

## 7. FORMALISATION

### 7.1 SCOPE

The methods dealt with in Chapters 4 to 6 have been presented (and developed) according to the specifics of the various case studies. In the present Chapter, these methods are generalised, as well as unified, into a cohesive methodology.

### 7.2 GENERALISED UNIFIED METHODOLOGY

#### 7.2.1 General

Figure 7-1 depicts the components of a combined flow diagram for the establishment of input loading for vehicle and transport structures, incorporating all the techniques developed during this study.

The diagram is divided by the bold dashed lines into three regions, namely, the essential data sources (measurements, surveys, simulation, failure data, sales data), the analysis and testing exercises (fatigue processing, statistical calculations, Monte Carlo simulation, durability testing, finite element analysis), as well as the results (maximum loading, fatigue design requirements, durability testing requirements). The above logic is similar to the logic adopted for the structure of this thesis.

The flow of the diagram commences at the red decision block. The two additional decision blocks are yellow and green, the former representing the important decision of how to utilise measurement data and the latter representing the comparison between predicted failures and failure data.

In the following paragraphs, each component in the diagram, as well as the diagram logic, are described.

#### 7.2.2 Commencement of Input Loading Establishment (Red Decision Block)

The availability of data sources drives the decisions made at the commencement of input loading establishment. If no prototype or similar vehicle (such as a previous model) exists, the only choice would be to perform a dynamic simulation. Such a case study has not been dealt with, but a typical example would be a new special purpose vehicle.

If a prototype or similar vehicle exists and no failure data exist for the structure or similar structures, measurements should be performed. Survey data is required if it is not possible to measure either a representative usage cycle, as was done for the road tankers and industrial vehicles, or to perform comprehensive measurements, as was done for the tank container.

#### 7.2.3 Measurement Profile

The measurement profile relates to the transducer configuration, as well as the operational cycles, events, terrain categories, etc. to be measured.

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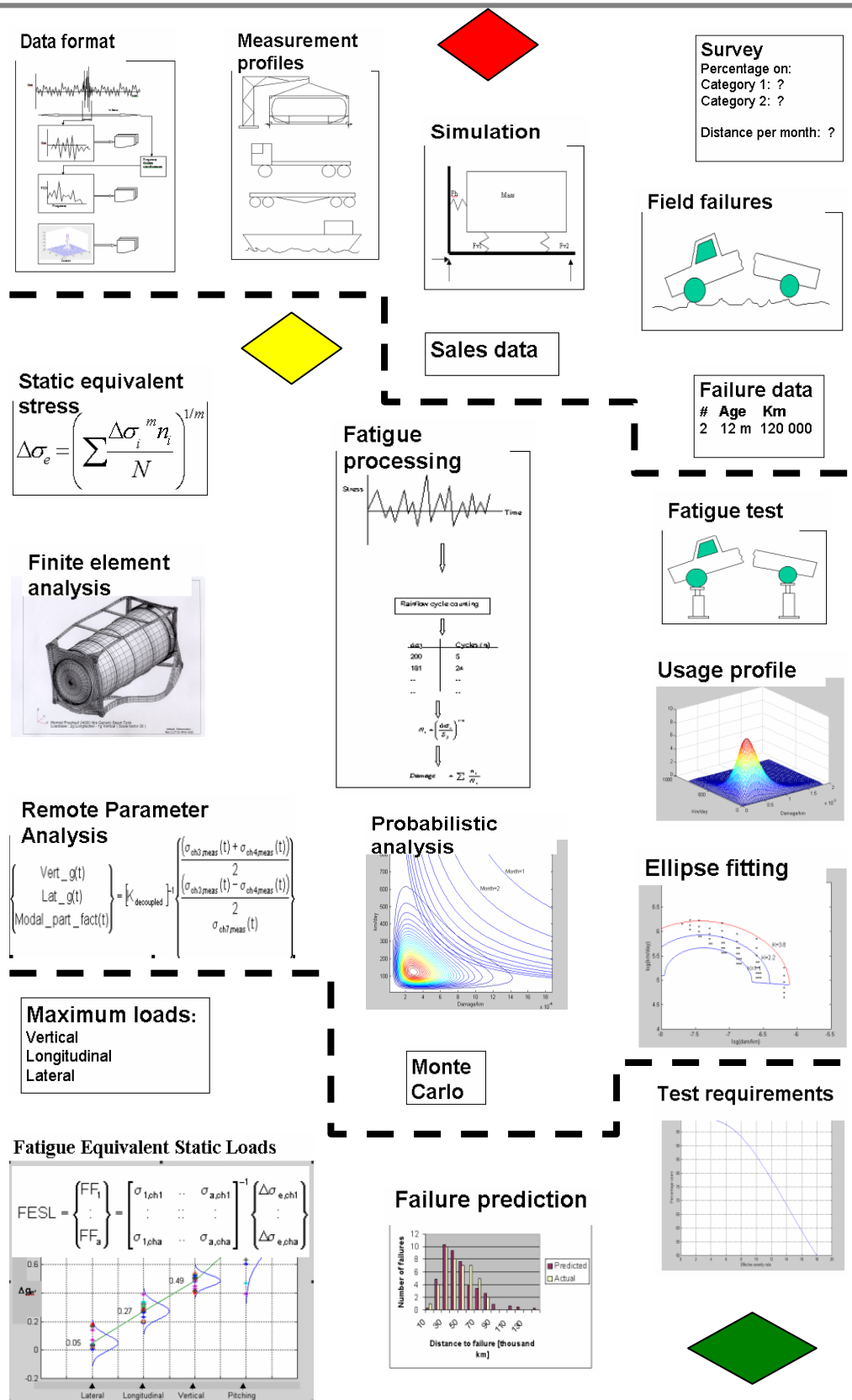


Figure 7-1 Components of generalised process

### **7.2.3.1 Transducer configuration**

As discussed in paragraph 4.2.5.1, the transducers should be grouped into three categories, namely:

- Transducers (strain gauges and accelerometers) should be placed to be able to deduce the fundamental load inputs to the vehicle structure. This would typically entail instrumenting the suspension components (e.g. strain gauges on an axle could be used to measure vertical and longitudinal wheel loads), the kingpin area (in the case of road tankers, to measure the loads transferred through the hitch), as well as accelerometers to measure the six rigid body degrees of freedom accelerations of the total structure. Calibration of loads from the measured strains may involve isolated finite element models or laboratory calibration. The loads measured are used as direct inputs for static or dynamic finite element analyses, or as control channels for load reconstruction laboratory testing. When inputs are required for dynamic finite element analyses, the choice of analysis method would decide which transducers are required, as discussed in paragraph 3.2.3.7.
- Strain gauges should be placed in 'clean' stress areas to measure nominal stresses sensitive to global bending, tensile and shear stressing due to vertical, longitudinal and lateral, mainly inertial, loading. Accelerated test track, or road testing, is performed using these channels for severity ratio calculation. Such results are also very valuable in combination with finite element analyses, enabling the derivation of fatigue equivalent static loading. Strain gauges to measure nominal bending stresses on the chassis beams of a vehicle structure, is an example of this category. These gauges are placed away from stress concentration areas to ensure that slight misplacement of the gauge does not influence the results. Strategically placed gauges may be used in combination with finite element analysis, to obtain stress vs time histories at critical positions in the vicinity of the gauges, for fatigue life calculation.
- The third category involves placing strain gauges in known high stress areas, where the results can directly be used to calculate fatigue damage. Placement of such gauges and correct interpretation of the results are involved exercises. Fatigue design codes generally require nominal stress histories, where the stress concentration caused by the weld detail, hole, etc., are already taken into account by the SN – curve.

### **7.2.3.2 Operational cycle**

An exercise based on a measured representative usage cycle, will only be valid in cases where the mission profile of the vehicle is well defined. In the case of the road tankers, it was argued that the measured trips would be representative of what the vehicles will be subjected to during their operational lifetimes. Formally, that assumption is rather unscientific, since it is based on a subjective choice of the measured trip. Such an assumption would be more valid in the cases of the industrial vehicles, where the only missions of the trucks are to carry loads on a reasonably static route.

In the case where comprehensive measurements are performed, as with the commercial vehicles case studies, the tacit assumption is made that all loading conditions are captured by the measurements. Again, fundamentally, such an assumption cannot be correct, since there will always remain a probability for more severe loading to occur. The uncertainty could be allowed for using an appropriate safety factor on the resulting loading requirements, but even then, the safety factor should be determined based on statistical processing of the measurement data.

### **7.2.3.3 Events**

In some cases, specific events may contribute significantly to the usage profile in terms of fatigue damage. Examples of this may be shunting of tank containers, or driving over a curb for vehicles. Measurements of such events should be performed as separate exercises and the damage contributions added to the stochastic data on the basis of estimated occurrences during a lifetime.

### **7.2.3.4 Terrain categories**

The IRI method, discussed in paragraph 3.5.5, provides the best scientific basis for defining terrain categories.

### **7.2.3.5 Driver influence**

Driver influence may be taken into account by using a representative profile of drivers during measurements.

## **7.2.4 Data Format**

### **7.2.4.1 Time domain**

Data recorded in the time domain allows editing and therefore the best integrity, but, in the case of comprehensive measurements such as was performed on the tank containers, may not be possible due to storage space restrictions. A combination of short duration events stored in the time domain, together with frequency domain and/or fatigue domain storage, is then recommended.

### **7.2.4.2 Frequency domain**

Storing data in the frequency domain allows reconstruction of time domain signals, but transient events would be lost.

### **7.2.4.3 Fatigue domain**

Data processing from fatigue domain data is discussed in paragraph 5.4.5. Reconstruction to time domain data is possible to some extent, as discussed in paragraph 3.4.3.2.

## **7.2.5 Simulation**

Multi-body dynamic simulation techniques to derive input data are discussed in paragraph 3.3. When measured data is not available, synthetic road profile data can be employed to derive dynamic loads for input into a fatigue assessment. Dynamic simulation may also be employed to derive dynamic loads when measured accelerations are available.

## **7.2.6 Survey**

Survey methodologies are dealt with in paragraph 4.2.7. Care should be taken in the design of the questionnaire, such that redundant questions are built in to allow cross checking. Typically 1% of the total population may be sufficient to obtain representative data, but then care must be taken to obtain an unbiased sample. The terrain categories discussed in paragraph 3.5.5 should be used.

### **7.2.7 Field Failures**

A powerful methodology to derive usage profiles from field failures is presented in paragraph 6.4. When field failure data is available, it should always be used to verify the testing or analysis results. Baseline tests, to reproduce field failures, should always be performed before qualification testing of a new or improved design. If this is done, the time-to-failure can very accurately be determined as the ratio between the times-to-failure of qualification test and the baseline test, multiplied by the time-to-field-failure. The complex, non-experimental processes used to arrive at fatigue life predictions can also be deterministically adjusted or calibrated using field failure information.

### **7.2.8 Ellipse Fitting**

The proposed curve fitting procedure, forming part of the methodology to derive usage profiles from field failure data, is described in paragraph 6.4.

### **7.2.9 Sales Data**

Sales data is required as input to failure rate predictions, as performed for the minibus.

### **7.2.10 Fatigue Processing**

The stress life approach, detailed in paragraph 3.4.2.1, is in most cases adequate to perform fatigue processing of measured data. Calculations can mostly be performed in the relative sense, where only the gradient on the SN-curve would have an influence. A gradient of  $-0.25$  (for parent metal failures) or  $-0.33$  (for weld failures) would typically be used. When input loading has been established and fatigue life predictions are performed, appropriate SN-curves need to be used, available from design codes.

The statement concerning the use of stress-life specifically refers to fatigue processing as opposed to fatigue life prediction, which implies mostly calculations in the relative sense, which is then only dependent on the fatigue exponent. Such relative calculations are not practical to be performed using strain-life methods, since then all four material properties would have an influence on the results and therefore it is common practice to use stress-life methods for such calculations.

For predicting fatigue life, strain-life methods would most commonly be used in the automotive environment, except for spot welds. The substantial additional complexity is mostly hidden from the analyst, since computer programs are used. It is however not very certain whether a substantial benefit is derived from using the more complex method in cases of high cycle fatigue. Berger et al. (2002) discuss a comparative study on 6 different steels, for 144 different cases. It was found that the nominal-stress approach gives a slightly more accurate prediction of fatigue life than the local-strain method. It is proposed that the reason for this may be that the latter is more susceptible to erroneous estimations of input data.

For heavy vehicles, fatigue problems are mostly associated with welding, implying the use of the stress-life method for life prediction.

### **7.2.11 Hybrid Remote Parameter Analysis / Modal Superposition Method**

Figure 3-18 was compiled in Chapter 3 to summarise the different existing fatigue assessment methods based on measurements and finite element analyses. During the ladle transport vehicle case study (paragraph 5.3) a hybrid method was developed, combining the remote parameter analysis and modal superposition methods. This

process is depicted by the thickened black arrows on Figure 7-2. *Unit loads* are used in a *static finite element analysis* to provide, together with the results of an *eigenvalue finite element analysis*, the elements for a *strain gauge / load transfer matrix*, as well as a *critical position / load transfer matrix*. The former is used to convert the *measured stresses*,  $\sigma(t)$ , to loads (including modal participation factors) in the time domain. The loads are inputs into the latter matrix, resulting in stresses in the time domain, which then are used for *fatigue analysis*.

The method allows for taking into account excited modes, requiring only dynamic finite element analysis to solve for the relevant mode shapes. The method, however, does not result in design independent design loads, which could be published in design codes. A method, incorporating the benefits of the hybrid remote parameter / modal superposition method, but resulting in design independent design loads, is proposed in the next paragraph.

### 7.2.12 Fatigue Equivalent Static Loading

The fatigue equivalent static loading method is described in paragraph 5.3. The method avoids the need for dynamic finite element analyses and results in design independent loads.

The process is depicted on the summary diagram in Figure 7-3, using thickened black arrows. *Measured stresses*,  $\sigma(t)$ , are cycle counted, using the *Rainflow counting* technique. The results are used to calculate *equivalent stress ranges* for each strain gauge position. *Unit loads* are used in a *static finite element analysis* to provide the elements for a *strain gauge / load transfer matrix*. This matrix is used to convert the equivalent stresses to equivalent load ranges. The loads are inputs into a *static finite element analysis*, resulting in equivalent stress ranges, which then are used for life prediction using the *stress-life* (or *strain-life*) method.

The method can be used for multi-axial loading (not to be confused with multi-axial fatigue), but may result in inaccuracies due to the loss of phase information. If care is taken concerning the direction of loads and the choice of measurement channels, conservative assessments can however be achieved.

The important assumption made for the FESL methodology to be valid, is that stresses due to dynamic vertical loading at all positions in the structure would have the same relative ratios to each other, as would be the case with a static finite element analysis with a simple vertical inertial loading. Under vertical dynamic loading, a vehicle structure would typically be excited in its first global bending mode of vibration, which would yield stress responses similar to a static inertial load response. Higher bending modes, twisting modes and local structural modes could however also be excited, which may cause high stresses in different areas. Resulting fatigue problems would then be due to resonance and would not necessarily be identified from a static analysis.

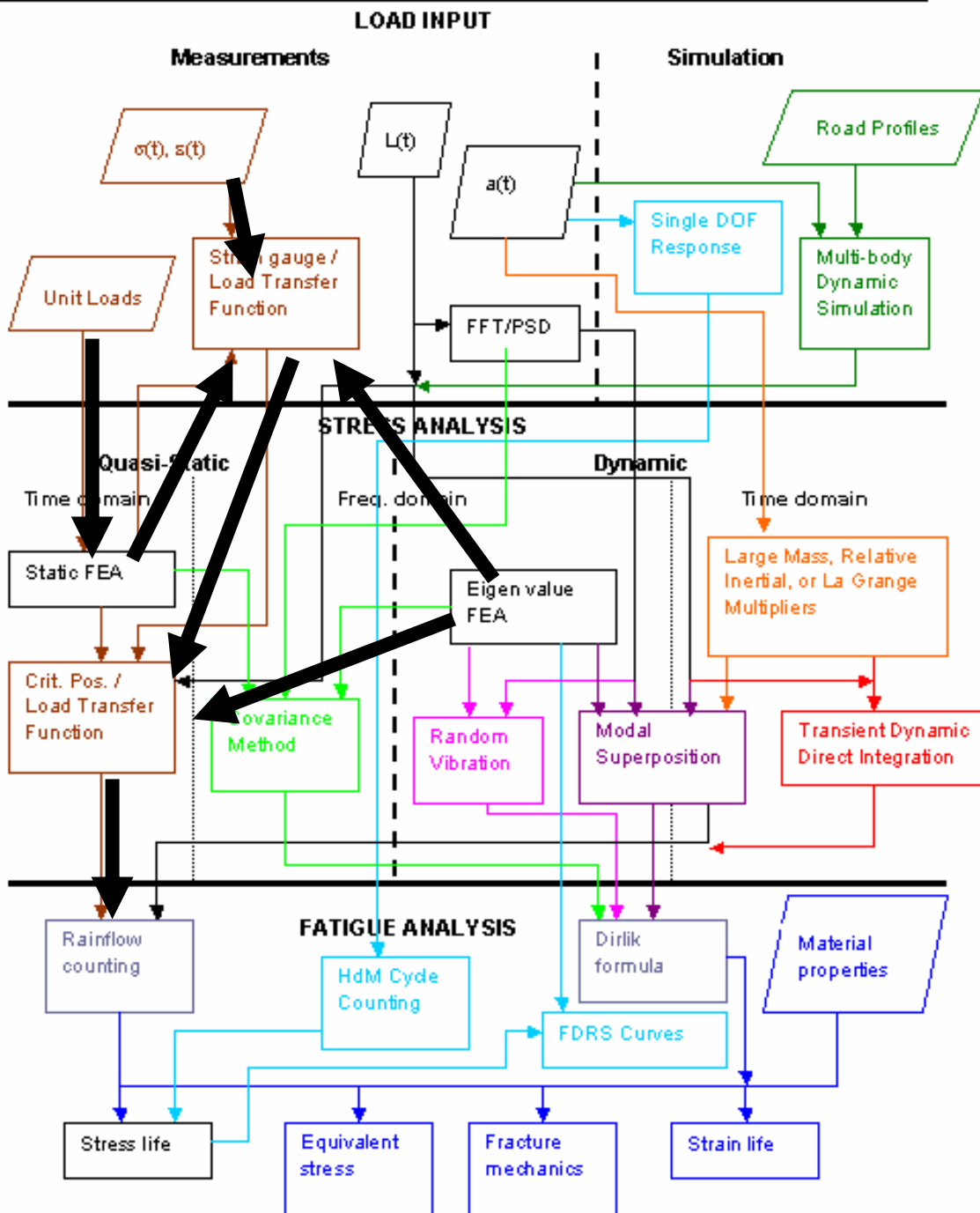


Figure 7-2 Hybrid remote parameter / modal superposition method



Although not pursued during the present study, it is proposed that, by combining aspects of the Fatigue Damage Response Spectra (FDRS) method, described in paragraph 3.5.8.2.5, with the modal superposition method, as well as the FESL method, this disadvantage could be overcome. The proposed concept would be that the FDRS are published, together with FESLs. The designer would obtain finite element eigenvalue solutions for the specific design and determine fatigue based, modal participation factors from the spectra, for modes found to be within the responding bandwidth. The analysis would then proceed as per the multi-axial FESL method, with the modal loads treated as additional ‘static’ loads. The additional aspects of the proposed process are depicted in Figure 7-3, using a thickened dashed arrow.

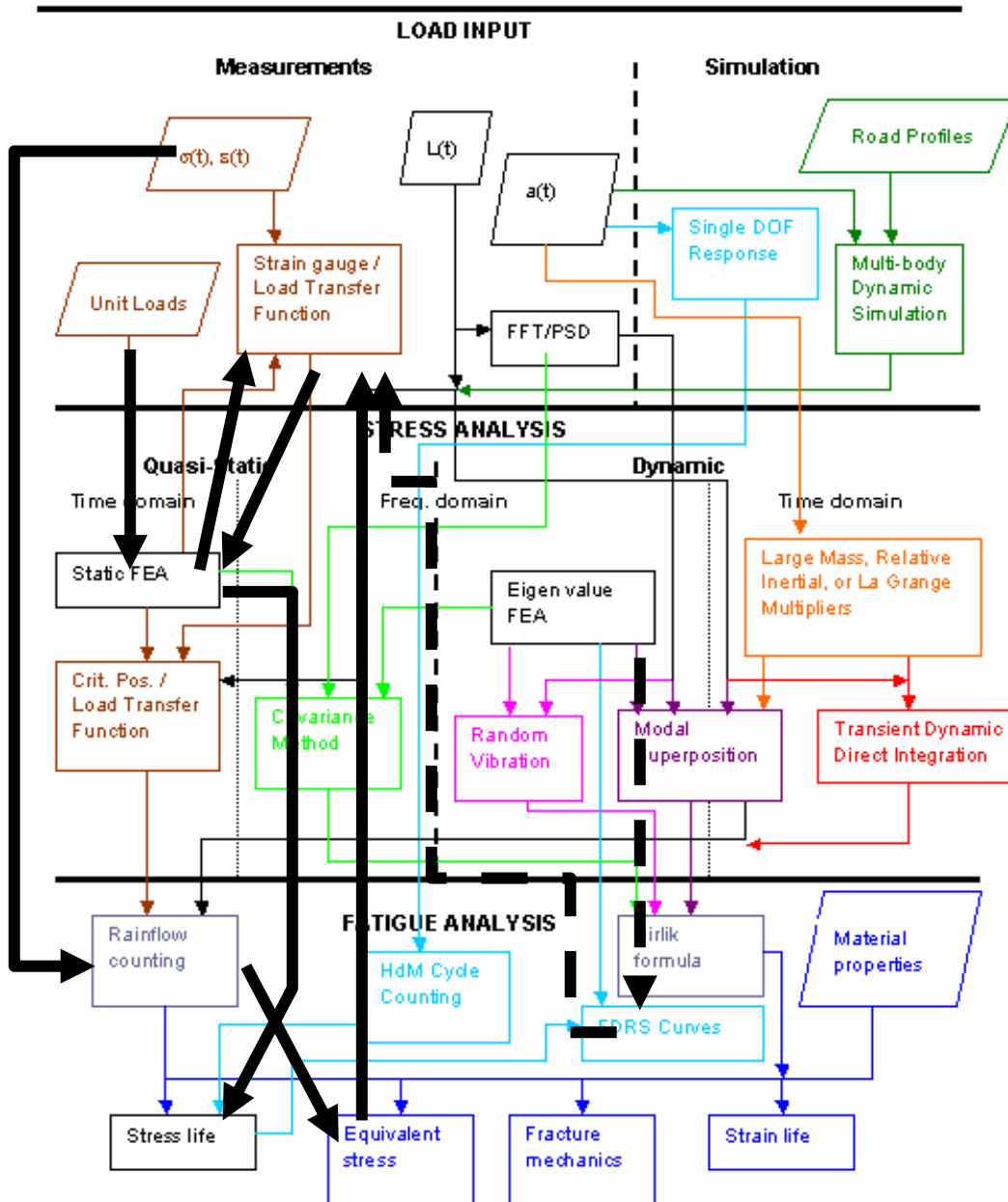
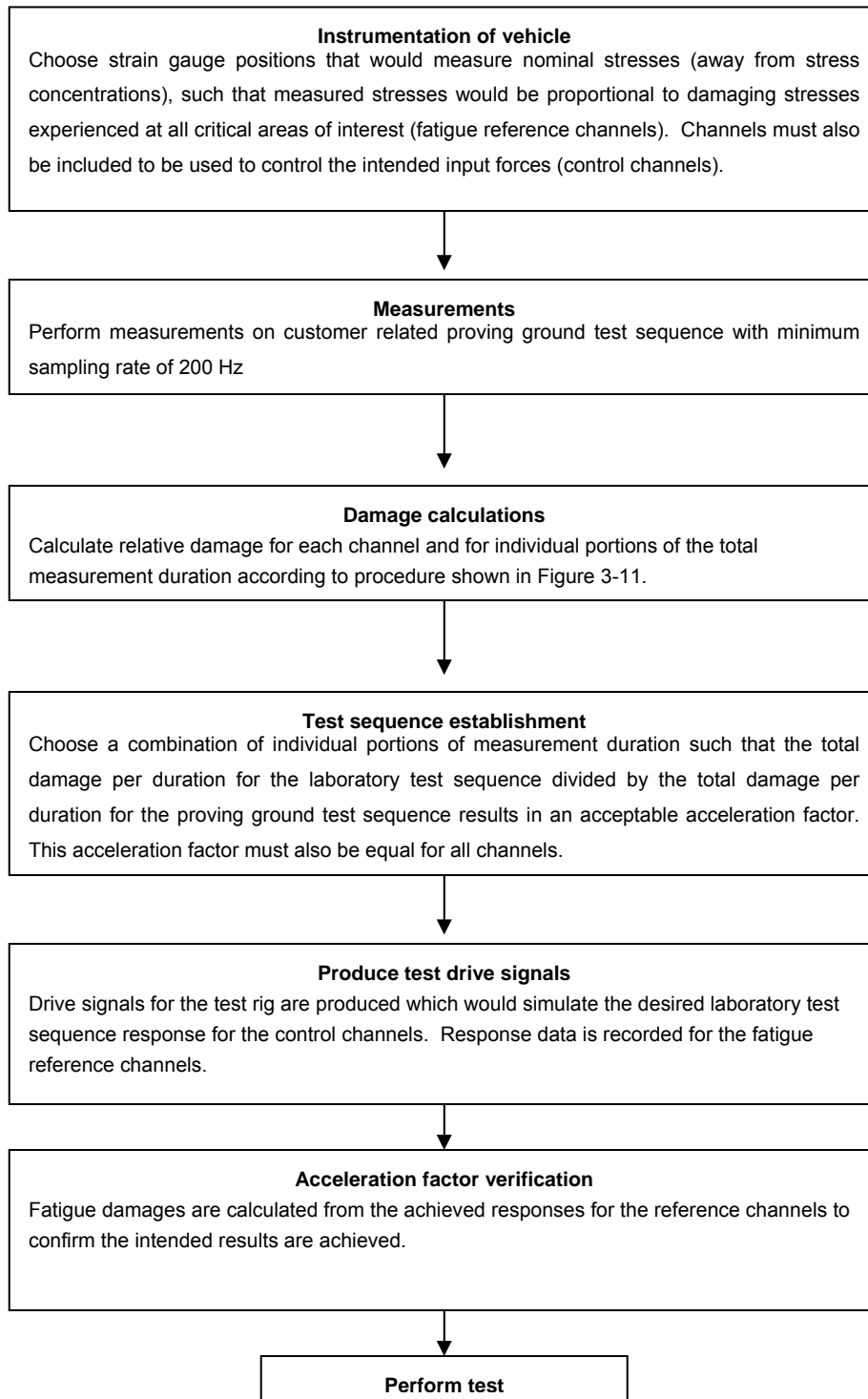


Figure 7-3 FESL process



### 7.2.13 Fatigue Test

The diagram depicted in Figure 7-4 captures the essence of the process of laboratory test development and correlation.



**Figure 7-4 Durability testing procedure**

## **7.2.14 Finite Element Analysis**

### **7.2.14.1 Static analysis**

Static analyses are used as part of the input loading establishment process as calibration. For maximum loads, or fatigue equivalent static loads, it may then also be used to calculate the resulting stresses.

### **7.2.14.2 Dynamic analysis**

The use of dynamic analyses is restricted by computing power and is therefore avoided when possible. The choice of which dynamic analysis technique is used (refer paragraph 3.2.3), is highly dependent on the measurement configuration used, or vice versa. Methods to include dynamic effects without the need for complete model dynamic analyses, are discussed in paragraph 3.2.3.8.

## **7.2.15 Usage Profile**

The statistical usage profile is an outcome of a process to establish input loads and is discussed in paragraph 5.4.6.

## **7.2.16 Monte Carlo**

The Monte Carlo simulation technique may be used to predict failure rates from statistical usage profiles and is discussed in paragraph 6.2.2.5.

## **7.2.17 Probabilistic Analysis**

The probabilistic analysis is used after the establishment of a statistical user profile to perform failure predictions or derive test requirements, as discussed in paragraph 5.6 and paragraph 6.2 respectively.

## **7.2.18 Failure Prediction**

The failure prediction is the outcome of the probabilistic analysis, or a finite element analysis with static equivalent or maximum loads, or of a dynamic finite element analysis. Comparison of these results with existing field failure results happens in the green decision block and should be done when possible.

## **7.2.19 Test Requirements**

Test requirements are the outcome of the probabilistic analysis (in terms of cycles to be completed on a test track or test rig), or of the FESL process, where these loads may be induced as sine waves on a test rig. In the latter case, if multi-axial loading is involved, the phase information will be lost, which may lead to inaccurate testing results, as discussed before.

Testing on a test rig may also be performed, directly using the measured results. The test severity would then be determined, based on fatigue processing of the measured results.

## **7.2.20 Fatigue Design Loads**

Fatigue design loads are the outcome of the static equivalent calculations, without the transfer matrix for uni-axial loads, or through the transfer matrix for multi-axial loads.

### 7.2.21 Maximum Loads

Maximum loads are derived from measurements, through the dynamic simulation if fundamental loads are required from indirect measurements.

## 7.3 CASE STUDIES ACCORDING TO GENERALISED PROCESS

### 7.3.1 Minibus

The minibus case study logic is depicted on the process diagram in Figure 7-5.

- Commencement: The process commences at the red decision block by employing three of the four possible sources of input loading, namely, measurements, surveys and field failure data.
- Measurement profile and data format (paragraph 4.2.3): Extensive measurements are performed on routes typically used by taxis, organising the data into files on different road categories, to capture all profiles. It is proposed that the use of the International Roughness Index (described in paragraph 3.5.5) to characterise the road types, would improve the methodology. The data is stored in the time domain.
- Processing decision: This case study did not involve any finite element analyses, since fatigue life prediction is achieved through physical testing.
- Fatigue processing (paragraph 5.5.3): The data is therefore fatigue processed, yielding damage per distance values for each category of road.
- Customer survey results (paragraph 4.3.3)
- User profile (paragraph 5.5.3.2): Survey results are combined with the fatigue processed output of the measurements to define a probabilistic definition of the user profile, in terms of two parameters, namely damage per distance and distance per time.
- Probabilistic analysis (paragraph 5.6.2): This profile is then employed to derive durability testing requirements, using two different methods. The analytical method is depicted in red.
- Failure prediction (paragraph 6.2.2).
- Monte Carlo (paragraph 6.2.2.5): Depicted in blue.
- Fatigue testing: In both cases, the results from fatigue testing are required. The fatigue testing is performed on a test rig, using measured data to derive drive signals.
- Failure data and comparison: Failure prediction results are successfully compared to field failure data, verifying the techniques employed.
- Ellipse fitting (paragraph 6.4): An alternative method for determining a user profile, employing only field failure data and fatigue testing results, is developed. This process is depicted in green.

The methodology developed during this case study, is similar to that found in literature (as described in paragraph 3.5.8.2.3), but it was compellingly substantiated through accurate field failure prediction. Also, its unique analytical formulation made it possible to develop a potentially powerful technique for deriving a probabilistic user profile from field failures.

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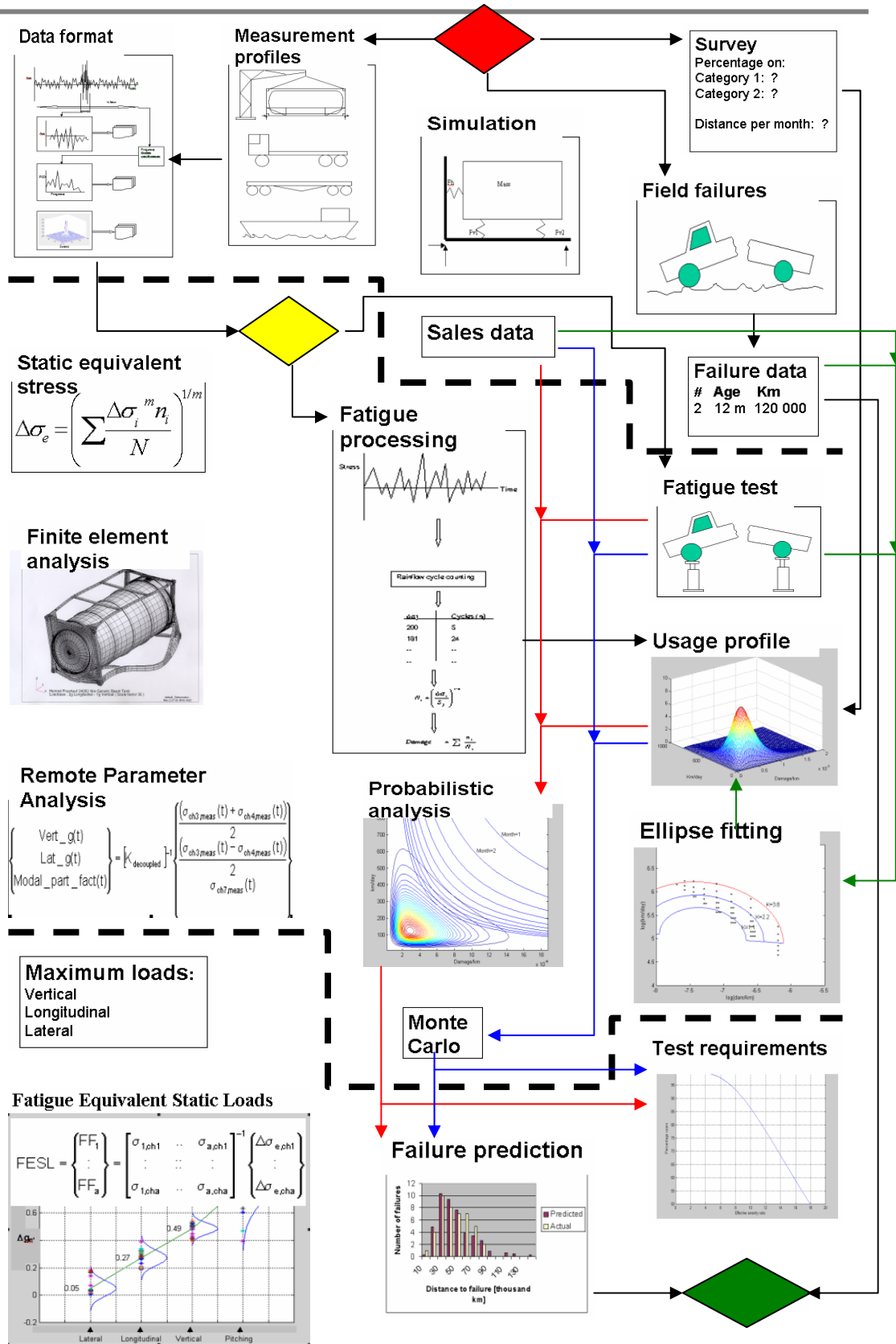


Figure 7-5 Minibus process

### 7.3.2 Pick-up Truck

The pick-up truck case study logic is depicted on the process diagram in Figure 7-6. This case-study was similar to the minibus case study, described above, differing only with respect to the fact that field failures were not available for verification purposes and that only the Monte Carlo method was used.

- Commencement: The process commences at the red decision block, employing measurements and surveys as sources for input data.
- Measurement profile and data format (paragraph 4.2.4): Extensive measurements are performed on routes typically used by pick-up trucks, organising the data into files on different road categories, to capture all profiles. The data is stored in the time domain.
- Processing decision: This case study did not involve any finite element analyses, since fatigue life prediction is achieved through physical testing.
- Fatigue processing (paragraph 5.5.4.1): The data is therefore fatigue processed, yielding damage per distance values for each category of road.
- Customer survey results (paragraph 4.3.4)
- User profile (paragraph 5.5.4.2): Survey results are combined with the fatigue processed output of the measurements to define a probabilistic definition of the user profile, in terms of two parameters, namely damage per distance and distance per time.
- Monte Carlo analysis (paragraph 5.6.3): This profile is then employed to derive durability testing requirements, using the Monte Carlo method.
- Fatigue testing (paragraph 6.2.3): The results from fatigue testing are required for failure prediction. The fatigue testing is performed on a test rig, using measured data to derive drive signals.
- Failure prediction (paragraph 6.2.3.6).

The case study demonstrated the Two Parameter Approach can be generically applied.

### 7.3.3 Fuel Tanker

The fuel tanker case study logic is depicted on the diagram in Figure 7-7.

- Commencement: The process commences at the red decision block, employing measurements and failure data as sources for input data.
- Measurement profile and data format (paragraph 4.2.5): Measurements are performed on a route typical of the mission of the vehicle. The data is stored in the time domain.
- Processing decision: The measured data is processed in terms of fatigue loading.
- Fatigue processing (paragraph 5.4.4.2): The data is fatigue processed, yielding stress ranges and number of cycles.
- Finite element analysis (paragraph 5.4.4.1): Firstly, the unit load stress at the measurement position is calculated to serve as input for the FESL calculation. After the FESL is calculated, it is induced as loading in a static finite element analysis to yield stresses, assumed to be ranges which are repeated 2 million times during the life.
- Equivalent stress calculation (paragraph 5.4.4.3): From the fatigue processed results, an equivalent stress range is calculated.
- FESL calculation (paragraph 5.4.4.3): The equivalent stress range is divided by the unit load stress to yield the FESL.

- Failure prediction (paragraph 6.2.4): The FESL finite element results are used to calculate fatigue lives at all critical positions.
- Comparison with field failures (paragraph 6.2.4): The predicted results are successfully compared to an actual field failure.

The case study also demonstrated and substantiated the uni-axial FESL method. The vehicles designed according to the process have achieved their design lives, except for failures caused by the unchecked design modification. A comparison between the FESL design criterion and design criteria for fuel tankers according to design codes, is presented in paragraph 6.3.2, demonstrating the improved sophistication achieved by the FESL method.

### 7.3.4 ISO Tank Container

The tank container case study logic is depicted on the diagram in Figure 7-8. The case study incorporated four parallel approaches, differentiated on the diagram using different coloured lines. Steps common to more than one approach are indicated using black lines.

#### 7.3.4.1 *Fatigue assessment through FESL finite element analysis*

- Commencement: The process commences at the red decision block, employing measurements as the source for input data.
- Measurement profile and data format (paragraph 4.2.6): Measurements are performed on five tank containers, over long durations, using specially developed dataloggers, on typical land sea and rail routes. The data is stored in the time domain, frequency domain and fatigue domain.
- Processing decision: The data is processed in terms of fatigue loading.
- Fatigue processing (paragraph 5.4.5.2): The data is fatigue processed in real time on the datalogger, yielding stress ranges and number of cycles.
- Finite element analysis (paragraph 5.4.5.5): Firstly, the unit load stresses at the measurement positions are calculated to compile a unit load transfer matrix for the FESL calculation.
- Equivalent stress calculation (paragraph 5.4.5.4): From the fatigue processed results, equivalent stress ranges are calculated for the seven strain channels.
- FESL calculation (paragraph 5.4.5.6): The multi-axial FESLs are calculated from the equivalent stress ranges, using the unit load transfer matrix. 35 different unit load transfer matrices are used (from the 35 combinations of 4 channels chosen from the possible 7) to yield 35 sets of FESL solutions. The mean values are chosen as the final result.
- Finite element analysis (paragraph 5.4.5.5): After the FESLs are calculated, they are induced as loading in a static finite element analysis to yield stresses, assumed to be ranges which are repeated 2 million times during the life. This exercise is depicted with red lines on the diagram.
- Failure prediction: The FESL finite element results are used to calculate fatigue lives at all critical positions, as indicated by the red line.

#### 7.3.4.2 *Fatigue assessment through FESL testing*

- Fatigue testing (paragraph 5.6.4): The same FESL results described in the previous exercise are used as input to fatigue testing in a laboratory, as indicated by the blue line.
- Failure prediction: The FESL fatigue testing results are used to calculate fatigue lives at all critical positions, as indicated by the blue line.

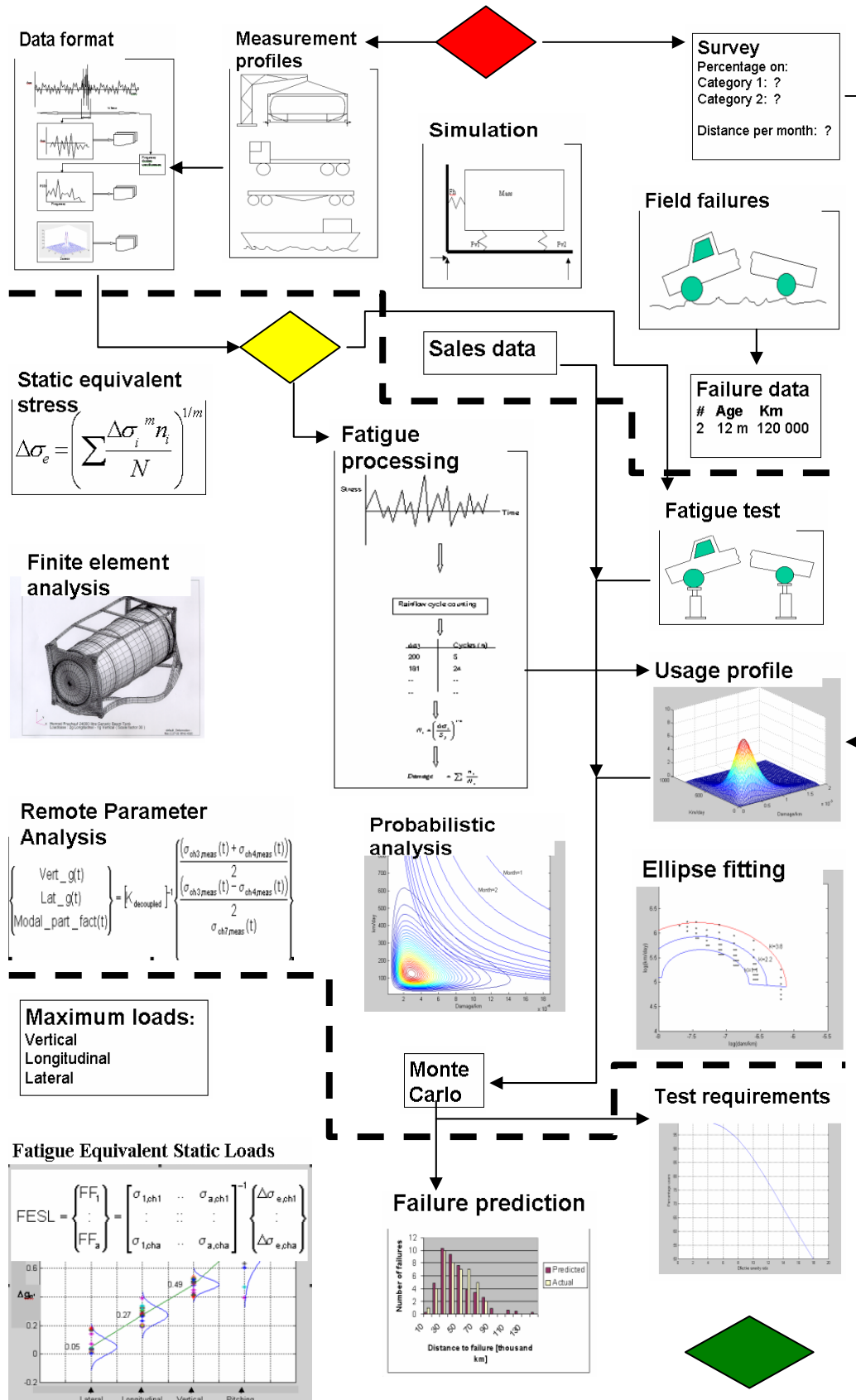


Figure 7-6 Pick-up truck process



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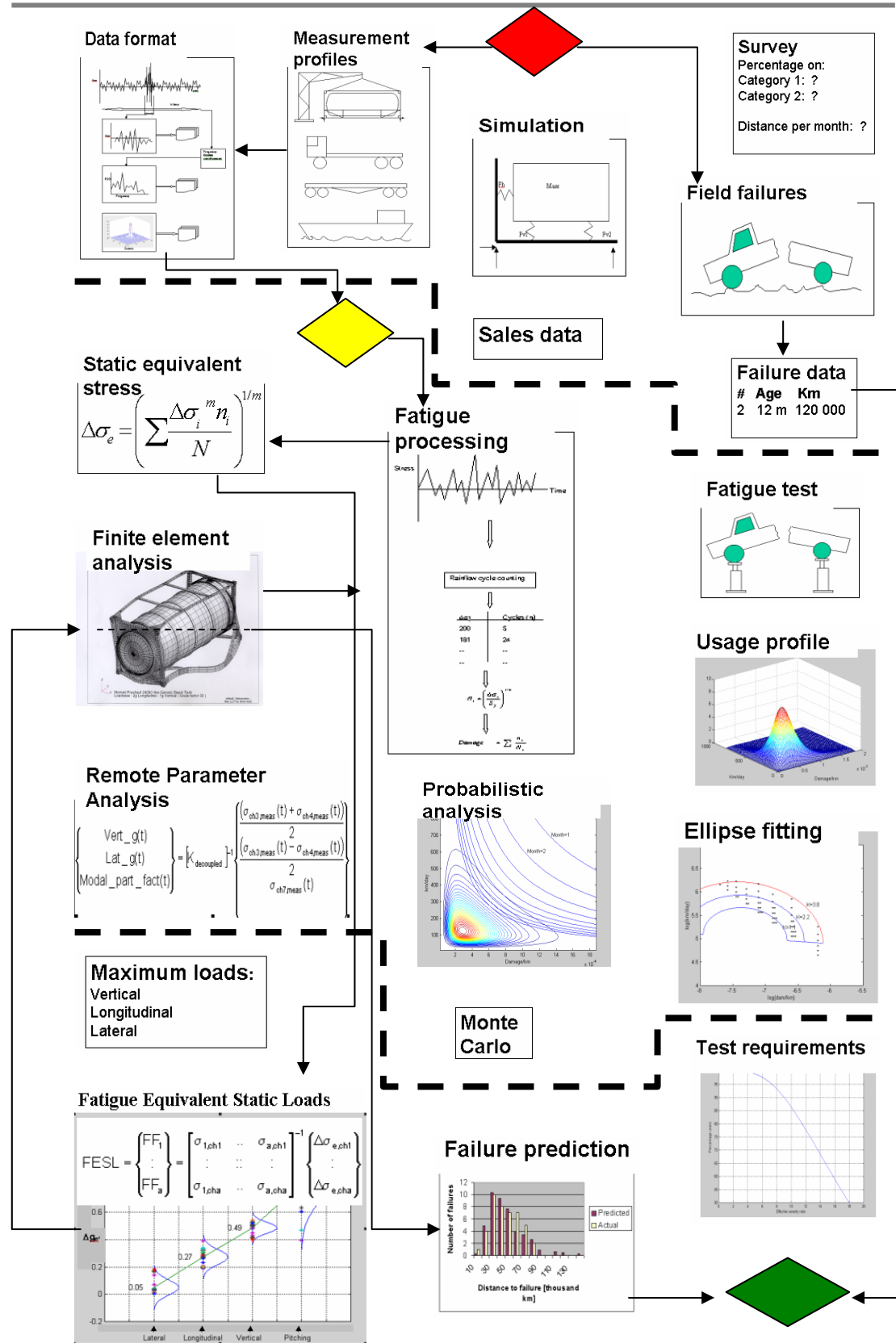


Figure 7-7 Fuel tanker process

#### **7.3.4.3 Fatigue assessment through dynamic finite element analysis**

- Processing decision: The accelerometer results, measured in the time domain, are used as inputs for the dynamic finite element analysis, as indicated by the green line.
- Dynamic finite element analysis (paragraph 5.2.3.2): A dynamic finite element analysis is performed.
- Fatigue processing: The stress results are fatigue processed, yielding stress ranges and number of cycles, as indicated by the green line.
- Failure prediction: The fatigue processed results are used to calculate fatigue lives at all critical positions, as indicated by the green line.

#### **7.3.4.4 Maximum load determination through multi-body dynamic simulation**

- Processing decision: The accelerometer results, measured in the time domain, are used as inputs for the multi-body dynamic simulation, as indicated by the pink line.
- Multi-body dynamic simulation (paragraph 5.2.2.1.2): A multi-body dynamic simulation is performed.
- Maximum loads: The simulation results are used to derive maximum g-loading.

The case study demonstrated the multi-axial FESL method. Several different tank container models have been successfully designed and tested using these results. The case study demonstrated the use of extensive measurements, with data recorded in different domains. The use of dynamic finite element analysis, as well as multi-body dynamic simulation, are also demonstrated.

#### **7.3.5 Ladle Transport Vehicle**

The ladle transport vehicle case study logic is depicted in Figure 7-9.

- Commencement: The process commences at the red decision block, employing measurements as the source for input data.
- Measurement profile and data format (paragraph 4.2.8): Measurements are performed on a prototype vehicle, on a typical operational route. The data is stored in the time domain.
- Processing decision: In this case study, the measured data is directly converted into load-time histories.
- Finite element analysis: Firstly, the unit load stresses (for vertical and lateral loads) at the measurement positions are calculated to compile a unit load transfer matrix for the load-time history calculation. Additionally, the modal stresses of a mode that was found to be excited during the measurements, are included in the transfer matrix. After the loads are calculated, they are induced as loading in a quasi-static finite element analysis to yield stress-time histories.
- Remote parameter analysis (paragraph 5.3.2.1): The measured results are multiplied with the transfer matrix to obtain load-time histories.
- Fatigue processing (paragraph 6.2.5): The stress-time histories are fatigue processed, yielding stress ranges and number of cycles.
- Failure prediction: The fatigue processed results are used to calculate fatigue lives at all critical positions.

This case study demonstrated the use of a combination of the remote parameter analysis method and the modal superposition method.

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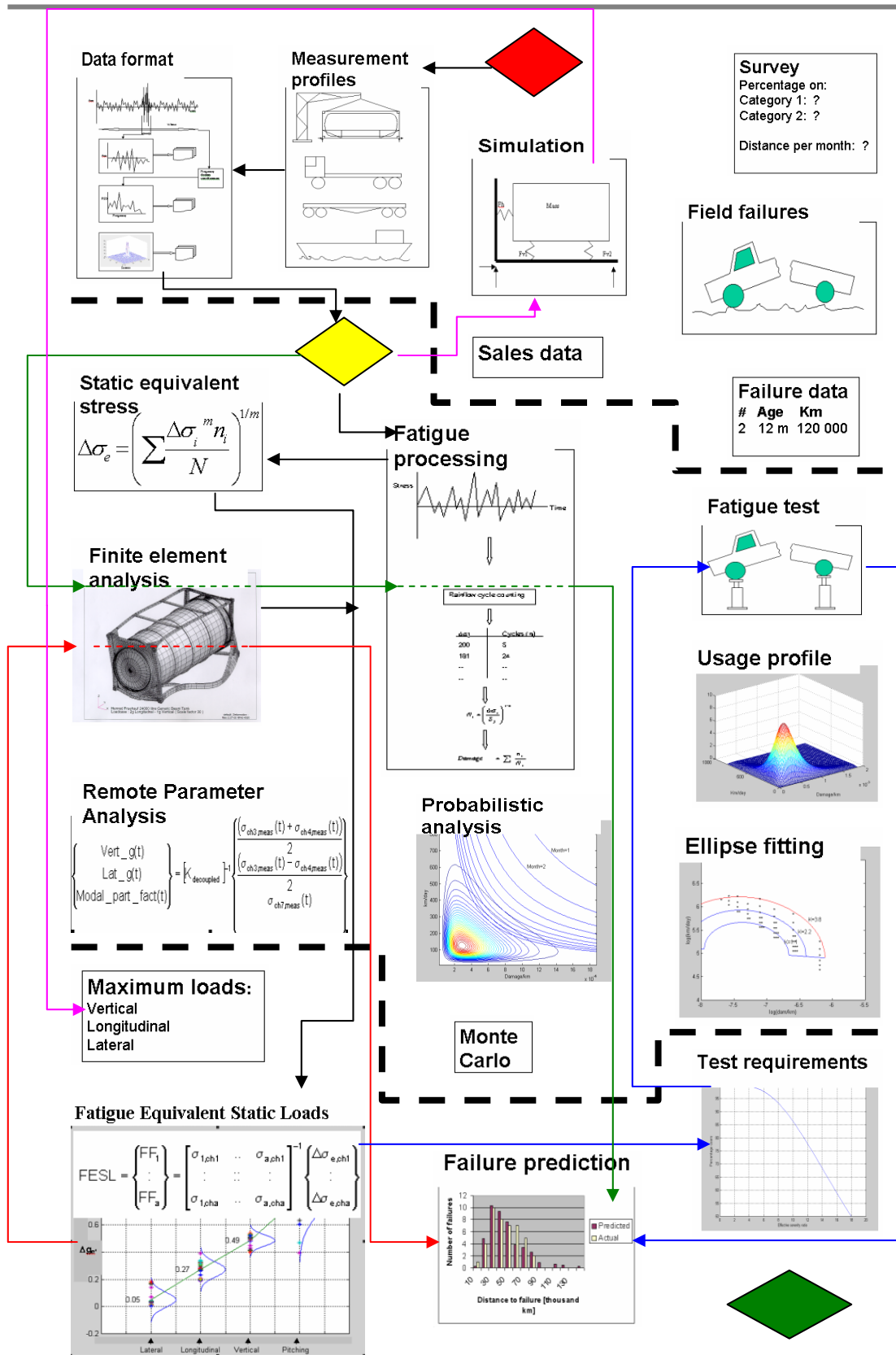


Figure 7-8 Tank container process

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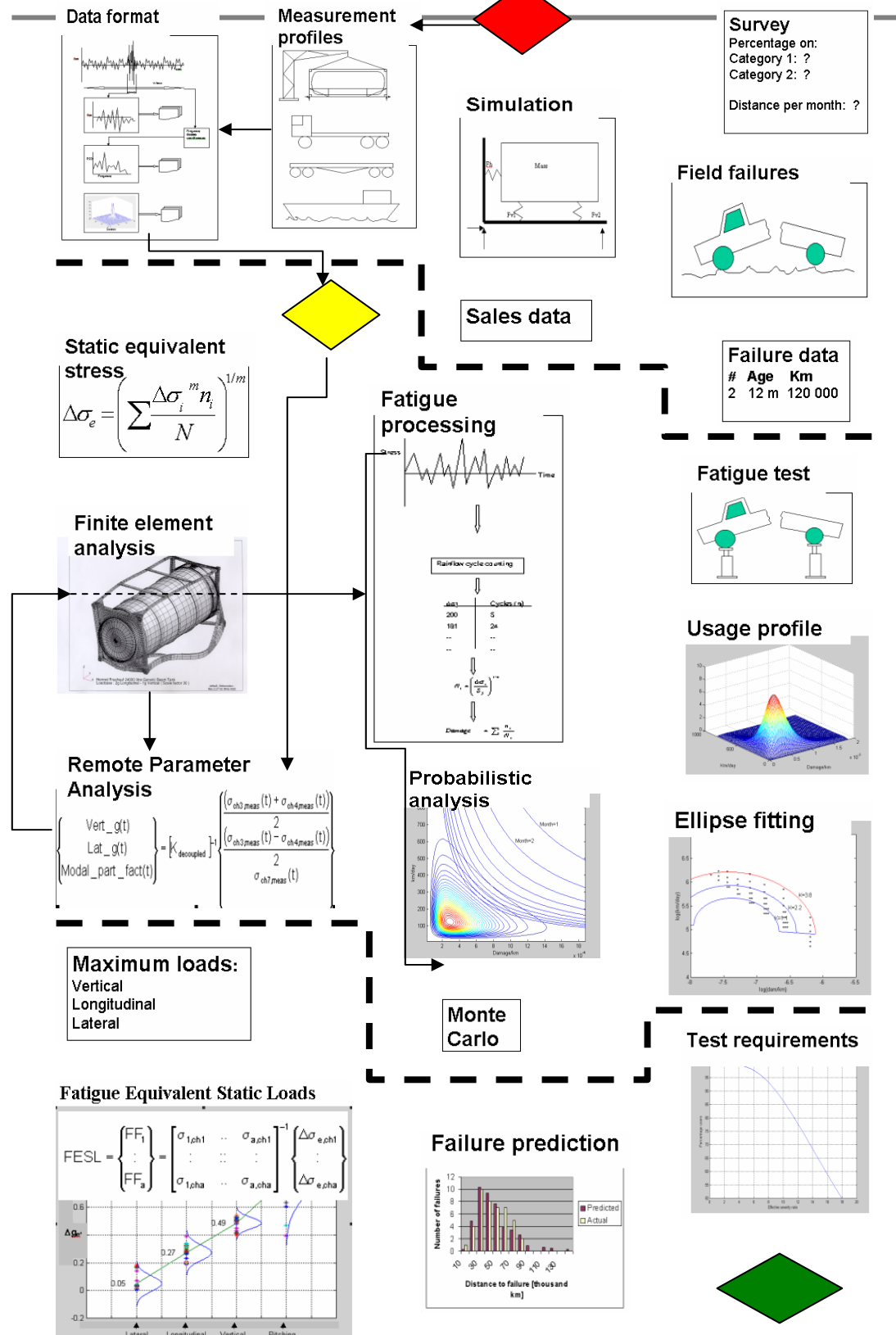


Figure 7-9 Ladle transport vehicle process

### 7.3.6 Load Haul Dumper

The load haul dumper case study logic is depicted on the diagram in Figure 7-10.

- Commencement: The process commences at the red decision block, employing measurements and failure data as sources for input data.
- Measurement profile and data format (paragraph 4.2.7): Measurements are performed on a route typical of the mission of the vehicle. The data is stored in the time domain.
- Processing decision: The measured data is processed in terms of fatigue loading.
- Fatigue processing (paragraph 5.4.6.2): The data is fatigue processed, yielding stress ranges and number of cycles.
- Finite element analysis (paragraph 5.4.6.1): Firstly, the unit load stress at the measurement position is calculated to serve as input for the FESL calculation. Two models are used to represent the travelling condition, as well as the condition while loading and tipping. After the FESL is calculated, it is induced as loading in a static finite element analysis to yield stresses, assumed to be ranges which are repeated 2 million times during the life.
- Equivalent stress calculation (paragraph 5.4.6.2): From the fatigue processed results, an equivalent stress range is calculated.
- FESL calculation (paragraph 5.4.6.3): The equivalent stress range is divided by the unit load stress to yield the FESL.
- Failure prediction (paragraph 6.2.6.1): The FESL finite element results are used to calculate fatigue lives at all critical positions.
- Comparison with field failures (paragraph 6.2.6.2): The predicted results are successfully compared to an actual field failure.

The case study also demonstrated and substantiated the uni-axial FESL method. Excellent correlation between predicted and actual failures is achieved. The expansion of the uni-axial FESL method to incorporate more than one constraint condition, is demonstrated.

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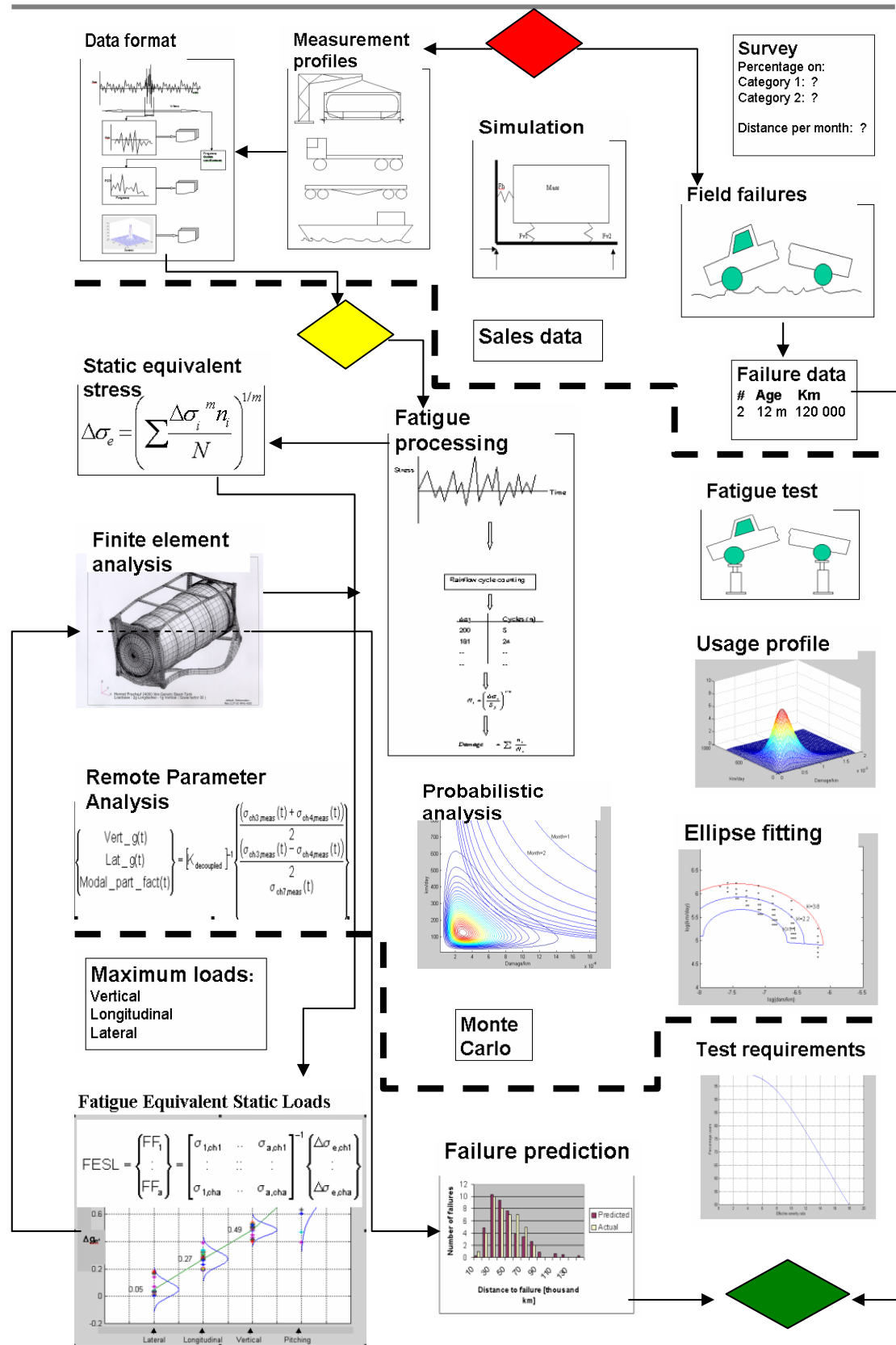


Figure 7-10 Load haul dumper process

## 8. CONCLUSION

The principal aim of the present study was the development of a generalised methodology for the determination of input loads for vehicle and transport equipment. This was achieved by combining researched current theory and best practices, with lessons learned during application on, as well as new techniques developed for, a number of complex case studies. The use of the generalised process diagram, depicted in Figure 7-1, to map the processes used during each case study, demonstrates the successful generalisation of the methodology. Apart from the above, the present study offers four individual, unique contributions.

Firstly, two methods, widely applied by industry, namely the Remote Parameter Analysis (RPA) method, which entails deriving time domain dynamic loads by multiplying measured signals from remotely placed transducers with a unit-load static finite element based transfer matrix, as well as the Modal Superposition method, are combined to establish a methodology which accounts for modal response without the need for expensive dynamic response analysis. This hybrid method, summarised in Table 8-1, may be compared to the existing alternatives, summarised in Table 3-4.

Secondly, a concept named *Fatigue Equivalent Static Load (FESL)* is developed, where fatigue load requirements are derived from measurements as quasi-static g-loads, the responses to which are considered as stress ranges applied a said number of times during the lifetime of the structure. In particular, it is demonstrated that the method may be employed for multi-axial g-loading, as well as for cases where constraint conditions change during the mission of the vehicle. The method provides some benefits compared to similar methods employed in the industry, such as the RPA method. The FESL method, summarised in Table 8-1, may be compared to the existing alternatives, summarised in Table 3-4.

**Table 8-1: Summary of FESL and Hybrid methods**

	Type	Load Input	Stress Analysis	Fatigue Analysis	Advantages	Disadvantages
<b>FESL method</b>	Quasi-static, time domain	Straingauge measurements	Static FEA	Rainflow counting + various fatigue life analysis methods	Can use remote measured strain gauge data, economic FEA, loading results suitable for code = design independent, rainflow only for measured channels	Not suitable for complex dynamic response
<b>Hybrid method</b>	Dynamic, time or frequency domain	Straingauge measurements	Eigen value FEA	Dirlik formula or Rainflow + various fatigue life analysis methods	Takes account of complex dynamic response, economic FEA, can measure remotely	Loading not design independent

The concept of defining fatigue load requirements as quasi-static loads, the responses to which are considered as stress ranges applied 2 million times during the lifetime of the structure, provides the same fatigue prediction results as would the RPA method for uni-axial loading, but with some benefits. The need for a load-stress area transfer function, with cycle counting for each critical element, falls away due to the fact that cycle counting is performed directly on the measured results, requiring only one finite element analysis with unit loads there-after and direct fatigue interpretation of scaled results in terms of the classification of joints and other critical areas. The incorporation of such requirements into design codes, in the traditional format of prescribed static loads with allowable stresses, is also achieved, with the only complexity added, being the fact that the allowable stress would be dependent on the critical area fatigue classification.



Thirdly, a complex analytical model named *Two Parameter Approach (TPA)* is developed, defining the usage profile of a vehicle in terms of a bivariate probability density distribution of two parameters (distance/day, fatigue damage/distance), derived from measurements and surveys. The method provides the same results achieved with a Monte Carlo simulation, employed before. Based on an inversion of the TPA model (which would not be possible using the Monte Carlo approach), a robust technique is developed for the derivation of such statistical usage profiles from only field failure data.

Lastly, the applicability of the methods is demonstrated on a wide range of comprehensive case studies. Importantly, in most cases, substantiation of the methods is achieved by comparison of predicted failures with 'real-world' failures, in some cases made possible by the unusually long duration of the study.

Sensible future work may be concentrated around three main objectives. Firstly, the most promising technique with which to circumvent the principal weakness of all the methods based on static equivalent fatigue loads, without having to perform time consuming dynamic finite element response analysis, but still resulting in design independent results, seems to be the (*Fatigue Damage Response Spectrum – FDRS*) method. This method could be combined with the FESL method, resulting in additional FESLs as a function of the principal natural frequencies of the structure.

Secondly, the use of the proposed techniques to compile new design codes for various applications, would be of benefit. Such an exercise would identify impractical aspects and other weaknesses of the methodology, as well as allow comparison with existing design codes, with which experience have been built up over years.

Thirdly, since all the work presented in this study disregards the possible accuracy benefits inherent in using the Strain Life approach rather than the Stress Life approach and also disregards the effects of multi-axial fatigue, further work on incorporating these more advanced theories into the generalised process, would be of interest.