Chapter 3

FORMULATION

3.1 Scope

The previous chapter discussed the various methods and theories practised by engineers to perform structural fatigue evaluations. This chapter will formulate and present the Fatigue Equivalent Static Load (FESL) methodology. Central to this chapter is figure 3.1. Figure 3.1 aims graphically to present the methodology of the chapter.

3.1.1 Determination of input loads

The fatigue equivalent static load method starts with obtaining the input loads that cause fatigue damage to a structure. The case-studies presented in this thesis exclusively used strain gauge and acceleration measurements. Various other techniques can also be used. Refer to Chapter 2, section 2.2 (also see Wannenburg [39]).

Irrespective of the method used to obtain the input loads, the quantities needed for the following step are either strains or loads that can be used ultimately to calculate damage.

3.1.2 Fatigue calculations

Stress conversion

The data obtained from the previous exercise is now used to calculate a *relative damage*. If strains were measured, the data must be converted to stress data. This can be done using either equations 2.1-2.3 or equation 3.1, depending on the strain gauge configuration. Stresses can also obtained be using other methods, for instance dynamic simulations or conversion of frequency domain data. The case-study of the large bus-bracket, made use of the measurement of the input forces. These forces were converted to stresses using laboratory calibration, as well as finite element analysis calibration.

$$\sigma(t) = E\epsilon \tag{3.1}$$

Cycle counting

The stresses obtained from the conversion process are now further refined using the rainflow cycle counting technique. Please refer to sub-section 2.4.2, page 26 for a detailed explanation. The result of the cycle counting process is stress ranges ($\Delta\sigma_i$) and the number of cycles (n_i).

Relative damage

The relative damage of the measurements is now calculated using the stress ranges and cycles ($\Delta\sigma_i$, n_i). The term *relative* is used because generic material properties ($\Delta\sigma_f$, b) are used in equation 3.2. Equation 3.2 and equation 3.3 are used to calculate the damage. The *relative damage* calculated will be used in the next step to calculate the equivalent stress.

$$N_i = \left(\frac{\Delta\sigma_i}{\sigma_f}\right)^{\frac{1}{b}} \tag{3.2}$$

$$D_r = \sum_{i=1}^{n} \frac{n_i}{N_i} \tag{3.3}$$

Equivalent stress

The previous step calculated a relative damage (D_r) using the measured input data. The relative damage can now be processed further to obtain the total damage (D_{tot}) that the structure would experience during its lifetime. Again, various methods can be employed to obtain the total damage, for example questionnaires to determine the usage of the vehicle combined with a statistical analysis (see Wannenburg [39]). Irrespective of the methods employed, a total damage is now used to calculate the equivalent stress that would cause the total damage. The methodology will now be explained. The stress-life equation 3.2 is modified to equation 3.4.

$$N_{eqv} = \left(\frac{\Delta\sigma_{eqv}}{\sigma_f} \right)^{\frac{1}{b}} \tag{3.4}$$

Miner's damage equation can be modified to incorporate the *equivalent number of cycles* (N_{eqv}) resulting from the equivalent fatigue stress ($\Delta\sigma_{eqv}$). The number of cycles of the 'measured' equivalent stress (n_{eqv}) is selected (almost) arbitrarily. Most of the welding codes define an infinite life-time at 2×10^6 cycles. Weld categories, as well as mother material, are usually also defined relative to this life-time. Therefore: $n_{eqv} = 2 \times 10^6$.

$$D_{eqv} = \frac{n_{eqv}}{N_{eqv}} \tag{3.5}$$

The equivalent damage (D_{eqv}) is now set equal to the total damage that the structure would endure during its life-time (D_{tot}). This total damage is therefore equal to an amplitude loading of $\Delta\sigma_{eqv}$ repeated 2×10^6 times, and was calculated using the measurement data. It could mean that the vehicle structure can travel 750 000 km during which it will bend 20 million times at different amplitudes. The accumulated damage would be equal to an amplitude loading of $\Delta\sigma_{eqv}$ repeated 2×10^6 times. This all depends on the way that the total damage (D_{tot}) was calculated, using the relative damage (D_r).

Substituting equation 3.4 into equation 3.5 results in equation 3.6.

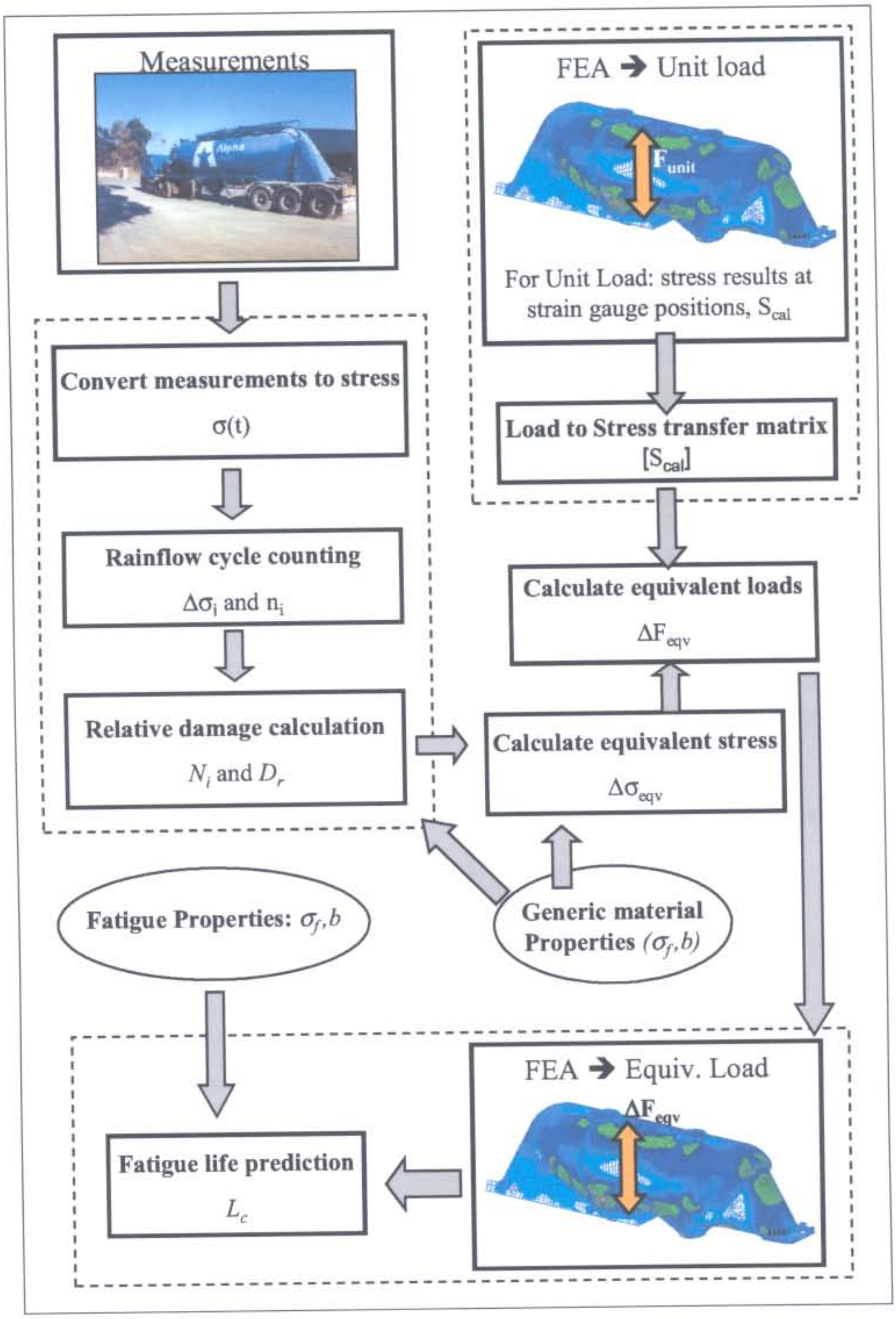


Figure 3.1: Fatigue equivalent static load

$$\Delta\sigma_{eqv} = \left(\frac{n_{eqv}}{D_{tot}}\right)^{b} \times \sigma_f \tag{3.6}$$

Fatigue equivalent static load

The finite element model is now used in this part of the process. The finite element model of the structure is subjected to a unit load (F_{unit}). The finite element analysis determines the stresses that the structure will experience because of the unit load. A *calibration* stress (ΔS_{cal}) can now be obtained at *the exact position where strain measurements were recorded.* An equivalent fatigue static load (ΔF_{eqv}) can now be determined using equation 3.7.

$$\Delta F_{eqv} = F_{unit} \times \frac{\Delta\sigma_{eqv}}{S_{cal}} \tag{3.7}$$

3.1.3 Assessment

The finite element model can now be analysed using the *fatigue equivalent static load.* The process of assessing the structure for fatigue damage can be summarized as follows:

- Analyze the finite element model, using the fatigue equivalent static load.
- Determine the highly stressed areas (*critical positions*).
- Determine the number of cycles to failure (N_c) for each critical position. Refer to equation 3.8.
- Calculate the damage (D_c) that the critical position will experience. Refer to equation 3.9.
- Determine the life of each critical position. Refer to equation 3.10.

When calculating the number of cycles to failure, each critical position must individually be assessed. The fracture stress (σ_f) is determined using an appropriate fatigue code [9], [15], [40]. Each critical position must be put equivalent to the appropriate weld category. Refer to section 2.4.3, page 31.

$$N_c = \left(\frac{\Delta\sigma_c}{\sigma_f}\right)^{\frac{1}{b}} \tag{3.8}$$

$$D_c = \frac{n_{eqv}}{N_c} \tag{3.9}$$

$$L_c = \frac{1}{D_c} \tag{3.10}$$

3.2 Closure

This chapter formalized the methodology of solving a structural fatigue related problem, using the Fatigue Equivalent Static Load method. Various case-studies are presented to show the usage of this methodology. The following chapter will present these case-studies to the reader.

Chapter 4

CASE-STUDY DEFINITION

4.1 Scope

This chapter discusses the various case-studies that were done to illustrate the theories of the Fatigue Equivalent Static Load method. The four case-studies are as follows:

- Aluminum dry-bulk tanker
- Sub-frame of a pick-up truck
- Suspension bracket of a large passenger bus
- Suspension bracket of a 4x4 pick-up truck

4.2 Aluminum Dry-bulk tanker

Various transport vehicle manufacturers have, due to the competitive nature of the transport industry, started manufacturing vehicles with lighter materials for example aluminum. This vehicle was instrumented and measured during a routine trip that would give a good indication of the loads the vehicle would experience (refer to figure 4.1). A finite element model of the $40m^3$ dry-bulk

Figure 4.1: Aluminium dry bulk tanker

tanker was created . The finite element model was subjected to a fatigue equivalent static load that was determined using measurements obtained during the measurement exercise (refer to figure 4.1).

4.3 Sub-frame of a pick-up truck

The need has arisen in the industry to supply a vehicle with a detachable load bay. The load bay (or swap-body) is an enclosed structure specifically designed to meet the requirements of the client. The sub-frame assembly would act as an interface between the chassis and the swap-body. The concern was raised that the chassis, on which the swap-body will fit, may endure a concentrated bending and twisting deformation in the area between the cab and the front most swap-body mounting. This is due to the fact that the swap-body is substantially stiffer than a normal load box. This problem could have dire consequence for the vehicle manufacturer. Rubber mounts between the chassis and the sub-frame would reduce this problem.

A quasi-static load was initially used to design a prototype sub-frame. Several iterations were done to optimize the design. The prototype sub-frame was used in the mock-up configuration during the first measurement exercise to obtain load inputs to the vehicle structure. The measurements obtained

Figure 4.2: Pick-up truck , with sub-frame and swop body

from the vehicle were used to calculate the loads of the dynamic analysis. The purpose of the dynamic analysis was to obtain the optimum rubber stiffness that is needed to isolate the swap-body from the chassis. The stiffness of the rubber should, however, not cause the swap-body to resonate. This was also addressed with the dynamic analysis. Recommendations were subsequently made regarding the rubber stiffness. The final part of the exercise was to verify the fatigue life expectancy of the pick-up truck's chassis. This was done by taking similar analysis measurements of a fully configured vehicle. The measurements were processed and fatigue calculations carried out. The result of these calculations was another quasi-static load that is applied to the chassis and the sub-frame. The results of these analyses are then evaluated using the European structural fatigue code [15].

4.4 Suspension bracket of a large passenger bus

This case-study deals with the design verification of the suspension bracket implemented on the tag axle of a large passenger bus. The suspension bracket previously used by the manufacturer experienced failures after a relatively short life in the field. The finite element analysis was used to determine displacements and stress levels based on given static forces determined by force and strain measurements. The static load on the FE model is calculated as follows:

- The force versus time data is subjected to a 'rain-flow' [1] [15] counting method. The result of this analysis will be used to calculate the respective damages to each measurement file.
- The accumulated damages for the test period can be computed, using Miner's law of linear damage accumulation [1]. The accumulated damage is used to compute a force (repeated 2×10^6 times) that is equivalent to the dynamic input to the structure.
- The equivalent static force is applied to the finite element model. The stresses are then evaluated according to the ECCS code for the fatigue design of steel structures [15]. The finite element analysis' stress results will be compared to the fatigue strength curves in the ECCS code to determine the fatigue life.

4.5 Suspension bracket of a 4x4 pick-up truck

This case-study investigated a shock absorber bracket that experienced failures on the vehicle manufacturer's durability track. The purpose of the case-study was to determine the cause of the cracking failure of the bracket after 35 000 km on the durability track and to propose a modified design. The project consisted

Figure 4.3: 4x4 pick-up truck

of an instrumentation and measurement phase, a data analysis phase, a finite element analysis phase and a fatigue assessment phase (refer to figure 4.3).

4.6 Closure

All of the case-studies were subjected to the same methodology formulated in the previous chapter. The following chapter will deal with the first phase of the Fatigue Equivalent Static Load method, namely the measurement phase.

Chapter 5

DETERMINATION OF INPUT LOADING

5.1 Scope

This chapter deals with the measurements of the various case-studies. The measurement of the loads that a vehicle will experience is an integral part of the design/assessment procedure. It is essential to determine the loads that the respective structures would have to endure throughout the course of their life-times. The measurement of loads is often neglected due to the uniqueness and the difficulty in obtaining the loads, especially during the design or assessment of fatigue loaded vehicle structures.

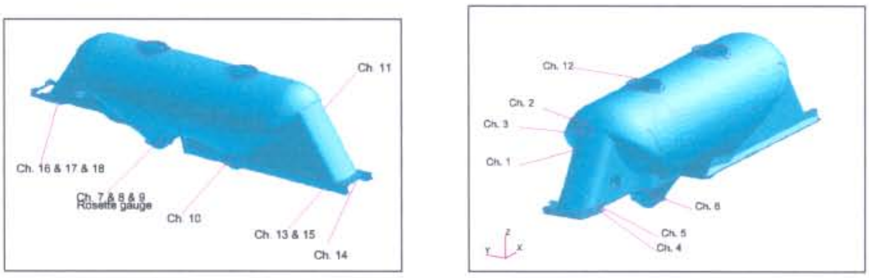


Figure 5.1: Bulk tanker: measurement positions

Figure 5.2: Bulk tanker: spreading operation, Heidelberg, Gauteng

5.2 Aluminum Dry-bulk Tanker

The aim of this measurement exercise was to determine the stresses/strains that the vehicle structure experiences during its life-time. These measurements, in conjunction with a finite element model, can then be used to determine a fatigue equivalent static load. This load can further assist in the optimal design of the vehicle structure.

5.2.1 Instrumentation

The tanker was instrumented using eighteen channels. Twelve of the channels were dedicated to strain gauge measurements and the remaining six channels used to measure the six degrees of freedom with the use of accelerometers (refer to table 5.1). Also refer to figure 5.1. The channels were digitally recorded with three *Spiders*[1] on a portable laptop computer.

[1]Spiders are electronic equipment specifically designed for multi-channel measurements

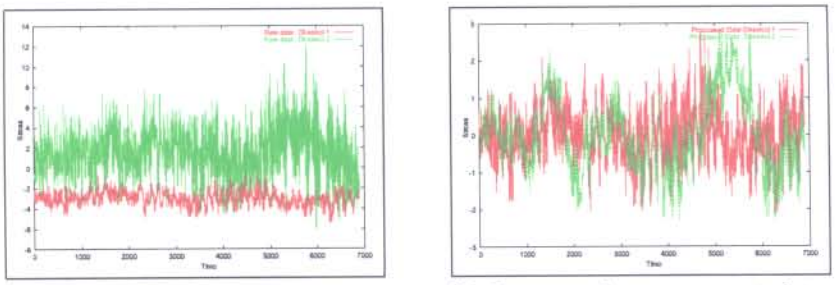
Table 5.1: Instrumentation detail - dry bulk tanker

Chan	Channel name	Description/position
1	Front boom	600mm from top of boom (vertical)
2	Front boom weld	300mm from centre, near top weld
3	Front dish weld	500mm from centre, dish to shell weld
4	Compressor mount	On compressor beam (on top-flange)
5	5th Wheel box member	Centre of pocket of rear cross-member
6	Side-plate bend front	10mm from both weld edges (vertical)
7	Rosette vertical	600mm from centreline of cone
8	Rosette 45 degrees	as above mentioned
9	Rosette horizontal	as above mentioned
10	Outer cone rear	630mm from centreline (vertical)
11	Rear boom centre	830mm from bottom of chassis
12	Top shell front	400mm from centre of top shell

5.2.2 Measurement trip

The opportunity arose to measure strains during a trip from Brakpan to a mine near Tzaneen. The trip encompassed various road conditions. The measurements started at Alpha Cement's depot at Brakpan, followed by secondary roads and highways enroute Pretoria. The N3 highway from Pretoria to Pietersburg was a relatively smooth stretch. From Pietersburg to Tzaneen, the tanker experienced various degrees of road surfaces. The Duiwelskloof pass with its steep decent, potholes and road improvement surface, proved to be a worthwhile candidate for the measurement exercise. A typical secondary road was measured from Tzaneen to the turn-off at the Marinda mine. The road to the Marinda mine was found to be an especially rough gravel road. Additional maneuvering at the mining complex was also measured.

Two days after the first measuring exercise, the tanker's performance was measured during a spreading operation. The measurements again started at Alpha Cement's depot in Brakpan. Secondary and highway surfaces were measured on the way to a building site near Heidelberg. Measurements encompassed a gravel road, maneuvering at the site, as well as the spreading operation (refer to figure 5.2).



(a) Raw measurement data (b) Proccessed measurement data

Figure 5.3: Measurement data

5.2.3 Measurement Data

During the two measurement exercises, a total of 114 usable files were recorded. The sampling frequency of the measurements was 300Hz. A few files exhibited spikes (extremely large peaks of stresses). These large peak stresses occurred randomly in some of the measurement files. The spikes also occurred randomly at the different channels. If a large force is applied to the structure, the strain gauges in the vicinity will experience deformations. The random occurence of very high stresses at different strain gauges, at different time intervals, indicated that these data is not because of input loads, but of measurement equipment defects. The integrity of all the files was assured with a *Matlab* program that removed all these spikes. The files also exhibited some drift over a period of time (a common occurence while measurements are taken over a long period of time, [4]). These drift tendencies were also removed with a *Matlab* program. Refer to figure 5.3(b) and 5.3(a) to view the raw and processed data.

5.2.4 Summary

The measurement exercises supplied the data to be processed in conjunction with the finite element model. The data will then be used to calculate a fatigue equivalent static load, as described in Chapter 6.

5.3 Sub-frame of a pick-up truck

The pick-up truck measurement was done in two phases. The initial measurements were taken on a vehicle with a prototype swap-body assembly. These measurements were mainly used for a dynamic analysis. The second measurement exercise, using the correct configuration, was used to calculate the fatigue damage.

5.3.1 Phase 1 measurements: prototype vehicle

The vehicle with the mock-up configuration was instrumented with strain gauges, a displacement transducer and accelerometers to obtain the input loading from the road surface. Figure 5.4 indicates a typical measurement position. The following sections were measured at Gerotek:

- Suspension track, driven at a speed of $10km/h$.
- Suspension track, driven at a speed of $20km/h$.
- Sinus, in-phase track.
- Sinus, out-of-phase track.
- Circular track, clockwise at $30km/h$.
- Gravel track.

The measurements were taken at a $400Hz$ frequency.

5.3.2 Phase 2 measurements: final vehicle

Measurements were taken on a vehicle with the correct configuration. The aim of the measurement exercise was to determine a fatigue equivalent static load that can be applied on the static finite element model. These measurements can also be used to calculate the fatigue life of the area where the half bridge strain gauges were applied. Two measurement exercises were performed on

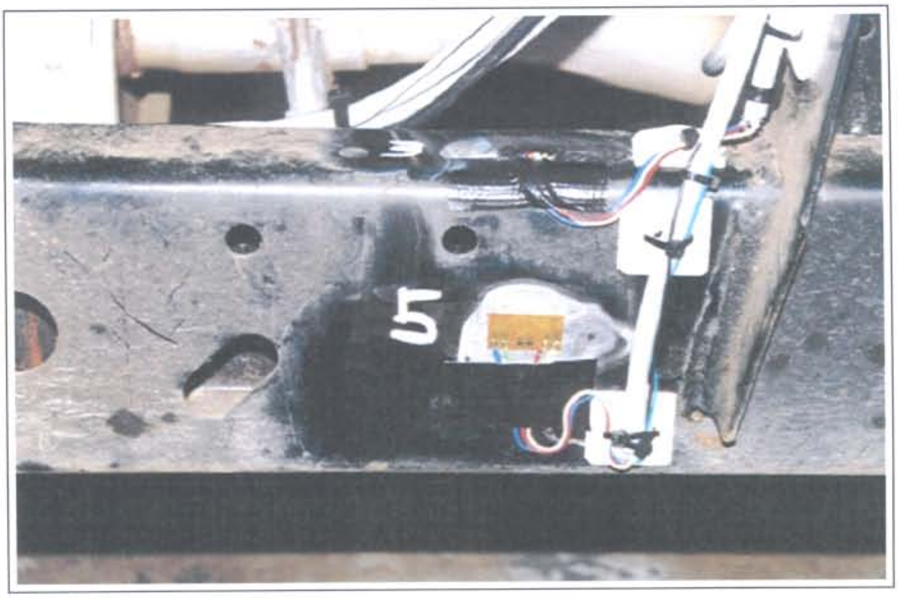


Figure 5.4: Strain gauge measurement equipment

the new vehicle. The first measurement was done on a vehicle with temporary rubbers at the sub-frame connection. The correct swap-body and sub-frame was, however, installed on the vehicle. The second measurement exercise was performed on a vehicle with the correct rubber mounts, as well as a new leaf-spring configuration. The *first* measurement exercise included the following surface sections:

- Gravel
- Secondary tar
- Highway

The *second* measurement exercise consisted of a fully loaded vehicle travelling only on gravel and secondary tar. These measurements can be combined to create a user profile of what the vehicle would endure during its lifetime. Figure 5.5 displays the strain gauge measurements taken on the gravel track.

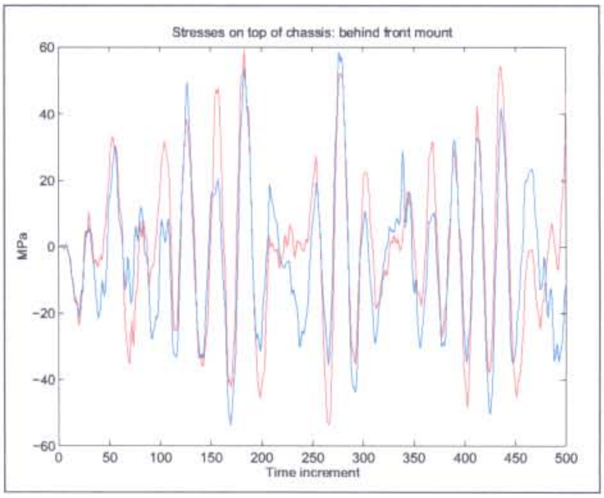


Figure 5.5: Strain gauge measurements - sub-frame

5.3.3 Summary

The measurement exercises provided the data needed for the calculation of the fatigue load to which the vehicle would be subjected. The following chapter will indicate how the measurement data were processed into useful fatigue information.

5.4 Suspension bracket of a large passenger bus

Measurements were performed on the bus in question. The tag axle was instrumented on both sides. Due to the shock absorber manufacturer's reluctance to provide the shock absorber characteristics, the left-hand shock absorber was instrumented on the shaft. This was necessary to measure the force exerted by the shock absorber on the suspension bracket. Measurements were taken on three different road surfaces: highway, secondary tar and gravel. The measurements were also conducted with a fully laden vehicle as well as an empty vehicle. The results of these different measurements were later used in the

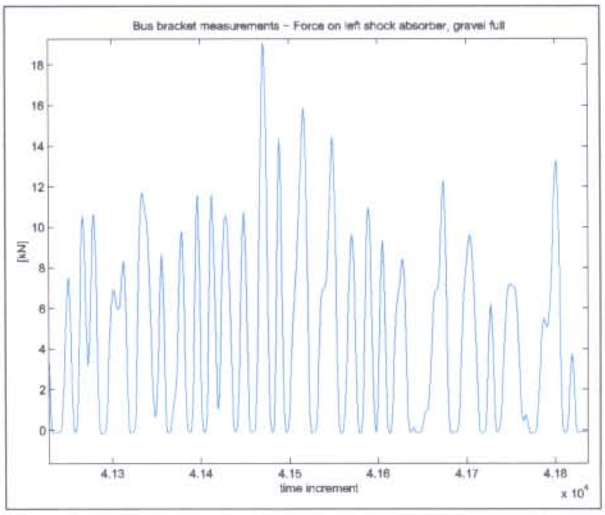


Figure 5.6: Measurement data - Bus bracket

fatigue analysis to create a combined road usage profile. Refer to figure 5.6.

5.5 Suspension bracket of a 4x4 pick-up truck

The client required that the component must be able to withstand a predetermined life-time on a durability track. The input forces of the shock absorber, as well as strains at two locations on the component, were measured.

Table 5.2: Measurement Channels - 4x4 pick-up suspension bracket

Chan.	Description/position	Purpose of measurement
1	Left wheel front shock absorber bracket strain gauge	Reference for FEA, at assumed crack initiation position
2	Left wheel front shock absorber bracket strain gauge	Reference for FEA
3	Left wheel front shock absorber displacement metre	Vertical relative velocity of shock absorber to calculate force on bracket

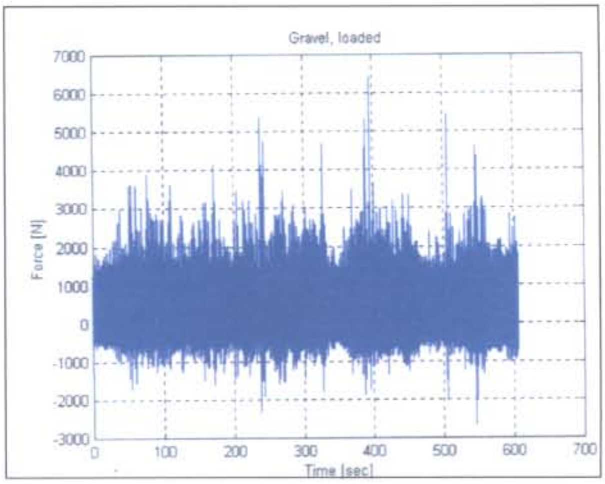


Figure 5.7: Input load measurements - 4x4 pick-up

5.5.1 Measurements

Table 5.2 lists the measurement channels that were applied. Figure 7.7 also shows the position of the cracking experienced during the durability testing. The measurements were successfully completed on representative sections of a durability route. This included empty and loaded measurements on the logs and track sections, as well as sections of the tarred and gravel roads on the route.

5.5.2 Calibration and Data Processing

The sampling frequency was $150Hz$. The measured displacement was calibrated ($1Volt = 180mm$) and then digitally differentiated to obtain velocity versus time data. This data was converted to force versus time data, using the characteristics of the shock absorber listed in Table 5.3. The force results for the loaded condition on the logs, track, gravel and tarred sections are depicted in Figure 5.7

The strain gauge data was converted to stresses, assuming linear elastic behaviour. The stresses were found to be small, implying that the crack does

Table 5.3: Shock absorber characteristics - 4x4 pick-up truck

Extension or Compression [m/s]	**Tensile Force [N]**	**Compressive Force [N]**
0.1	1330	410
0.3	1990	725
0.6	3040	1150
1.0	4550	1800

not initiate on the edge of the bracket. The measured force versus time histories were subsequently calibrated using the finite element model (refer to equation (5.1)) The measured data now consists of stress versus time data.

$$S_{cal} = \left(\frac{S_{FEA}}{F_{FEA}}\right)_{cal} \times F_{meas} \tag{5.1}$$

where :

S_{cal} = calibrated stresses

S_{FEA} = calculated FEA stress

F_{FEA} = applied FEA force

F_{meas} = measured forces

5.5.3 Summary

The input loading of the shock absorber was determined for various loading conditions experienced on the durability route. The input load data was converted to measured stress data, using finite element calibration, and can now be used in the fatigue processing as described in the next chapter.

5.6 Closure

This chapter dealt with the measurement process of obtaining the fatigue loads to which the vehicle structures were subjected to. The various case studies illustrate a few different methods of obtaining these loads. The following chapter will discuss the fatigue calculations performed for the case-studies.