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ASSESSMENT OF DUCTILE ENDURANCE OF EARTHQUAKE RESISTING STEEL MEMBERS

by

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Abstract

This thesis provides a structural and materials engineering explanation for many of the running fractures that occurred in steel structures during the destructive Kobe and Northridge earthquakes in the mid 1990s. A method is developed that allows the ductile endurance of structural steel members subjected to cyclic plastic deformation during earthquakes to be assessed and for pre-necking running fractures to be avoided.

The study commenced following the 2000 World Earthquake Conference in Auckland. The conference brought together the findings of the huge research effort, in America, Japan, Europe and New Zealand, that followed the Kobe and Northridge earthquakes. The running fractures that had occurred in steel structures represented an unpredicted failure mode that structural engineers have not known how to predict or suppress through the engineering design process. A clear fundamental understanding of the causes and how to prevent the fractures did not arise from the conference. In fact apparently conflicting results were reported. Full scale cyclic tests in New Zealand on structural assemblies had not resulted in running fractures, whereas tests in American and Japan had.

Structural engineers designing earthquake resistant structures rely on constructional steel to be materially homogeneous and nominally tri-linear in behaviour. Steel is expected to behave elastically under regular in-service loading, have a reliable and flat yield stress-strain characteristic, and under overload then develop predictable levels of strain-hardening in conjunction with significant plastic elongation up to its ultimate tensile strength. Steel is expected to eventually fracture after further plastic elongation and necking. Ductile design strategies and methods utilise the plastic elongation characteristics of steel to protect structures in earthquake. Plastic deformation is considered to beneficially dissipate energy generated in the structure by a severe earthquake and also dampen the structure’s response. The occurrence of running fracture without significant cyclic plastic deformation and before section necking in steelwork, therefore undermines the basis of the ductile seismic design approach.

The initial part of the thesis is devoted to bringing together the fundamental aspects of materials engineering related to fracture of constructional steel. This is intended to provide a bridge of knowledge for structural engineering practitioners and researchers not fully conversant with materials engineering aspects of fracture. Fracture behaviour in steel is a broad and complex topic

that developed rapidly in the twentieth century driven by the demands of technological growth. The unexpected fracture of welded liberty ships at sea in World War 2; the need for reliable long term containment for the nuclear reactors in the 1950s and 1960s; and prevention of fatigue failures in aircraft frames since the 1950s all drove engineering research into steel fracture behaviour.

There are many subtle variations in definitions in the published literature on fracture that can be confusing. Therefore an attempt has been made to clarify terminology. The term brittle fracture in particular is only used in this thesis as applying to running fracture when the general or far field tensile stresses are below the yield stress of the steel. The term pre-necking or running fracture is preferred to describe the condition more broadly which may occur prior to and also after general yielding, but before section necking. Running fracture is a manifestation of pre-necking fracture in which insufficient plastic flow is available in the assembly to absorb the energy released upon fracture.

The experimental studies investigated the behaviour of constructional steel commonly used in New Zealand, at various levels of plastic strain. This started with Charpy V-Notch (CVN) testing which revealed that a significant transition temperature shift and curve shape change occurs with increasing plastic strain and the associated strain-hardening. This showed that the ability of steel to avoid pre-necking or running fracture reduces as the level of plastic strain-hardening increases.

Temperature controlled Crack Tip Opening Displacement (CTOD) testing was then undertaken. The setting of testing temperatures for the CTOD tests were guided by review of the CVN test results, using published CVN to fracture toughness correlation methods. However running cleavage fractures developed in the CTOD specimens at higher than predicted temperatures of 10 ^{o}C and 20 ^{o}C. These are typical service temperatures for structures in New Zealand and so are very likely to occur at the time of an earthquake. The implication from this is that there are levels of strain-hardening and conditions of material notching constraint that can lead to pre-necking and running fracture in New Zealand fabricated steel structures, under severe earthquake loading.

Care was taken in the CTOD testing to monitor and maximise the capture of data electronically using a specially developed Direct Current Potential Drop method. This allowed the test results to be analysed and considered in varying ways, leading to a consistent assessment of the CTOD, crack growth, and the specific work of fracture in each test piece.

While CTOD test results have sometimes been published by structural and welding engineering researchers in the wake of Kobe and Northridge, the results were typically of little use for this study as the CTOD initiation point was generally not identified effectively. The effect of remote plastic flow in the specimens was also not adequately accounted for. The CTOD test results were often simply used to help correlate other factors observed by the researchers. Side-grooving of specimens was not reported as having been used in any of the published results reviewed. When conducting CTOD test with highly ductile constructional steels it is very difficult to get useful CTOD results if the specimens are not side-grooved, as significant necking and tunnelling will otherwise occur and limit the usefulness of the results.

Work by Knott and also by McRobie and Smith was seminal in terms of identifying some critical aspects of plane strain development in CTOD tests, and the links to non-metallic particle density with respect to fracture toughness and CTOD at initiation. Some of their findings with regards to the effect of pre-strain on CTOD initiation were subsequently found to confirm the experimental findings in this study.

No effective methodology for prediction of pre-necking or running fracture in a structural member or assembly when subjected to gross plastic cyclic deformation was found to exist in the literature. It was concluded however that the principles of specific work of fracture, and monotonic and cyclic fracture similitude were particularly relevant. These were therefore utilised in the development of the design method proposed in this thesis. The CTOD test results were reviewed, isolating the remote plastic flow component, to determine the critical specific work of fracture property R_c of the steels tested.

A meeting with Professor Kuwamura at the University of Tokyo was providential, allowing discussion of his similitude principle, and observations in person of some of the fractured specimens developed during his full scale test series'. Running fractures with cleavage were evident in the specimens, with their tell-tale chevron markings. He had predicted running fracture problems in structures in Japan ahead of the Kobe earthquake and been largely ignored. His insights were subsequently seriously considered in Japan after the earthquake.

He and his colleagues developed the principle of structural similitude that relates monotonic fracture displacement ductility to cyclic fracture displacement ductility for a particular assembly. This arose from their observation that running fractures developed from ductile crack formation at blunt notches in structures. The similitude principle has echoes of the Coffin-Manson approach to ductile crack initiated low cycle fracture. The principle of similitude has a log–log relationship as does the Manson-Coffin relationship. So where notch plasticity controls the initiation of fracture in a structural assembly it is conceptually reasonable to expect that the number of cycles to initiation of fracture from a notch will have a log–log relationship to the amplitude of the cyclic strain developed in the notch.

Kuwamura found that steel assemblies with lower CVN energy had reduced cyclic fracture endurance than the same assemblies made with steel with higher CVN impact energy. However no method of predicting performance of any particular assembly could be developed from his observations. The benefit of his method primarily relates to the minimising of testing necessary to assess the fracture limited cyclic displacement ductility of a structural assembly. However it doesn't provide a means for designing a structural assembly to achieve specific levels of ductile endurance other than clearly identifying the need to use steel with good CVN characteristics.

The most significant development arising from this thesis is therefore the development of a design method to assess cyclic ductile endurance. The method utilises the specific work of fracture properties obtained from CTOD specimens of the steel in conjunction with a relatively simple fracture mechanics assessment and an elasto-plastic finite element analysis (FEA). The FEA model is used to determine the displacement ductility of the assembly at the calculated onset of pre-necking fracture. The elasto-plastic stress–strain properties of the steel in various pre-strain states required for the FEA may be derived from tensile testing. Kuwamura's similitude principle is then used to predict cyclic plastic endurance at various constant displacement ductility amplitudes. The method is extended using Miner's rule to allow for the effects of increasing variable amplitude cyclic plastic loading.

In summary the thesis explains why pre-necking and running fractures occur in steel members subjected to cyclic plastic deformation during a severe earthquake. In addition a method for consistently assessing the ability of structural steel assemblies to achieve a specified level of ductile endurance during earthquakes is proposed. The method is verified against published results for a cyclic test of a simple steel member with a crack at mid-span.

Dedication

To my wife Kay, and children Benjamin, Barnabas and Abigail. and my parents.

Above all this is dedicated to my inspiration, the Lord Jesus Christ.

“Call to Me and I will answer you and I will tell you great and mighty things which you do not know”

Jeremiah 33:3

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kJ/m^2 Steel

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Glossary of Terms

A Proportionality constant used in CVN to K_{Ic} correlations

$\mathbf{A_f}$ Flange area

ABAQUS Finite element analysis software

AISC American Institute of Steel Construction Inc.

ATC-24 Applied Technology Council cyclic testing guideline

a Crack length

$\mathbf{a_{crit}}$ Critical crack length at which fracture will occur.

$\mathbf{a_o}$ Initial crack length

B Clear outstand width of a steel section flange; Breadth or thickness of a CTOD specimen; Proportionality constant

$\mathbf{B_{eff}}$ Effective section thickness of side-grooved CTOD specimen per BS7448.4

$\mathbf{B_N}$ Net section thickness of side-grooved CTOD specimen per BS7448.4

bcc Body centred cubic grain structure

$\mathbf{b_f}$ Flange width

C-Mn Carbon-manganese steel

COD Crack Opening Displacement. Term superseded by CTOD

CTOD Crack Tip Opening Displacement

CVN Charpy V-Notch

d Clear depth of a steel section web

D Grain diameter

DCPD Direct current potential drop method of monitoring crack growth.

e material thickness

$\mathbf{e_{max}}$ Maximum engineering pre-strain in test specimens

$\mathbf{e_s}$ Engineering strain at commencement of strain hardening

$\mathbf{e_y}$ Engineering strain at attainment of upper yield stress

E Young’s modulus

E* Effective Young’s modulus under plane strain conditions

EC3 Eurocode 3

FEA Finite element analysis

FEMA Federal Emergency Management Agency

f Void fraction after Gurson

f_o Initial void fraction

f_c Critical void fraction

fcc Face centred cubic grain structure

f_y Yield stress

f_u Ultimate tensile stress

G_c Critical strain energy to generate crack growth

G_{Ic} Critical plane strain energy release rate to generate crack growth

hcp Hexagonal close packed crystal structure

HAZ Heat Affected Zone adjacent to weld

HRR Hutchinson-Rice-Rosengren singularity in the crack-tip region

HSLA High Strength Low Alloy steel

I_{xx} Second moment of inertia of section

J_c J-integral at crack initiation

J_{Ic} J-integral at crack propagation on 1-1 plane at crack initiation under plane strain

K Applied stress intensity at a crack tip

K_c Critical stress intensity at the crack tip perpendicular to the crack propagation

K_{max} Calculated stress intensity at the maximum load obtained in a CTOD test.

K_Q Calculated stress intensity at fracture obtained in a CTOD test.

K_R Stress intensity at crack propagation derived from an R-curve

K_{Rc} Equivalent elastic stress intensity at fracture derived from an R_c

K_t Stress concentration factor

K_{Ic} Critical stress intensity at the crack tip perpendicular to the crack propagation or I-I plane for plane strain conditions

K_{Id} Critical stress intensity at the crack tip perpendicular to the crack propagation or I-I plane for cracking under plane strain condition, for dynamic loading.

K_{ε} Strain concentration factor for use in Neuber postulate.

K_{σ} Stress concentration factor for use in Neuber postulate.

k Average shear yield strength

k-line The point of tangency of the fillet between the web and flange, and the web surface.

k-zone The steel at the junction of a beam flange and web within the cross-sectional area bounded by the joining fillet.

kN Kilonewton

L Average inter-particle gauge length

LBZ Local brittle zones found in welds.

LEFM Linear Elastic Fracture Mechanics

LODMAT Lowest one day mean ambient temperature

$M_{os.hinge}$ Over-strength plastic section capacity

M_{pl} Section plastic moment capacity

M_{Rc} Critical cracking moment

M_{y} Yield moment calculated at first yield of the extreme fibres of the section

MMA Manual metal arc welding process

MnS Manganese sulphide

MPa Megapascals

m Adjustment factor to convert δ_c to R to allow for remote plastic flow.

N Number of cycles under cyclic loading

N_{f} Number of quarter cycles under cyclic loading to fracture

N* Axial design action

N_{y} Nominal axial yield strength

NDT Nil ductility temperature generally corresponding to the upper limit of lower shelf notch toughness dominated by plane strain behaviour. Typically corresponding to the development of 27J in CVN tests.

NZHERA New Zealand Heavy Engineering Research Association (Inc.)

n number of complete cycles: being 4 quarter cycles

p stretch zone width

Plane strain The stress condition at a particular location along a crack front in which the transverse restraint is fully rigid, measured in terms of strain on the 3-3 plane ε_{33}=0.

Plane stress The stress condition at a particular location along a crack front in which the transverse restraint in terms of stress on the 3-3 plane σ_{33}=0.

PCMC Pre-cleavage micro-cracks

PS Pre-strain

PWRI Japanese Public Works research Institute

q Plastic constraint factor: the ratio of notched to un-notched flow stress

q_1, q_2, q_3 Continuum mechanics material parameters after Gurson and Tvergaard

R_c Critical crack resistance at which crack will run without further energy input.

R_0 Crack resistance at first cracking

rad. Radians of rotation

RKR Ritchie Knott Rice model

SG Segment generator control on MTS testing machine

Q_f Monotonic fracture load per Kuwamura

Q_{max} Maximum cyclic fracture load per Kuwamura

R Stress ratio in fatigue testing; Fracture toughness or crack propagation energy

R_m Ultimate tensile strength

R_o Average radius of inclusions

$R_{p0.2}$ 0.2% proof stress

r_c Crack tip radius

r_y nominal plastic zone radius at a crack tip

S Plastic section modulus

S_p Structural performance factor in accordance with NZS 1170.5 Loadings Standard

SAC The SAC steel project funded by FEMA to solve the problem of running behaviour of welded steel frame structures that surfaced in the January 17, 1994 Northridge earthquake.

SAW Submerged Arc Weld

SEM Scanning electron microscope

SENB3 Simply supported three point bend specimen

SN490 Japanese constructional steel grade with nominal UTS of 490 MPa.

SWF Specific Work of Fracture

SZW Stretch zone width

SZW_c Critical stretch zone width at crack initiation

t_w Web thickness

T Temperature

T_s Service temperature

TK28 Test temperature at which 28J CVN obtained

T_f Flange thickness

U Electrical potential

U_o Initial electrical potential prior to crack growth

UTS Ultimate tensile strength

u Displacement

u_{el} Elastic component of displacement

W Width of CTOD specimen

WSMF Welded Steel Moment Frame

X Applied force

X_o Average inclusion spacing

X_{Rc} Critical cracking force

Yield Ratio Ratio of yield stress to ultimate tensile stress f_y/f_u

Y Stress intensity coefficient

y half the distance between probes across crack for DCPD monitoring

Z Elastic section modulus

Z_{ex} Effective section modulus about x axis reduced for element slenderness effects

Z_{web} Elastic section modulus of the web only

$\alpha(\frac{\sigma}{\sigma_y})$ Correlation for K_{Ic} other than $x=100\,\mathrm{MPa}\sqrt{\mathrm{m}}$

$\beta(x)$ Correlation for K_{Ic} other than $x=100\,\mathrm{MPa}\sqrt{\mathrm{m}}$

γ_p Irreversible work on fracture surface dissipated during plastic flow at the crack tip

Γ Plastic work done in specimen due to remote plastic flow away from the crack tip.

γ_s Effective surface energy of a potential crack face

ΔA Change in crack area

Δa Change in crack length

$\Delta\delta_p$ Half-cycle plastic displacement

ΔK Change in stress intensity

ΔT_e Thickness correlation temperature

ΔT_v Loading rate correction temperature

δ_c Crack tip opening displacement at fracture

δ_{ci} Crack tip opening displacement at initiation of cracking of a specimen

δ_f Total monotonic displacement of load at fracture

δ_i Crack tip opening displacement at initiation of cracking of a material

δ_{iel} Elastic component of crack tip opening displacement at initiation of cracking

δ_{ipl} Plastic component of crack tip opening displacement at initiation of cracking

δ_m Crack tip opening displacement at first attainment of maximum force plateau in accordance with BS7448.1

δ_{pM} Total monotonic plastic displacement of an applied load at fracture

δ_u Crack tip opening displacement for fracture prior to attainment of maximum force plateau but after development of significant plasticity in accordance with BS7448.1

δ_y Elastic displacement of the load relative to the support, corresponding to the development of fully plastic moment of a beam at the face of the column. In accordance with ATC-24.

ε true strain

ε_c True strain at initiation of cracking

ε_{cw} True cold work pre-strain

ε_{max} Peak strain

ε_s Strain at commencement of strain hardening

ε_u Uniform true strain capacity

ε_yTrue yield strain

ε_z Orthogonal component of true strain

η_p Cumulative cyclic plastic displacement ratio at fracture.

η_{pM} Plastic displacement ratio at fracture under monotonic load.

Λ Elastic strain energy

λ Element slenderness ratio for local buckling assessment

θ_p Plastic rotation of the beam tip relative to the column, prior to moment capacity dropping below the fully plastic moment of a beam, at the face of the column. In accordance with AASHTO LRFD Bridge Design Specification, 1998

θ_y Elastic rotation of the beam tip relative to the column, corresponding to the development of fully plastic moment of a beam at the face of the column

μ Displacement ductility

μ_p Cyclic displacement ductility amplitude.

ν Poisson’s ratio

Ω Complimentary strain energy

ϕ Material strength reduction factor in NZS 3404 Steel Structures Standard

$\Sigma\Delta\delta_p$ Cumulative absolute plastic cyclic displacement at fracture

σ True stress

σ_0 True stress at initiation of plastic strain

σ_{fl} Flow stress

σ_{fr} Fracture stress

σ_H Hydrostatic mean stress

σ_{ideal} Ideal cleavage strength

σ_{Mises} Von Mises stress

σ_u Ultimate tensile stress

σ_x Orthogonal stress component

σ_y Yield stress; Orthogonal stress component

σ_z Orthogonal stress component

σ_{crit} Critical section stress at which fracture will occur

τ_{peak} Peak stress triaxiality beneath a notched surface

$\boldsymbol{\tau_y}$ Dislocation shear yield stress of a crystal