4. MEASUREMENTS, SURVEYS AND SIMULATION

4.1 SCOPE

Input loading may typically only be derived from one or a combination of the following sources:

- Measurements
- Surveys
- Simulation
- Field failures

The first three of these sources are dealt with in this chapter in terms of the case studies, the last one being a derivative of verification of failure predictions with field failures and therefore dealt with in Chapter 6.

4.2 MEASUREMENTS

4.2.1 General

The most important source for deriving input loading must be measurements. Measurements can only be performed if vehicles are available, albeit prototypes or similar models. This would mostly be the case. Measurements were performed for all the case studies and are presented in the context of each case study.

4.2.2 Methodology

It is important to note that measurements, especially using strain gauges, are commonly and mostly mistakenly, regarded as exercises to quantify stresses. Strain gauge measurements are not very effective for such a purpose, due to two reasons:

- Strain gauges are placed at specific positions and can only measure where they were placed. To know where to measure is often not possible without finite element analysis.
- In terms of fatigue, the critical stress areas mostly exhibit high stress gradients. Placing strain gauges to accurately measure these gradients is mostly not practical.

It is therefore argued in the present study, that strain gauge measurements are purposed to quantify input loading and not stresses. Such loading is then used as inputs to finite element analyses (then only quantifying the stresses) or testing.

With the above in mind, the general measurements methodology involves the following basic steps:

- Planning: Measurements are a means to an end and careful consideration must be given to the end usage of the results. All possible input loads to the structure must be identified and decisions to leave some out must be well founded. Additional strain gauges, sensitive to such loads, would typically be placed to verify such assumptions.
- Configuration: Transducers must be placed at positions that will be sensitive to the inputs to be quantified. Preferably, each transducer should be sensitive to only one input, but normally cross coupling will be unavoidable. There will be a minimum of as many transducers as inputs to be measured, but it is good practice to have a few

redundant channels. Strain gauges should be positioned in areas of nominal (preferably uni-axial) stresses.

- Instrumentation: Details of the instrumentation must be well documented, including accurate positions, signs, gauge factors, calibrations, etc. Where possible, known loads must be used to record the calibration values with the same settings as used during the measurements. This must be done before and after the measurements, since adjustment of gains to avoid overloading, is often required during the measurements. Zero readings should be taken before and after the measurements and the zero conditions should be documented. A trial run, with inspection of the data, is good practice, to ensure optimum gain settings.
- Measurements: Measurements must be performed during representative operational conditions. Sampling rates must be chosen to ensure capturing of significant data. Typical fatigue causing frequencies from road inputs are between 0 Hz and 20 Hz. Sampling rates of 200 Hz would mostly ensure reliable data in the frequency band of interest. Possible resonant effects may require higher sampling rates.

4.2.3 Minibus

4.2.3.1 Instrumentation

A minibus vehicle was instrumented (refer to paragraph 2.2.1). The vehicle was of a model that has been on the market for several years and it was its replacement that prompted the project. During the life of the existing model, fatigue failures have occurred on chassis crossmembers. It was intended to use these failures to calibrate the mission profile results. Strain gauges measuring shear strains were applied to each torsion bar forming part of the front suspension. These measured signals are directly proportional to the relative displacement between the front wheels and the chassis, as well as therefore to the vertical spring loads induced by the front wheels on the suspension and through the suspension to the chassis. It was argued that these measurements would then be directly related to the major portion of the damage induced on the chassis and suspension components. For the failed crossmember this certainly would be the case, since only the torsion bar loads are reacted there. The shock absorber forces, which would be proportional to the derivative of the relative displacement (velocity), are reacted on a bracket to the front of the chassis.

It was subsequently demonstrated that relative damages calculated using the relative velocities were similar to those calculated using relative displacements. This may be explained by the fact that the damage calculated from the displacements underestimates the higher frequency content, but overestimates the lower frequency content, compared to the damage calculated from the velocity. Possibly more important is the fact that the damages were used in a relative sense (damage of one type of road divided by the damage of another), negating to some extent absolute errors.

A transducer was installed on one front wheel to measure the revolutions of the wheel. This signal was used to measure the distance travelled during the measurements.

The signals were amplified with a carrier wave amplifier and then stored on a magnetic tape recorder. After the measurements, the data was read into a computer at a sampling rate of 128 Hz. At the time, the capacity of the equipment available forced a compromise on the sampling frequency used.

The measurements were performed on different category roads typically used by taxis, as well as on the manufacturers vehicle test track.

4.2.4 Pick-up Truck

4.2.4.1 Instrumentation

The placement of the measuring positions on the vehicle was planned so as to include all major suspension, chassis and body structure elements. The aim was to have the transducers so placed as to collect the vehicle's measured response to the following fundamental types of input loading:

- Vertical wheel inputs
- Lateral wheel inputs
- Longitudinal wheel inputs
- Global twisting inputs
- Body vibrations

The following reasoning was applied. From experience it is known that the damaging inputs into the suspension and chassis of the vehicle can be characterised by measuring positions on the suspension components which are respectively sensitive to the vertical, longitudinal and lateral wheel forces. The twisting inputs induced into the vehicle have been collected by placement of a transducer on one of the chassis cross members. In order to characterise the relative independent body vibrations, transducers were placed at the left top door corner and the left rear panel of the load box. Table 4-1 lists the positions of the various measuring points.

Table 4-1 Pick-up truck measurement configuration

Channel number	Position	Transducer type
1	Left front wheel acceleration – vertical	Accelerometer – 30g
2	Right front wheel acceleration – vertical	Accelerometer – 30g
3	Right rear wheel acceleration – vertical	Accelerometer – 15g
4	Left rear wheel acceleration – vertical	Accelerometer – 15g
5	Left front coil spring	Strain gauge
6	Right front coil spring	Strain gauge
7	Right rear differential	Strain gauge
8	Left rear differential	Strain gauge
9	Left front strut	Strain gauge
10	Right front beam outside	Strain gauge
11	Left beam centre between wheels	Strain gauge
12	Round cross member	Strain gauge
13	Left top door corner	Strain gauge
14	Loadbox left rear panel	Strain gauge

The signals were amplified with a carrier wave amplifier and then stored on a magnetic tape recorder. After the measurements, the data was read into a computer at a sampling rate of 200 Hz.

4.2.4.2 Measurements

The measurements were performed on a wide range of typical road types across the country. Recordings were done for the laden and unladen conditions.

During the measurements, each section of road selected to be sampled was subjectively assigned to one of the same categories used for the questionnaires. Customer road (usage profile) measurements were performed throughout South Africa to ensure the inclusion of a wide range of roads that might be used by pick-up truck owners. The roads were divided according to their characteristics into the following categories:

- Rural good tar roads
- Rural bad tar roads
- Urban tar roads
- Mountainous and winding tar roads
- Rural good gravel roads
- Rural bad gravel roads

The suspension track at the Gerotek vehicle test facility near Pretoria was also measured with the purpose of obtaining sequences that might be used for the accelerated road simulator test.

4.2.5 Fuel Tanker

4.2.5.1 Instrumentation

After completion of the first prototype vehicle of the new design, comprehensive measurements were performed. Strain gauges and accelerometers were used.

The placement of transducers was divided into three categories:

- Transducers were placed to obtain fundamental kinematics and load inputs into the structure to be used as inputs to a dynamic finite element analysis. The finite element analysis will yield dynamic stress results to be processed to obtain fatigue life estimates for all critical areas of the structural design.
- Transducers were placed in known critical areas to measure stresses, which could be used as reference and verification for the finite element analysis. For this purpose, strain gauges were placed to measure nominal stresses in as many areas required to reasonably characterise the stress response of the structure. Fatigue life estimates are also obtained directly from these transducers for all the areas identified as critical after the static finite element analysis
- Gauges were placed in critical areas where the design for future vehicles has been changed, or manufacturability problems have been experienced during the construction of the prototype unit. The data from this third category was used directly, or indirectly, together with finite element analysis, to obtain fatigue life estimates.

4.2.5.2 Measurements

The measurements included a typical 300 kilometre trip with a liquid load, as well as a return empty trip.

4.2.6 ISO Tank Container

4.2.6.1 General

During this case study, a much more involved measurement exercise was performed compared to the other case studies. As introduced in Chapter 2, the objective was to establish the operational loading conditions for ISO tank containers. These containers are employed on road, rail and sea and travel (without drivers) all over the world. Special equipment, trade named 'XLG 2000 Data Logger', was developed for this purpose. A South African electronic firm, Datawave, was commissioned for this development.

4.2.6.2 Transducers

Transducers were specially chosen such that container design independent loads could be quantified, as well as verification of the processing algorithms could be achieved.

4.2.6.2.1 Accelerometers

For the former purpose, eight accelerometers were placed on the structure (seven at corner castings, implying reasonable independence of the specific tank container design) and one on the vessel itself. The positions and directions of measurements of the accelerometers are depicted in Figure 4-1.

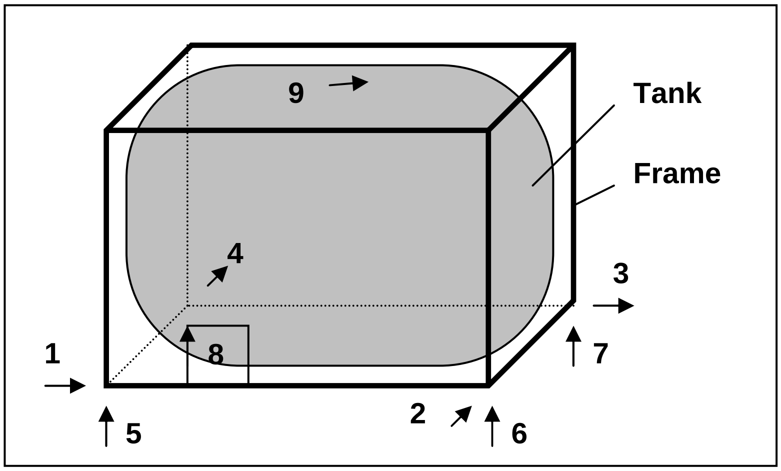

Figure 4-1 ISO tank container measurement configuration

- Channels 1 and 3 : Longitudinal accelerations at the corner castings.
- Channels 2 and 4 : Lateral accelerations at the corner castings.
- Channels 5 to 8 : Vertical accelerations at the corner castings.
- Channel 9 : Longitudinal accelerations recorded on the tank.

From this configuration of the accelerometers it is possible to determine the 6 rigid body modes of the frame, as well as the twisting movement:

- Vertical translation : (ch5 + ch6 + ch7 + ch8)/4
- Longitudinal translation : (ch1 + ch3)/2
- Lateral translation : (ch2 + ch4)/2
- Pitch : (ch5 + ch8 – ch6 – ch7)/2/length of tank

- Roll : (ch5 + ch6 – ch7 – ch8)/2/width of tank
- Yaw : (ch2 – ch4)/length of tank
- Twist : (ch5 – ch8) – (ch6 – ch7)

It is evident that there was one redundant accelerometer on the frame. This was a safety precaution in case of malfunctions. The accelerometer on the tank itself (channel 9) was used as a reference.

4.2.6.2.2 Strain gauges

The strain gauges were placed at the areas sensitive to vertical, longitudinal and lateral loading independently (not peak stress areas). From this data fatigue life predictions could be made for the specific tank design, which could then be compared to the calculated predictions of a finite element model, using the loads derived from the accelerometer data, for verification purposes.

4.2.6.3 Data recording domains

The datalogger records measured data in three different domains. The reason for this was that it would be impractical to store unprocessed data. The special data reduction algorithms that were part of the datalogger intelligence made it possible to store what would have been 460 GByte of data during a typical 6 week trip using only 3 MByte.

The datalogger stores one hour of continuously sampled data, which it then swaps into a buffer space for processing, whilst sampling the next hour. The data is then processed and stored in three domains (refer to Figure 4-2).

A: The overloads are short time events (approximately 2 seconds long) which incorporate high peaks (e.g. railway shunting or handling at the depots). The data logger is able to identify these overloads and stores it in memory with a capacity for 256 events. Each time a smaller event in the memory is overwritten with a larger one. The data is sampled with a sampling frequency of 602 Hz.

B: Data containing an hour’s acceleration information is transformed to the frequency domain. The transformed data represents the statistics for the recorded hour. The memory is able to collect 1016 of these data files, with a sampling frequency of 301 Hz. From this data time domain data could be recreated, losing only the transient events.

C: Cycle and strain range counted information from the data measured by the strain gauges, is saved in the form of rainflow matrices. As mentioned before, this data is used to verify the fatigue calculations from the frequency domain data.

4.2.6.4 Data assembly and storage

Data was extracted by computer at certain depots after completion of typically 6 week trips. The data was sent via e-mail to the University of Pretoria, where the data was stored. After extraction, the dataloggers were reset, to commence a new set of measurements. Problems were encountered where the loggers were not reset, so that the data sent from the next depot, under a new name, was the same as the previous set. The files were named so as to link them to a specific tank, as well as the route followed.

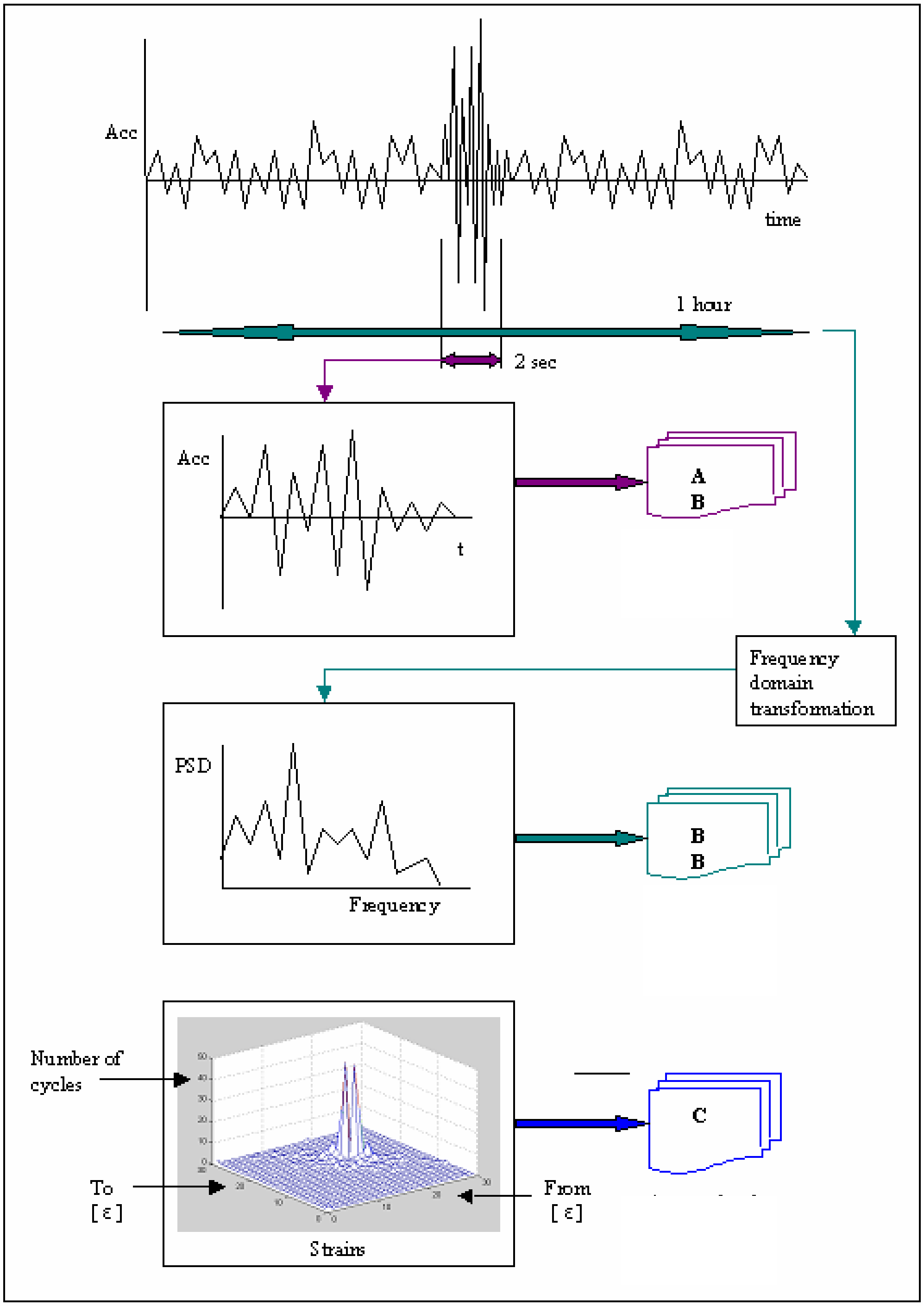

Figure 4-2 Data recording domains of datalogger

4.2.6.5 Datalogger

The components of the specially developed datalogger are diagrammatically depicted in Figure 4-3.

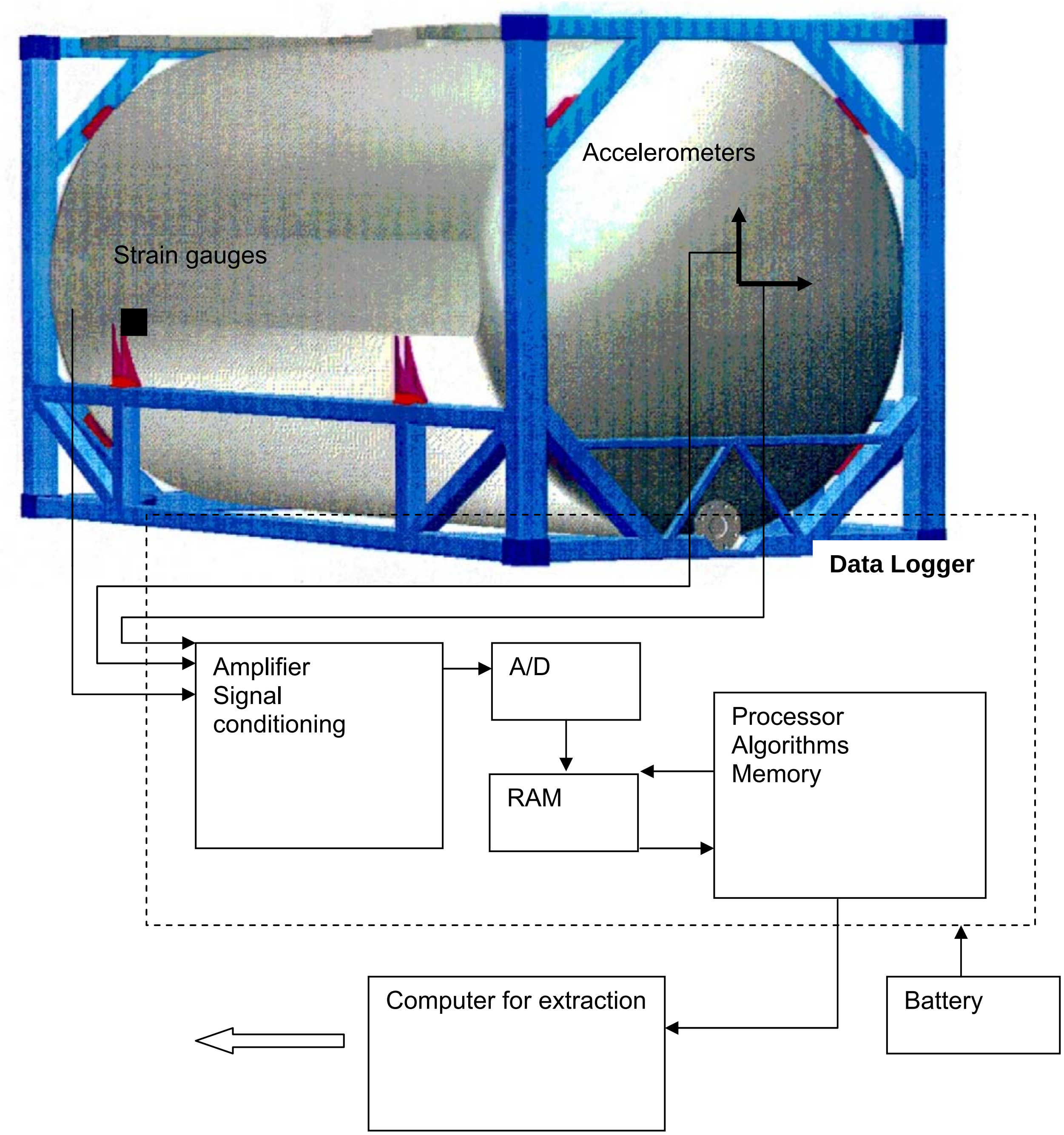

Figure 4-3 Components of datalogger

4.2.6.6 Routes and cargo

The establishment of the routes of the tank containers during measurement periods was of importance to be able to link events to certain conditions. Route logging data from the operators was available for this purpose, being coupled to the dates stored with the data on the datalogger. Problems were experienced with the dates from both the datalogger and the operator information, which made some sets of data unusable. The operator data also did not include sufficient detail (only the point and time of departure and the point and time of arrival were available) to be able to know for certain which modes of transport were involved during the trip. Some intended linking was therefore not achievable.

Also of importance was to know whether the tank was full or empty for each hour of data sampled in the frequency and time domains (an acceleration multiplied with the gross mass gives a much higher load than when multiplied with the tare mass). The uncertainty concerning the events during a trip, made it impossible to determine this from the operator data. Special techniques had to be developed to determine from the frequency contents of the data (when full the frequencies tend to shift lower on the accelerometer placed on the tank), whether the tank was full or empty.

4.2.7 Load Haul Dumper

4.2.7.1 Instrumentation

The vehicle was instrumented with eleven strain gauges, two displacement transducers and two accelerometers. The two accelerometers were positioned on the axles of the vehicle and measured the vertical acceleration. The two displacement transducers were used to measure the displacement of the dumping and tilting hydraulic cylinders, but were damaged during the measurement by the low roof. The main purpose of the displacement transducers was to give an indication whether the bucket is up or down, and tilted or not. Fortunately a real-time camera was mounted on the vehicle, which took a photo every three seconds for the full duration of the measurement. The position and orientation of the bucket can be determined from these photographs.

The strain gauge positions are depicted in Figure 4-4 to Figure 4-7. Channels 7 and 8 were located on the widest section of the boom, about 25 mm from the bottom edge of the plate. These two channels measured stresses parallel to the bottom edge of the plate.

Channel 6 was located on the front chassis 100 mm below the top edge of the side plate, coincident with the front axle centre line. The gauge measured stresses in the horizontal direction. Channels 4 and 5 were located 105 mm below the bottom edge of the top plate on the rear chassis, also coincident with the axle centre line.

Channels 1, 2 and 3 were located on the articulation joint. Channels 2 and 3 were located on the bottom hinge plate on the front chassis, coincident with the centre line of the joint. Channel 2 was on the top side and channel 3 on the bottom side of the plate. Channel 1 was located on the bottom side of the lower plate of the top hinge of the articulation joint on the rear chassis, also coincident with the centre line of the joint.

Channels 9 and 10 were mounted on the canopy roof, with channel 10 measuring plate bending stresses in the centre of the roof, and channel 9 measuring stresses on the edge of the roof plate.

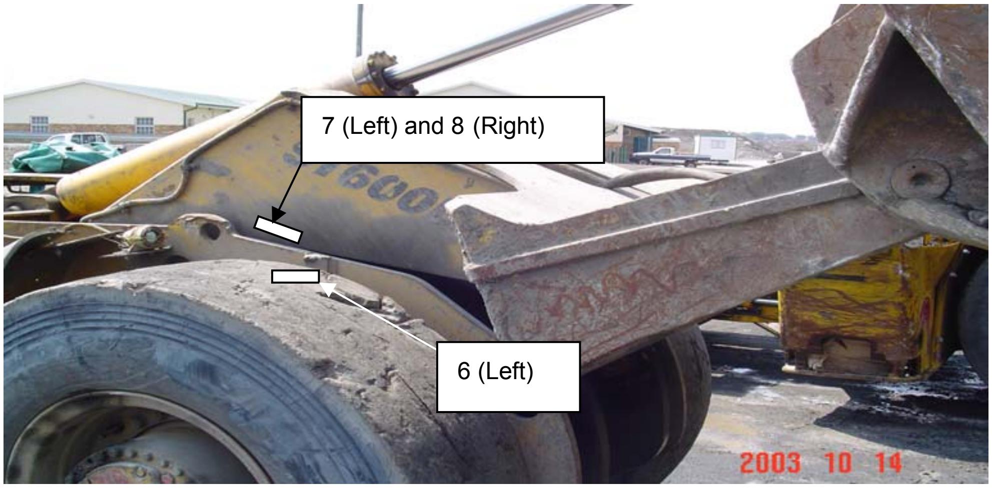

Figure 4-4 Channels 6, 7 and 8

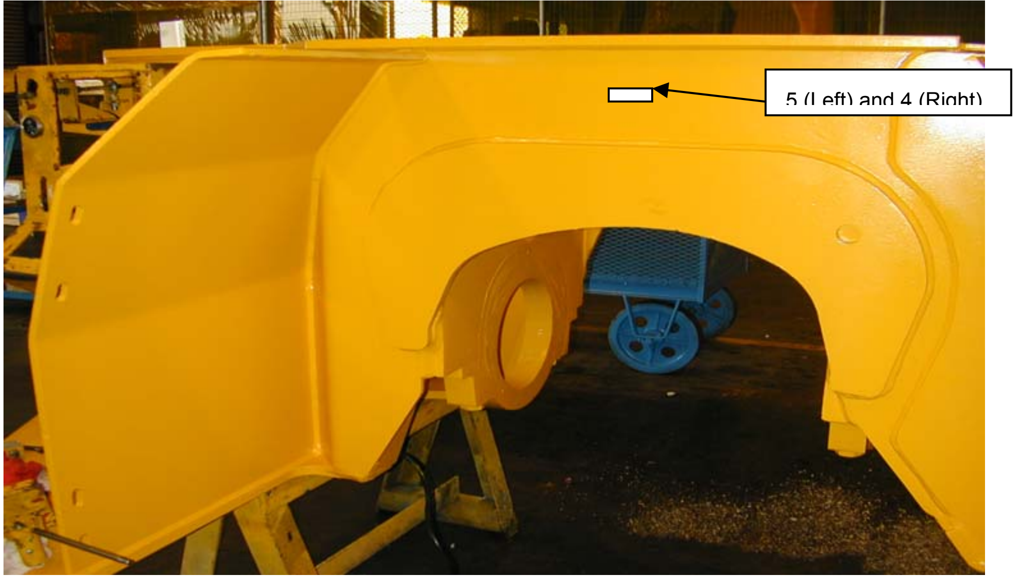

Figure 4-5 Channels 4 and 5

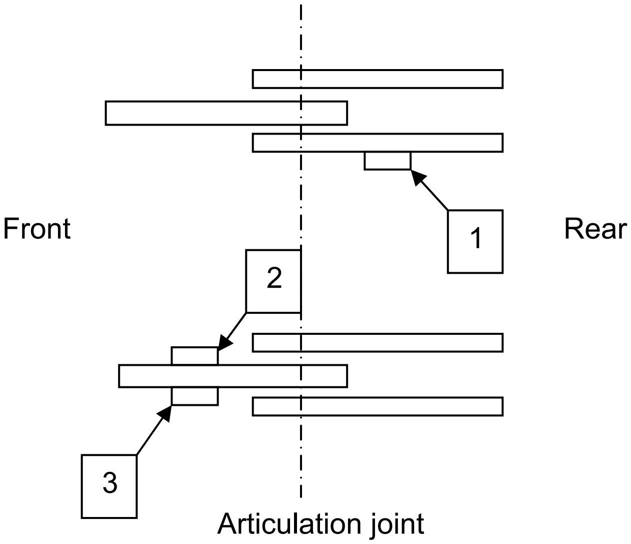

Figure 4-6 Channels 1, 2 and 3

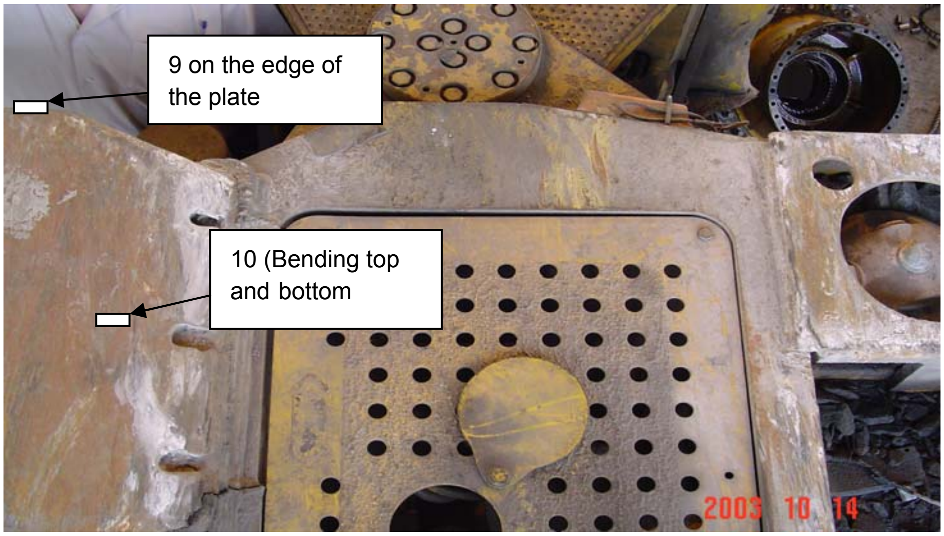

Figure 4-7 Channels 9 and 10

4.2.7.2 *Measurements*

The measurements were performed at the Waterval platinum mine near Rustenburg. The vehicle was underground for an hour and a half, and data was recorded for the full duration. The vehicle was operated by a regular LHD operator, performing typical tasks. The data was recorded with a SOMAT field computer at a sample rate of 200 Hz.

4.2.8 Ladle Transport Vehicle

4.2.8.1 *Instrumentation*

The configuration for the LTV measurements is detailed in Table 4-2.

Table 4-2 LTV measurement configuration

Channel No.	Position
1	Lid arm, above tower pivot, left side.
2	Lid arm, above tower pivot, right side.
3	Chassis, above bogie, left side.
4	Chassis, above bogie, right side.
5	Crank, above the main shaft, left side.
6	Crank, above the main shaft, right side.
7	Tower cross member quarter point, left side.
8	Tower cross member quarter point, right side.
9	90° element of critical gauge.
10	45° element of critical gauge.
11	0° element of critical gauge.

The data was recorded on an HBM Spider sampling at 200 Hz, and then downloaded onto a laptop computer.

4.2.8.2 Measurements

Measurements were performed with the vehicle operating typically in the Aluminium Smelter Plant. The events that occurred during the measurement exercise are described below.

Two trips were recorded for the LTV on two routes and stored separately. The events which occurred are shown in the tables below.

Table 4-3 Route 1 events

Event #	Description
1	Start vehicle.
2	Force cranks down to ensure that the bed is properly lowered.
3	Travel empty to fetch full ladle test weight.
4	Pick up full ladle test weight.
5	Travel forward and backwards.
6	Put down full ladle test weight.
7	Travel empty to weigh bridge to fetch empty ladle.
8	Pick up empty ladle #20.
9	Travel along route C2.
10	Put down empty ladle
11	Waiting for full ladle.
12	Picked up full ladle #25.
13	Travel to weigh bridge.
14	Put down full ladle
15	Travel empty approximately 40m forward to park and download data.

Table 4-4 Route 2 events

Event #	Description
1	Start vehicle.
2	Travel empty to weigh bridge to fetch empty ladle.
3	Pick up empty ladle #45.
4	Travel along route C1.
5	Put down empty ladle
6	Used the LTV to nudge the ladle and stand into the correct position and waited for full ladle.
7	Picked up full ladle #7.
8	Travel to weigh bridge.
9	Put down full ladle.
10	Travel empty to the mobile workshop.

4.3 SURVEYS

4.3.1 General

As discussed in paragraph 3.5.2, the influence of driver behaviour, driving patterns and road profile usage on the structural input loading of a vehicle is of importance. Often the only way to quantify these parameters is through user surveys. In this section, two user surveys, performed for the light commercial vehicles, are discussed.

4.3.2 Methodology

Thorough planning of user surveys is of utmost importance. The type of technical information required, makes it difficult to formulate the questions such that non-technical persons would be able to provide reliable answers. As an example, a question concerning the percentage distance of usage travelled on bad gravel roads, which has a significant influence on fatigue calculations, may attract biased answers for two reasons. Firstly, non-technical, or even technical persons will often over estimate this percentage, firstly due to the fact that such travelling makes a much larger impression on them than their every day travelling to work and back (being uncomfortable and typically during a special outing), and secondly, answering the question accurately in terms of distance instead of duration (travelling on bad gravel roads would typically be at very slow speed), is difficult. Care should therefore be taken to add redundant questions, so as to verify possible inaccurate answering.

A questionnaire exercise is best performed by professional companies which have access to manufacturer’s sales databases. The optimal method is person-to-person surveys, which, for practical reasons, are normally conducted by phone. According to the market research company employed during the minibus case study, the return rate is typically less than 10 % for questionnaires sent out by post.

4.3.3 Minibus

4.3.3.1 Questionnaire exercise

A questionnaire was compiled, in collaboration with the Centre For Proactive Marketing Research, which was filled in by a number of taxi operators. The following information contained in the questionnaire was used for statistical processing:

- Percentage of total distance travelled on the following roads:
    Highway
    Central town
    Suburban
    Country
    Smooth gravel
    Rough gravel
    Very rough gravel

- Average distance travelled per day

The questionnaire was filled in by 122 minibus taxi operators of all different makes and models operating in different regions in the country.

4.3.4 Pick-up Truck

4.3.4.1 Questionnaire exercise

A questionnaire was compiled, in collaboration with the Centre For Proactive Marketing Research, which was completed by 170 pick-up truck owners. The following information contained in the questionnaire was used for the statistical processing (differing somewhat from the definitions used during the minibus project due to lessons learned):

- Percentage of distance travelled on the following roads:
  Rural good tar roads
  Rural bad tar roads
  Urban tar roads
  Mountainous and winding tar roads
  Rural good gravel roads
  Rural bad gravel roads

- Average distance travelled per month

Data concerning different cargo loads and travelling speeds was also obtained and utilised in the fatigue processing of the measured data.

4.4 SIMULATION

4.4.1 General

In instances where a prototype vehicle, or a similar model do not exist, inputs can be derived through computer simulation. A multi-body dynamic model of the vehicle, including the suspended inertia, the springs and dampers and unsprung masses of the suspension systems and wheels, as well as sometimes, global stiffness characteristics of the vehicle structure, is excited by known terrain profiles, to produce time domain solutions of suspension forces that may then be used as inputs for finite element analyses.

Dynamic simulation also may be used as part of the establishment of maximum loads and static equivalent fatigue loads to avoid the demands of dynamic finite element analyses.

4.4.2 ISO Tank Container

Accelerations were measured on the corner castings of a tank container during normal operation. These inputs were transformed to six rigid base degrees of freedom. A finite element analysis of the container structure was used to derive the three translational and three rotational stiffnesses affecting the motion of the centre of gravity of the container relative to the input base motion. A dynamic simulation, described in paragraph 5.2.2.1.2 was performed, to solve for the six fundamental input loads on the tank.

4.5 CLOSURE

In this chapter, the methods to determine input loading were described for the various case studies. These inputs can then be used to derive design and testing requirements, which is the subject of the next chapter.