UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

A STUDY OF FATIGUE LOADING ON AUTOMOTIVE AND TRANSPORT STRUCTURES

by

Johann Wannenburg

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Dedicated to my late father,
Jan Wannenburg,
who introduced me to thesis writing
(Wannenburg (1966))
at an early age and with who's help
this thesis may have been completed years earlier.

ABSTRACT

It is accepted that defective structural designs are mostly caused by insufficient knowledge of input data, such as material properties or loading, rather than inadequate analysis or testing methods. In particular, 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 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. The present study deals with methods for the establishment of input loading for automotive and transport structures. It is attempted to generalise and unify new and existing techniques into a cohesive methodology. This is 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, involving road tanker vehicles, light commercial vehicles, industrial vehicles, as well as tank containers. 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. 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. 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. Based on an inversion of the TPA model, 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.

OPSOMMING

Dit is bekend dat defektiewe struktuurontwerpe meestal veroorsaak word deur onvoldoende kennis van insette, soos materiaaleienskappe of belastings, in stede van ontoereikende analise- of toetstegnieke. In besonder is belastings geassosieer met voertuig- of vervoertoerustingstrukture, nie triviaal om te bepaal nie. Sulke belastings word veroorsaak deur stogastiese en ongedefinieerde prossesse soos drywer/operateur aksies en struktuur-terrein interaksie. Die fundamentele prosesse betrokke by die bepaling van insetbelastings is metings, vraelyste, simulasie, estimasie en berekening uit falingsdata. Hierdie prosesse het dan as uitsette, ontwerpkriteria, kodevereistes, en/of toetsvereistes. Die huidige studie handel oor metodes vir die bepaling van insetbelastings vir voertuig- en vervoerstrukture. Daar word gepoog om bestaande en nuwe tegnieke in ’n omvattende en generiese metodologie saam te vat. Dit word bereik deur ’n kombinasie van bestaande teorieë en beste praktyke soos gevind in die literatuur, lesse geleer uit die toepassing daarvan op, asook nuwe tegnieke ontwikkel vir ’n aantal komplekse gevallestudies, wat tenktrokke, ligte kommersiële voertuie, industriële voertuie en tenkhouers insluit. Bykomend tot bogenoemde doelwit, maak die studie ook vier unieke, individuele bydraes. Eerstens is twee tegnieke, wyd toegepas deur die industrie, naamlik die Indirekte Parameter Analise tegniek, wat behels om belastings in die tyd-domein te bereken deur vermenigvuldiging van indirek geplaasde meetkanaal resultate met ‘n oordragfunksie, verkry uit die resultate van ‘n statiese eenheidlas eindige element analise, sowel as die Modale Superposisie tegniek, saamgevoeg om ‘n tegniek te vestig waar modale responsie in ag geneem kan word sonder die nodigheid van duur dinamiese responsie analises. Tweedens is ’n konsep, genoem *Vermoeidheids-Ekwivalente Statiese Belasting,* ontwikkel, waar vermoeidheidsbelastingvereistes gedefinieer word as kwasi-statiese inersiële belastings, die responsies waarvan beskou word as spanningsbereike wat ’n spesifieke aantal kere toegepas word gedurende die leeftyd van die komponent. In besonder is daar gedemonstreer dat die tegniek toepaslik is in gevalle van multi-assige inersiële belasting, asook wanneer randvoorwaardes verander gedurende die missie van die voertuig. Die metode bied ’n paar voordele bo soortgelyke tegnieke wat deur die industrie gebruik word. Derdens is ’n komplekse analitiese model, genoem die *Twee Parameter Metode,* ontwikkel, waar die gebruikersprofiel van ’n voertuig gedefinieer word in terme van ‘n bivariate waarskynlikheidsdigtheidsfunksie van twee parameters (afstand/dag, vermoeidheidskade/afstand), bepaal uit rekstrokiemetings en vraelyste. Gebaseer op ’n inverse van die model, is ’n robuuste tegniek ontwikkel wat die bepaling van so ’n statistiese gebruikersprofiel, slegs uit veldfalingsdata, moontlik maak. Laastens is die toepaslikheid van die tegnieke gedemonstreer op ‘n wye verskeidendheid van omvattende gevallestudies. Van spesifieke belang is die feit dat in meeste gevalle, die geldigheid van die tegnieke bewys kon word deur vergelyking tussen voorspelde falings en praktyk falings, waarvan sommige slegs moontlik was as gevolg van die ongewone lang tydsduur van die studie.

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The Author
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LIST OF SYMBOLS

ρ	Correlation coefficient
γ	Irregularity factor
σ	Stress
ε	Total local true strain
$\Delta\varepsilon$	Local strain range
$\Delta\sigma$	Nominal stress range
$\Delta\sigma_e$	Equivalent nominal stress range
$\Delta\sigma_l$	Local stress range
$\sigma(t)$	Stress as a function of time
σ_{1g}	Stress due to 1 g inertial loading
σ_a	Stress amplitude
σ_c	Stress at critical position
Δe	Engineering strain range
γ_f	Load factor
ε_f	True fracture ductility
Δg	Range of applied inertial loading
Δg_e	Range of equivalent applied inertial loading
ΔK	Stress intensity range
γ_m	Material factor
ϕ_r	Mode shape
ω_r	Natural frequency
η_r	Principal coordinate
μ_y	Mean of random variable y
σ_y	Variance of random variable y
$[B]$	Stress-load matrix
$[c]$	Damping matrix
$[C]$	Damping matrix in principal coordinates
$[D]$	Rigid body transformation matrix
$[k]$	Stiffness matrix
$[K]$	Transfer matrix, stiffness matrix in principal coordinates
$[m]$	Mass matrix
$[M]$	Mass matrix in principal coordinates
$[P_y]$	Load covariance matrix
A	Area
a	Crack length, acceleration
$a(t)$	Acceleration as a function of time
b	Fatigue strength exponent
C	Fatigue crack growth (Paris) equation coefficient
c	Fatigue ductility exponent
D	Fatigue damage
D_f	Damage to failure
D_{tt}	Damage induced by test track
e	Engineering strain
E	Young's modulus
F	Force
FF	Fatigue factor
f	Frequency
$f(x)$	Probability density function of variable x
g	Gravitational acceleration
G	Power Spectral Density
I	Second moment of area

IRI	International roughness index
k	Stiffness
K	Stress intensity factor
K’	Cyclic strength coefficient
K_t	Theoretical stress concentration factor
L	Length, load
m	Mass, fatigue crack growth (Paris) equation exponent, gradient of curve, spectral moment
n	Number of applied cycles
N	Number of cycles to failure
n’	Cyclic strain hardening exponent
n_e	Number of equivalent applied cycles
N_e	Number of equivalent cycles to failure
n_i	Number of applied cycles for i^{th} stress range
N_o	Number of positive sloped zero crossings per second
N_p	Peaks per second
p	Forces
P	Forces
P_f	Probability of failure
P_{RR}	PDF of rainflow ranges
P_s	Survival probability
S_f	Fatigue coefficient
t	Time
TD	Total fatigue damage
u	Displacement
v	Velocity
V	Volts
x_1	Damage per kilometre
x_2	Kilometre per day

LIST OF ABBREVIATIONS

A/D	Analogue to digital
APD	Amplitude probability density
ASME	American Society of Material Engineers
BS	British standard
ECCS	European Commission for the Construction of Steel
FDRS	Fatigue damage response spectrum
FEA	Finite element analysis
FESL	Fatigue equivalent static load
FF	Fatigue factor
FFT	Fast Fourier transform
HAZ	Heat affected zone
IFFT	Inverse fast Fourier transform
IRI	International roughness index
ISO	International Standards Organisation
LHD	Load haul dumper
LTV	Ladle transport vehicle
MAM	Mode acceleration method
MDM	Mode displacement method
PC	Personal computer
PDF	Probability density function
PSD	Power spectral density
RAM	Random access memory
RPA	Remote parameter analysis
RPC	Remote parameter control
SN	Stress – life
SRS	Shock response spectrum
TPA	Two parameter approach
US	United States