THE UNIVERSITY OF
TECHNOLOGY, SYDNEY

Faculty of Engineering

Experimental and Numerical Investigation into Impact Bending Collapse of Rectangular Hollow Sections

A thesis submitted for the degree of

Doctor of Philosophy

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CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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GLOSSARY AND NOTATION

RHS - Rectangular hollow section. Used in this thesis to cover steel cold-formed thin-walled rectangular and square hollow sections.

Plastic hinge - The localised region of plastic deformation and buckling that developed in the cantilever specimen. See § 1.3.

Effective Hinge Centre - The point about which the length of specimen beyond the hinge zone appeared to rotate following formation of the hinge buckle. The effective hinge centre was typically located within ±5 mm from the geometric centre of the buckle. See § 1.3.3.

Hinge Zone - The 85 mm length of specimen, from the root of the specimen, over which the potentiometer device described in Section 3.5.6 measured relative rotation. See § 3.5.6 and § 4.2.1.

Energy consistent hinge moment - Hinge moment defined such that the integral *hinge moment Vs hinge zone rotation* was equal to hinge zone energy. See § 4.2.2, Eqn. 4.1.

Normalised pendulum rotation - Approximately the pendulum rotation that would have been measured if the pendulum pivot were at the effective hinge centre. See § 4.3.2.2.

Normalised pendulum moment - The work conjugate to normalised pendulum rotation. See § 4.3.2.2.

Dynamic Factor - For a given quantity or response the dynamic factor is the ratio of the impact value to the corresponding quasi-static value. See § 4.2.1.

FRF - Frequency Response Function. See § 4.5.4.

MPC - Multi-point constraint. See § 7.3.2.1.

UTS - Ultimate tensile strength.

Symbols

θ	Hinge zone rotation.
M-θ	*Hinge moment Vs Hinge zone rotation* response curve.
β	Pendulum rotation.
β'	Normalised pendulum rotation.
ϕ	Pendulum rotation due to elastic + plastic curvature of the length of specimen beyond the hinge zone.
ϕ'	Normalised pendulum rotation due to elastic + plastic curvature of the length of specimen beyond the hinge zone.
γ	Specimen tip rotation due to elastic + plastic curvature of the length of specimen beyond the hinge zone.
a	Offset of the effective centre from pendulum axis
M_{fp}	Fully plastic moment of the RHS section
f_c	Low-pass filter cut-off frequency [Hz].
D	Cowper-Symonds coefficient defined in Equation 2.1 [s^{-1}]
q	Cowper-Symonds coefficient defined in Equation 2.1
f	Flow stress strain rate sensitivity scaling factor. See § 8.2.
F_{dyn}	"dynamic factor" used to scale a quasi-static gross hinge or quasi-static specimen response quantity. See § 8.2.
δ	General measure of component displacement. See § 8.2.2 Eqn. 8.3.

Superscripts and Subscripts

EC	Energy consistent.
Pre	Pre-buckle phase.
Post	Post-buckle phase.
Trans	Transitional phase between pre-buckle continuous beam response and post-buckle mechanism response.
pb	Response post-buckle formation.
h	Quantity associated with plastic hinge response
elas	Elastic component of the response.
plas	Plastic component of the response.
pend	Quantity associated with pendulum response.
spec	Quantity associated with specimen response.
hinge zone	Quantity associated with hinge zone response.

ABSTRACT

This thesis describes a program of research into the plastic *moment – rotation* (M-θ) response of rectangular hollow section (RHS) steel tubes subjected to impact bending loads. The context for this research was the use of RHS in buses and vehicle rollover protection structures (ROPS) where the "plastic hinges" that form in the RHS members act as energy absorbing "crumple zones".

In the design of such structures for crashworthiness, there is a need to understand the response of the plastic hinges to impact loading and this research has assessed the following methods used to determine the *moment – rotation* characteristics of plastic hinges under impact bending loads:

- physical impact tests;
- finite element modelling; and
- the use of "dynamic magnifiers" to scale the results of quasi-static tests and analyses.

In dynamic tests, the specimen's inertia complicates the measurement of plastic hinge properties. These complications were addressed by the design and development of a novel pendulum bend rig and instrumentation and the meticulous processing of test data. The test rig and procedures were successfully used to measure the bending collapse of 50x50x2 grade C350LO RHS specimens to a hinge rotation of 35°. Comparisons between the measured impact and quasi-static responses enabled the influence of the loading rate on plastic hinge response to be quantified.

It is shown that the difference between the impact and static responses is essentially due to the RHS material's strain rate sensitivity. This influence of strain rate on the mechanical properties of the RHS material was characterised by a programme of uni-axial tensile tests at strain rates ranging from 10^{-4} to $10\ s^{-1}$.

Detailed finite element analyses of the local buckling response were conducted using HKS ABAQUS–Standard. Excellent agreement between the predicted and measured impact M-θ responses of the local buckle was obtained using a "pseudo-dynamic" analysis procedure. This procedure correctly accounted for the effect of material strain rate sensitivity within a static analysis by controlling the loading rate.

A critical assessment was made of the quasi-static scaling approach to predicting component impact response. The limitations of predicting impact moment and energy responses using a single scaling factor were demonstrated. It is shown that the most reliable results are obtained using a scaling factor derived experimentally. A theoretical approach proposed in the literature to predict RHS plastic hinge impact response is shown to overestimate the impact response of the RHS tested in this study. An alternative theoretical scaling factor is proposed that gave an improved prediction of RHS impact response.