Effect

The tank types as mentioned in Section 3.1 have some constructive design properties such as, holes, ribs, recesses, corner radius and fixing points. The nomenclatures of these properties are shown in Figure 4.8 and numerical values are given in Table 4.3 for each tank type.

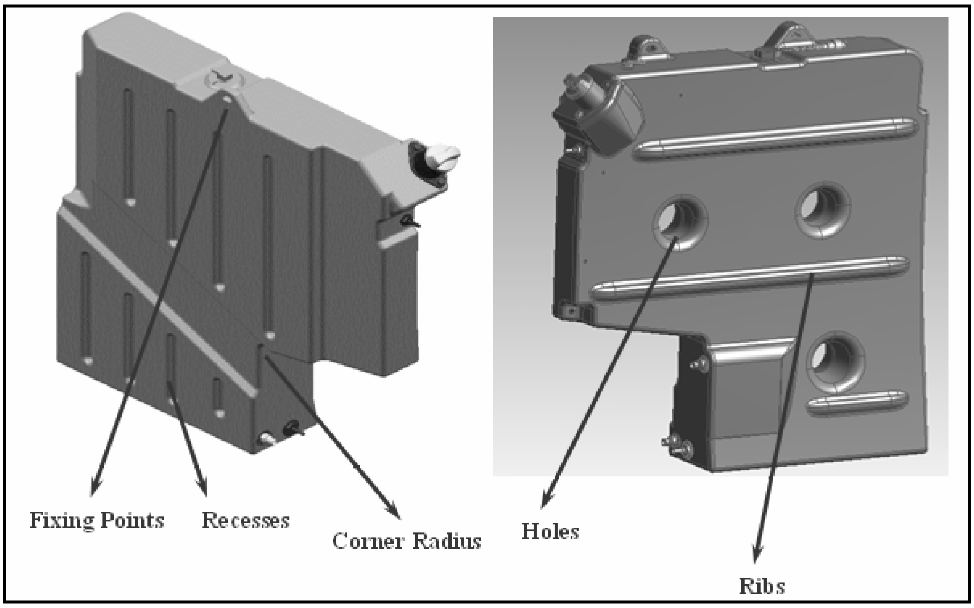

Figure 4.8. Nomenclature of Constructive Properties

Table 4.3. Design Specification of Plastic Tanks

Constructive Points	Type 1	Type 2	Type 3	Type 4
Wall Thickness (mm)	5	5	6	6
Recesses Width (mm)	20	No Recesses	No Recesses	No Recesses
Rib Height (mm)	13	13	13	13
Holes Radius (mm)	25	25	25	25
Bottom Corner Radius (mm)	10	10	25	25
Number of Holes	1	3	3	4
Number of Fixing Points	1 above, 1 middle of front side, 4 bottom	2 above, 4 bottom	2 above, 4 bottom	2 above, 4 bottom
Known Failure Area	Bottom Hole	Bottom Corner	Upper Hole	No Crack

For example, ribs and recesses are often added to rotationally molded parts to stiffen them and depend mainly on their height and width. Likewise, holes provide stiffness for plastic tanks and improve airflow for heat transfer. Another main concern with molded-through holes is sloshing. Therefore the number of holes and diameter are important to reduce the liquid sloshing in tanks. Besides, the corner radius of plastic tanks is also an important parameter which affects the durability. The radius value should be correctly chosen to avoid the stress concentration at critical corners [14].

These constructive points affect the durability of plastic tanks directly and thus another comparative damage analysis has been done by evaluating constructive properties of AdBlue tanks, see Figure 4.9 and Table 4.4.

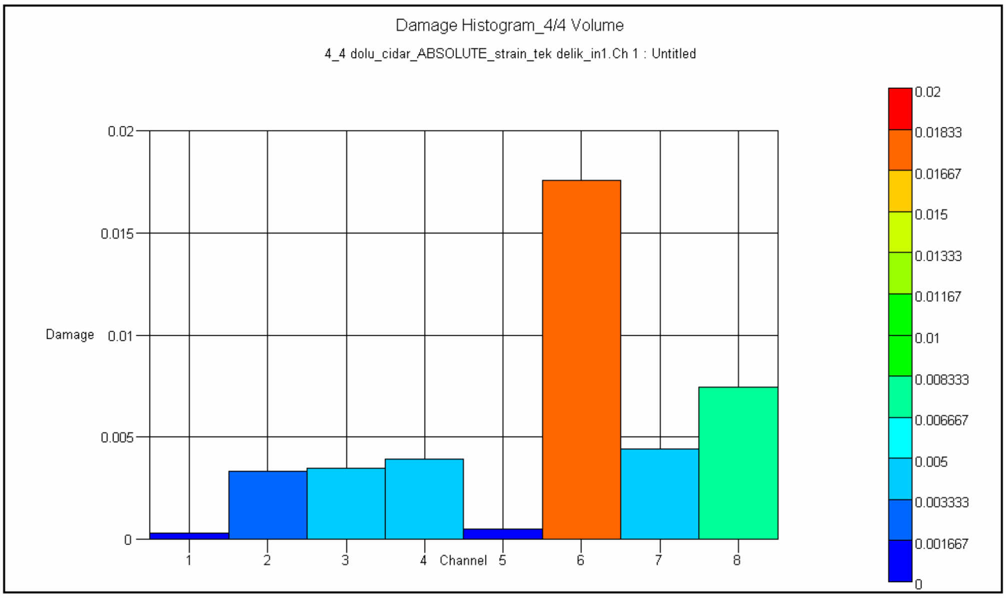

Figure 4.9. Damage Comparison of Failure Areas between Various Tank Types

Table 4.4. Data Acquisition Locations

Channel Number	Data Acquisition Area
1	Type -1 Side Wall
2	Type-1 Bottom Hole
3	Type-2 Upper Hole
4	Type-3 Upper Hole
5	Type-4 Upper Hole
6	Type-2 Bottom Corner
7	Type-3 Bottom Corner
8	Type-4 Bottom Corner

After the comparative damage analysis between various tanks, the desired values of these constructive properties are showed in Table 4.5.

Table 4.5. Desired Values of Constructive Properties of AdBlue Tanks

Constructive Properties	Desired Values
Wall thickness	≥ 6 mm
Ribs height	≥ 13 mm
Recesses width	≥ 18 mm
Hole radius	≥ 25 mm
Bottom corner radius	≥ 25 mm

It’s assumed that, ribs height and recesses width principally is recommended higher than 13 and 18 mm respectively. Also, on critical locations such as corner and holes radiuses are suggested higher than 25 mm. Finally, wall thickness is recommended higher than 6 mm [14].

Based on all these results, it’s assumed that the analyzed parameters which affect durability of tanks should be applied with correct methodology, as seen in Table 4.6

Table 4.6. Failure Avoidance Methodology

<table>
<tr><th>Specifications</th><th colspan="2">Desired Values</th></tr>
<tr><td>Wall thickness</td><td colspan="2">≥ 6 mm</td></tr>
<tr><td>Ribs height</td><td colspan="2">≥ 13 mm</td></tr>
<tr><td>Recesses width</td><td colspan="2">≥ 18 mm</td></tr>
<tr><td>Number of holes</td><td colspan="2">1 Hole (same location on type-1)</td></tr>
<tr><td>Hole radius</td><td colspan="2">≥ 25 mm</td></tr>
<tr><td>Bottom corner radius</td><td colspan="2">≥ 25 mm</td></tr>
<tr><td>Fixing points</td><td colspan="2">1 fixing point above of tank and 1 fixing point in the middle of front side of the tank. 4 fixing points bottom of tank</td></tr>
<tr><td rowspan="2">Estimated critical strain value</td><td>Hole area</td><td>Corner area</td></tr>
<tr><td>≤ 2000 μm/m</td><td>≤ 3000 μm/m</td></tr>
<tr><td>Natural Frequency Response of Side Walls</td><td colspan="2">Away from 9-12 Hz range</td></tr>
</table>

5. DISCUSSION AND CONCLUSION

Based on the results of this study, a guideline for determining a methodology for failure avoidance of AdBlue tanks has been developed. In this study, it has been observed that there are some main factors which affect the fatigue life of AdBlue tanks. With respect to durability point of view, the effect of estimated critical strain value, AdBlue level, test excitation frequency, fixing points and constructive properties has been investigated in this methodology.

When these effects are analyzed one by one, the results show that each effect causes severe damage on various locations of these tanks. After evaluating strain measurements during the Hydropuls test, it is concluded that improving on these factors increase sufficiently the fatigue life of tanks.

The strain measurements show that estimated damage occurs between 2000-3000 µm/m strain values on high stress concentration areas. Also, it is interesting to note that the fuller than ¾ tank, the smaller the damage scenario for the bottom corner and hole areas due to the geometrical diversity of the tanks.

Another main concern affecting fatigue life of tanks is test excitation frequency. The measurements show that the estimated natural frequency of side walls of the tanks should be away from 9-12 Hz which is the effective test frequency interval acting on the tanks from proving ground testing.

Apart from these, the location and number of fixing points cause serious damage effect on critical areas of tanks. It was found out that the tanks should be allowed to move freely by using the correct number of fixing points.

Finally, modifications on constructive properties, such as 6 mm wall thickness, 13 mm ribs height, 25 mm recesses width, 1 hole, 25 mm corner and 25 mm hole radius are recommended for better structural durability. Furthermore, with all these tests and improvements, this methodology which was enhanced for AdBlue tanks can be a beneficial reference for the plastic fuel tanks that will be tested in the future.

REFERENCES

[1] **Wright, Don H.,** 1993 Testing Automotive Materials and Components, Society of Automotive Engineers, Inc.

[2] **Himeki, H., Kumagai, H. and Morohoshi, K.,** 2006. Fatigue Behavior Analysis and Durability Evaluation of Plastic Fuel Tank, *SAE Technical Paper Series*, 2006-01-0782

[3] **Zenner, H.,** 2001. Betriebfestigkeit, TU Clausthal.

[4] **MTS,** Durability Test Technology Handbook

[5] **Halfpenny, A., Kemmerich, T.**, 2005. Fatigue Design of Vibrating Components, nCode International.

[6] **ICE-Flow**, 2007. Glyph Reference Guide, nCode International, *Document No:GW4-09-07*

[7] **Sonsino, C.M.,** 2007. Fatigue Testing Under Variable Amplitude Loading, *International Journal of Fatigue*, **29,** 1080–1089.

[8] **Khan, A. S. and Wang, X.,** 2001. Strain Measurements and Stress Analysis, Prentice Hall, Upper Saddle River, N.J.

[9] **ESAM (Electronic Signal Acquisition Module),** User's Manual

[10] **ICE-Flow,** 2005. GylphWorks 3.0. Tutorials, nCode International

[11] **Lee, Y.,** 2005. Fatigue Testing and Analysis, Elsevier Inc.

[12] **MTS,** 1999. Series 661.18 Force Transducer Datasheet.

[13] **MTS,** 1994. Series 252 Servovalves Datasheet.

[14] **Toprak, M.,** 2008. Determination of a Methodology for Failure Avoidance of AdBlue Tanks, *Test Report*, Mercedes-Benz.

AUTOBIOGRAPHY

Metin TOPRAK was born in Istanbul in 1983. He received his primary degree from Hasan Ali Yücel Primary School (1990-1994); and high school degree from Kartal Anatolian High School (1994-2001). He started his B.Sc. education at Mechanical Engineering Department of Yıldız Technical University in 2001. After receiving his B.Sc. degree in 2006; he has started his M.Sc. education at Automotive Programme of Mechanical Engineering Department in Istanbul Technical University. Since 2008, Toprak has also been working in Mercedes-Benz Türk A.S. Development Bus Test Center Department as a Test Engineer.