1. INTRODUCTION

The engineering discipline of structural mechanics comprises specialist fields such as structural dynamics, strength of materials, finite element methods, fatigue, durability testing and fracture mechanics. In basic terms, each of these subjects is based on mathematical models used to simulate the behaviour of structures in terms of outputs such as deflections, stresses, vibration and various failure mechanisms. All structural mechanics models may be written in the following form:

$$[\text{Deflection, stress, strain, stress intensity, etc.}] = f(\text{Geometry, material properties, loading})$$

The sophistication of these mathematical models range from being based on fundamental principles such as equilibrium and compatibility, to power law curve fitting on regions of empirical data. Sufficiently accurate models are however available for most practical cases.

In a study into the sources of inaccuracies in fracture mechanics calculations, Broek (1985) shows that inherent mathematical modelling inexactness is mostly orders of magnitude less contributing than erroneous input data. Svensson (1997), states that variations caused by, for instance, different wind loads, roads or drivers, can be of considerable importance for the prediction uncertainty of fatigue calculations. Dressler and Kottgen (1999) state that in industries that cannot closely control the usage of their products by their customers, such as the ground vehicle industries, loading and its variation due to different customer usage profiles is the most important variable in fatigue – more important than the usual scatter of material properties. Socie and Pompetzki (2004) state that it is much more difficult to assess the variability in service loading than in the material properties. Similar comments are made by Rhaman (1997), concerning finite element calculations. It may therefore be argued that defective structural designs, excluding failures caused by manufacturing defects, are mostly caused by insufficient knowledge of input data.

Of the input data required, geometry is usually well-defined. In some cases, notably with fatigue crack initiation and propagation analysis, the accuracy of material properties presents difficulties. In the vast majority of practical applications, however, the major concern involves the determination of input loading. Quantification of the structural loading associated with earthquakes and wind forces for buildings, wave forces for offshore platforms and ships, aerodynamic forces during aircraft manoeuvres and digging forces for earthmoving equipment, could be cited as examples.

Similarly, loads associated with automotive and transport (trucks, trailers, containers, trains) structures are nontrivial to quantify. Such loads arise from stochastic and ill-defined processes such as driver/operator actions and structure-terrain interaction.

The present study deals with practical methods for the establishment of input loading for automotive and transport structures through measurements and other methods and its application to structural design, finite element analysis and testing, with the purpose of assessing fatigue durability. It is attempted to also formulate a generalised unified methodology, generalising and unifying the new techniques and existing methods into a cohesive methodology.

The fundamental processes involved with the determination of input loading are measurements, surveys, simulation, estimation and calculation from field failures. These processes result in design criteria, code requirements and/or testing requirements. A number of complex case studies are presented to develop and illustrate the concepts. These case studies involve light commercial vehicles, road tankers, industrial vehicles, as well as ISO tank containers.

The structure of the thesis is based on the above logic. In Chapter 2, the case studies are defined. Chapter 3 deals with the current theory and practice of structural analysis and testing, as well as input loading determination. In Chapter 4, measurement, surveying and simulation methods, developed by the author and applied to the case studies, are presented. In Chapter 5 these results are processed to establish design and testing requirements. Chapter 6 serves the dual purpose of presenting a method for derivation of a usage profile based field failure data, as well as substantiation and correlation of the previous results, using field failure data. In Chapter 7, the processes and techniques presented in the study are formalised and final conclusions are drawn in Chapter 8.

The principal objectives and hypotheses of the study may be summarised as follows:

- It is argued that the formalised determination of input loading is not given its deserved prominence in the research of design and testing technology of automotive and transport structures.
- It is assumed that the fatigue failure mechanism is the major cause of failures of automotive and transport structures.
- It is suggested that accurate prediction of field failures is possible, using well established analysis and testing methods, if input loading is scientifically determined.
- It is proposed that the usefulness of input loading determination methods would be greatly enhanced in industry if it results in quasi-static, inertial loading, since thereby it would be design independent and would avoid the need for expensive dynamic analyses.
- While it is supposed that in most cases, uni-axial, road induced, vertical loading, dealt with in a quasi-static, deterministic manner, would be the predominant load case causing fatigue in automotive and transport structures, it is endeavoured to also address multi-axial loads, modal responses, as well as the stochastic nature of input loading.

2. DEFINITION OF CASE STUDIES

2.1 SCOPE

In this chapter the various case studies dealt with during this study, are defined in terms of problem definitions and basic methodologies.

2.2 LIGHT COMMERCIAL VEHICLES

2.2.1 Minibus

The case study is also described by Wannenburg (1993).

2.2.1.1 Problem definition

Durability qualification testing of new motor vehicle models involves the (usually accelerated) simulation of normal operational conditions on test routes, test tracks, or in the structural testing laboratory. In most cases however, the definition of normal operational conditions presents a major challenge. Often this definition is achieved rather unscientifically, based on decades of experience with similar models. Ideally, an optimal durability test requirement should be set such that an optimum balance is achieved between the costs of testing and development, and the cost of having failures occur in service (due to warranty claims, loss of market confidence, etc.). For safety critical components, the cost of testing and development is not a driver, but the imperative of defining operational conditions accurately is as apparent.

For this case study, a scientific methodology is presented, based on a probabilistic approach, which aims to define operational conditions in a statistical manner in terms of fatigue damage. The results thus obtained empower manufacturers to scientifically establish optimal durability requirements.

The development of the methodology that will be presented has been based on a rather unique problematic situation facing manufacturers of 12 - 16 seat minibus vehicles for the Southern African market. In this region, where third-world rural areas and first-world cities are situated close together, minibus vehicles are largely employed as taxis in an extensive transportation industry to transport commuters of the rural areas to and from the cities. This industry is very competitive and speed and number of passengers carried on each trip are survival issues. This often leads to serious overloading of the vehicles, which are then driven at high speeds on overworked secondary tar and dirt roads.

Since these extreme conditions have not been included in the original usage profiles by the developers of the vehicles, it is often necessary to adapt the vehicle designs for this market. Adapted designs require qualification through testing and there was therefore a need to establish optimal durability requirements for these vehicles.

2.2.1.2 Methodology

The process comprised five phases:

- Measurements were performed on typical routes across the country used by taxis. A typical minibus vehicle was instrumented with strain gauges for this purpose. A durability test track was also measured.

- Fatigue calculations were performed on the measured signals to obtain relative damage caused by each category of road.
- The data obtained from a questionnaire survey filled in by taxi operators was used to determine relative damage per kilometre induced on the vehicles by each participant by multiplying the percentages driven on each category road with the damage/km for each category road obtained from the fatigue calculations. Probability density functions were fitted to this data as well as to the data concerning the distance travelled per day by each participant, which could then be used to derive durability requirements in terms of years without failure or distance without failure. Verification of these results was achieved by using the results to obtain a theoretical prediction of the failures that had occurred in practice on a specific chassis crossmember and comparing this to the actual failure data.
- The first step of the verification was to perform laboratory tests on the component, by simulating an appropriate sequence of the durability track in a test rig until failure occurred to determine the relative damage to failure.
- Based on the test results as well as data of sales of vehicle type in question, the theoretical distributions obtained from the measurements, fatigue calculations and questionnaires, were used to predict the failures of the component in practice. These predicted results were then compared to actual failure results. Based on this comparison the theoretical distributions were adjusted to achieve close correspondence between theory and practice.

2.2.2 Pick-up Truck

The pick-up truck case study is also described by Van Rensburg and Wannenburg (1996).

2.2.3 Problem definition

The need was identified to qualify a 1 tonne pick-up truck for South African conditions. It was proposed to perform a road simulator durability test and in parallel perform an exercise to establish the usage profile with respect to structural fatigue inputs for South African road conditions. The purpose of the latter was to be able to establish the severity of testing in terms of customer road usage unique to South African conditions.

It was agreed that the road simulator test would be continued until the equivalent of a set target distance of road usage for a set percentile customer, had been simulated. Failures experienced during this test were then to be evaluated in terms of failure rate predictions that may be experienced by the customer fleet, based on the established statistical usage profile.

This case study report deals with the details and results of the testing and the usage profile establishment, as well as the failure rate prediction.

2.2.3.1 Methodology

The project comprised seven phases:

- Measurements were performed on typical roads across the country used by these vehicles. A vehicle was instrumented with accelerometers and strain gauges for this purpose.
- Measurements were also performed on a vehicle test track with a fully laden and unladen vehicle.

- Fatigue calculations were performed on the measured strain data as well as the test rig response strain data to obtain a relative damage per km per channel for all types of road and test sections.
- The data obtained from a questionnaire completed by pick-up truck owners was used to determine relative damage per kilometre induced on the vehicles by each participant by multiplying the percentages driven on each category road with the damage/km for each category road obtained from the fatigue calculations.
- An accelerated laboratory durability fatigue test was conducted on the vehicle.
- The data contained in the questionnaires was used to determine the usage profile of the vehicles.
- The usage profile distributions were then used to quantify failures experienced on the test rig in terms of usage profile distances.
- Using the established usage profiles, as well as other input data such as sales history, failure rate predictions for critical components that had failed during the test, were performed, using a statistical simulation model. The results of this simulation essentially are to be used for decision making with respect to the structural integrity of the vehicle.

2.3 FUEL TANKER

2.3.1 Problem definition

A new dual purpose, aluminium road tanker was developed (See Figure 2-1). The trailers are designed with flat decks to facilitate the transport of dry load cargo. This enables the operator to transport liquid loads in one direction (e.g. in South Africa from the coastal oil refineries to Gauteng) and general freight on the decks during the return trip. The profitability of the vehicle is greatly improved.

The design presented challenges in terms of the box shaped design of the tanks, requiring significant internal reinforcing, the use of aluminium in combination with the drive towards a lightweight design, implying concerns in terms of fatigue durability, as well as the uniqueness of the application, presenting the problem of determining the loading conditions.

2.3.2 Methodology

The durability assessment comprised the following steps:

- Finite element assisted design according to available design code prescribed loads.
- Building of prototype vehicle.
- Strain gauge measurements on prototype vehicle for typical operational cycles.
- Establishment of design criteria for fatigue loading.
- Redesign and extensive fatigue assessment using finite element and measurement results.

Figure 2-1 Fuel tanker

2.4 ISO TANK CONTAINER

2.4.1 Problem Definition

Tank containers transport bulk products (mostly liquid and often dangerous) by ship, rail and truck. The container structures are subjected to exceptionally harsh dynamical loading conditions such as impact loading in train shunting yards, abusive handling by cranes and forklifts in depot yards, dynamic loading in storms when stacked 8 high in ship holds and fatigue loads induced by rough roads.

Figure 2-2 ISO tank container

Design loads for ISO tank containers are prescribed by codes such as ISO 1496-3:1991(E). Such loads are static and attempt to account for dynamic and fatigue effects through safety factors. Field failures, often resulting from abusive loading events, but sometimes resulting from normal fatigue loading, have been experienced by all manufacturers on designs that have passed the ISO static loading and impact tests. This prompted detailed finite element analyses to solve such problems, which showed up structural weaknesses, mostly in terms of fatigue, which did not show during ISO testing.

The knowledge gained through such exercises was used by manufacturers to design new models. Detailed finite element analysis methods were used during these design efforts, using ISO loads as inputs, as well as measured impact loading, but still without quantitive knowledge of normal fatigue loading.

In order to further reduce possible risks associated with the new designs, consideration was given to perform structural dynamic testing, especially to determine the fatigue durability of the designs. It was however argued that to be able to perform fatigue life estimates through finite element analysis, or through testing, both require prescribed loading magnitudes and number of cycles (performing tests with guessed loads would not be sensible). This argument prompted the project. The purpose of the project was thus to determine from extensive measurements, the characteristics of normal, abnormal and abusive loads on tank containers.

2.4.2 Methodology

- A specialised instrument (datalogger) was developed, which was fitted to a number of tanks that were sent into operation.
- A number of tank containers was instrumented with strain gauges and accelerometers and continuous measurements over long periods of time were accumulated and sent via the internet to a data collection facility.
- Special algorithms were developed and implemented to derive from the data new design and testing criteria for tank containers.
- The results thus obtained were unique in the industry (from the point of view of comprehensiveness) and would facilitate both safer, as well as more optimised (lower tare) designs.

2.5 INDUSTRIAL VEHICLES

2.5.1 Load Haul Dumper

2.5.1.1 Problem definition

Load Haul Dumpers (LHD) (refer to Figure 2-3), are employed in underground mines to load blasted rock at the stope face and transport it to tipping stations, from where the product is transported via conveyors. Such vehicles operate in the harshest of road conditions and this, coupled to high dynamic loads induced during loading and dumping, imply fatigue problems. The need for structural design criteria for such vehicles arises from the production requirement for reliable vehicles with predictable lives.

2.5.1.2 Methodology

- Finite element models of two different LHDs, operating in different mines, were generated, and used to determine suitable positions where strain gauges could be located to measure the input load responses.
- The vehicles were instrumented with strain gauges, and the strains during the typical operational cycles of the vehicles were recorded.
- The results of these measurements were used to calculate static equivalent fatigue loads, which in turn could be introduced into the finite element model to perform fatigue life predictions on the total vehicle structure.
- Due to the fact that significant fatigue failures have been experienced on one of the vehicle types, it was also possible to verify the methodology, by comparing the predicted failures with actual failures.

Figure 2-3 Load Haul Dumper (LHD)

2.5.2 Ladle Transport Vehicle

2.5.2.1 Problem definition

A newly designed Ladle Transport Vehicle (LTV) is to be put into operation in an Aluminium Smelter plant. The vehicle has an articulated arrangement, with the trailer having a U-shaped chassis and lifting bed, which allows the vehicle to reverse into a ladle mounted on a pallet. The filled ladle may then be lifted and locked for transport. In the tilting version of the design, the ladle can be tilted at the off-loading station. The lifting bed is lifted vertically, guided by vertical pillars and when reaching the top, commences tilting (refer to Figure 2-4). The case study presented here deals with the non-tilting version of the design.

The objective of the project was to determine input loads during typical operation, to allow a fatigue durability assessment of the vehicle structures to be performed.

2.5.2.2 Methodology

A finite element model of the LTV structure was generated and used to determine suitable positions where strain gauges could be located to measure the input load responses.

- A vehicle was instrumented with strain gauges and the strains during the typical operational cycles of the vehicles were recorded.
- The results of these measurements were used to calculate static equivalent fatigue loads, which in turn could be introduced into the finite element model to perform fatigue life predictions on the total vehicle structure.
- From the results of the measurements, it was realised that account would also have to be taken of higher order mode shapes.

Figure 2-4 Ladle Transport Vehicle (LTV)

2.6 CLOSURE

The case studies defined in this chapter are each dealt with in detail in the following chapters. The presentation logic emphasises a structured treatment of the techniques developed and employed for the establishment of input loading for vehicular structures, which implies the fragmentation of the case study arrangement in the different chapters. The processes followed for each case study are shown as part of the generalised methodology in diagrams presented in Chapter 7.