

FIRE AND BLAST INFORMATION GROUP TECHNICAL NOTE

An Advanced SDOF Model for Steel Members Subject to Explosion Loading: Material Rate Sensitivity

Technical Note 10

- This document is a deliverable of the Fire and Blast Information Group (FABIG)
- FABIG would like to encourage comment and feedback from its membership. If you have any comments on this Technical Note or any other FABIG activities please address them to the FABIG Project Manager at The Steel Construction Institute

© 2002 The Steel Construction Institute

Neither this publication nor any part thereof may be reproduced, stored or transmitted, in any form or by any means – electronic, photocopy or otherwise, without the prior permission in writing of the Steel Construction Institute. Illustrations and tables may not be copied in part or in whole.

This publication is provided for use by FABIG members and shall not be lent, re-sold, hired out or otherwise circulated without the prior written consent of the publishers.

Although care has been taken to ensure, to the best of our knowledge, that all data and information contained herein are accurate to the extent that they relate to either matters of fact or accepted practice or matters of opinion at the time of publication, the Steel Construction Institute, the authors and the reviewers assume no responsibility for any errors in or misinterpretations of such data and/or information or any loss or damage arising from or related to their use.

This publication is supplied to the members of the Fire and Blast Information Group

The Steel Construction Institute, Silwood Park, Ascot, Berkshire, SL5 7QN, United Kingdom

Tel: +44 (0) 1344 636525, Fax: +44 (0) 1344 6636570

Email: fabig@steel-sci.com, Website: www.fabig.com

May 2007

FOREWORD

This Technical Note has been prepared as one of the FABIG deliverables to FABIG members.

The single-degree-of-freedom (SDOF) model in this document extends the SDOF model previously developed in FABIG Technical 7 to include strain rate effects and to provide more rational ductility measures than those based on the rate-insensitive model.

This Technical Note was compiled by Dr Viken Chinien of the Steel Construction Institute. It is based on the work that was carried out by Professor Bassam A Izzuddin, Professor of Computational Structural Mechanics at Imperial College, under contract to the Steel Construction Institute.

Contents

FOREWORD	v
GLOSSARY OF HUMAN FACTORS TERMS	vii
1. INTRODUCTION	1
2. OBJECTIVE	3
3. BENEFITS FROM THE APPLICATION AND IMPLEMENTATION OF HUMAN FACTORS	5
3.1 General issues	5
3.1.1 Introduction	5
3.1.2 Compliance with standards and expectations	5
3.1.3 Benefits to safety & health	5
3.1.4 Benefits to operability	5
3.2 Cost-Benefit Analysis	6
4. APPLICATION OF HUMAN FACTORS STUDIES	7
5. TOOLS AND METHODOLOGIES	11
5.1 Currently available tools and methodologies	11
5.1.1 Allocation of Function	12
5.1.2 Hierarchical Task Analysis (HTA)	12
5.1.3 Human Error Analysis (HEA)	14
5.1.4 Human Reliability Analysis	15
5.1.5 Link Analysis	16
5.1.6 Distributed Cognition	17
5.2 Developing approaches	17
5.3 Integration of Human Factors tools and methodologies	18
Appendix A APPLICATION AND EFFECTS OF HUMAN FACTORS ON DEVELOPMENT STAKEHOLDERS THROUGHOUT THE PROJECT LIFECYCLE	20
Appendix B ADDITIONAL HUMAN FACTOR RELATED GUIDEWORDS TO BE USED IN HAZOP/HAZID TYPE REVIEWS	45
Appendix C HUMAN FACTOR BENEFITS AND EXAMPLE MEASURES	54
Appendix D BIBLIOGRAPHY OF REFERENCES AND STANDARDS	62

CONTENTS

	Page
FOREWORD	iii
1. INTRODUCTION	1
2. PROBLEM CHARACTERISTICS AND ASSUMPTIONS	3
3. FORMULATION METHOD	5
3.1 Cross-sectional Response	5
3.2 Bending Stage	6
3.3 Catenary Stage	7
4. CROSS-SECTIONAL RESPONSE	9
4.1 Major-Axis Bending	9
4.2 Minor-Axis Bending	9
5. DYNAMIC STRENGTH	11
5.1 Bending Stage	11
5.2 Catenary Stage	11
5.3 Evaluation of Model Parameters	12
6. DUCTILITY MEASURES	13
7. MODEL SOLUTION PROCEDURE	15
8. EXAMPLES AND VERIFICATION	17
8.1 Cross-section Response	17
8.2 UDL Blast loading	17
9. CONCLUSION	23
REFERENCES	25
APPENDIX A NOTATION	27
APPENDIX B FIGURES	31
APPENDIX C TABLES	37

1. INTRODUCTION

This Technical Note describes an extension to a sophisticated SDOF model for steel members subject to explosion loading [1].

The previous model [1] accounted for:

i) generalised support conditions for bending and axial actions; and ii) the catenary effect in axially-restrained members, under uniformly distributed (UDL), blast loading. However, that model did not incorporate material rate sensitivity, which has considerable influence on the blast response of steel members. The present work extends the previous model to deal with the strain-rate effect, and to provide more rational ductility measures than possible with rate-insensitive modelling.

The Technical Note proceeds by providing an overview of the problem characteristics as well

as the formulation method used in developing the new SDOF model, where consideration is given to material rate sensitivity in accordance with the Cowper-Symonds model [2]. The details of the overall model are then provided, mainly in the form of parametric tables, covering both the bending and catenary stages of the plastic rate-sensitive member response. Finally, several verification and application examples are provided, with particular emphasis given to the new developments, where comparisons are made against the nonlinear finite element analysis program ADAPTIC [3]. These examples demonstrate the calculation process involved in applying the new SDOF model, and illustrate the very good accuracy which the new model achieves.

2. PROBLEM CHARACTERISTICS AND ASSUMPTIONS

A simplified SDOF model was previously formulated [1] for a steel beam under dynamic loading, where the problem characteristics were as follows:

- The member has uniform cross-sectional properties along its length.
- The cross-sectional response is elastic/perfectly plastic (i.e. no strain hardening).
- The member has two end supports where transverse displacements are restrained (Figure B.1).
- Arbitrary elastic/perfectly plastic conditions are considered for the two end supports for both rotational and axial deformations (Figure B.1).
- The strain-rate effect is ignored.
- The dynamic blast loading is UDL.
- The initial static loading is UDL.
- The mass is uniformly distributed along the member length.
- Both bending and catenary actions are considered.

The following assumptions were made to facilitate the formulation of a relatively uncomplicated model which should nevertheless capture the essential problem characteristics:

- The member response under initial static loading is elastic.
- The location of the internal plastic hinge is governed by the blast load configuration.
- The interaction between the plastic bending moment and axial force is linear (Figure B.2).

The model is now extended here to account for the strain-rate effect, where the following additional assumptions are made:

- Material strain-rate sensitivity is governed by the Cowper-Symonds model.
- The cross-sectional response under a constant deformation rate is elastic/perfectly plastic, with an enhanced dynamic plastic strength that is determined from rigid/plastic theory as a function of the deformation rate.
- The plastic curvature rate decreases rapidly along the member away from the point of maximum bending moment, justifying the related assumption of lumped plastic-hinge rotation.
- The dynamic strength of a plastic hinge remains constant over the response duration, and is determined from a deformation rate associated with a plastic collapse mechanism and an average displacement rate, accounting, where appropriate, for the plastic-hinge length.
- Where the static plastic capacity of a support is less than that of the beam, the plastic hinge is completely in the support (i.e. outside the beam), and the corresponding dynamic strength is obtained directly in terms of the support deformation rate.
- The shape of the plastic bending moment diagram is governed by the blast load configuration.

Full details of the notation employed throughout this work are provided in Appendix A.

3. FORMULATION METHOD

This work extends the previous SDOF model [1] to deal with the influence of material rate sensitivity on the blast response of steel members. With the strain-rate effect defined on the material level, according to the Cowper-Symonds model [2], its influence is first considered on the cross-sectional response and subsequently on the overall member response.

3.1 Cross-sectional Response

The material response under a constant strain rate ($\dot{\epsilon}$) can be idealised, in the absence of strain hardening, as elastic/perfectly plastic with an enhanced dynamic yield strength (σ_d) (Figure B.3). According to the Cowper-Symonds model:

$$(1): \quad \sigma_d = \sigma_y \left(1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/n} \right)$$

where n and D are material rate-sensitivity parameters, and σ_y is the static yield strength.

For mild steel ($n = 5$) and ($D = 40 \text{ sec}^{-1}$), though the extended SDOF model is formulated for generic n and D parameters, and is therefore also applicable to other materials provided ($n \geq 4$).

The cross-sectional response under a constant deformation rate can also be idealised as elastic/perfectly plastic. The enhanced dynamic plastic strength can be obtained from first relating the material strain rates to the generalised cross-section plastic strain rates (Figure B.4):

$$(2): \quad \dot{\epsilon} = \dot{\epsilon}_p = \dot{\epsilon}_{cp} - y \dot{\kappa}_p$$

where $\dot{\epsilon}$ is the centroidal axial plastic strain rate, $\dot{\kappa}_p$ is the plastic curvature rate, and y is the distance of a material fibre from the reference centroidal line. The material plastic strain rate ($\dot{\epsilon}_p$) is identical to $\dot{\epsilon}$ in the plastic range, since material strain hardening is ignored.

The dynamic plastic moment and axial force capacities can then be determined from

consideration of the plastic stress distributions under constant $\dot{\kappa}_p$ and $\dot{\epsilon}_{cp}$, respectively:

$$(3): \quad \begin{aligned} M_d &= \int -\sigma_d y dA = \int \pm \sigma \left(1 + \left(\frac{\pm y \dot{\kappa}_p}{D} \right)^{1/n} \right) y dA \\ &= M_p \left(1 + \left(\frac{\dot{\kappa}}{D_\kappa} \right)^{1/n} \right) \end{aligned}$$

$$(4): \quad \begin{aligned} F_d &= \int \sigma_d dA = \int \sigma_y \left(1 + \left(\frac{\dot{\epsilon}_{cp}}{D} \right)^{1/n} \right) dA \\ &= F_p \left(1 + \left(\frac{\dot{\epsilon}_{cp}}{D} \right)^{1/n} \right) \end{aligned}$$

where $\dot{\kappa}_p$ and $\dot{\epsilon}_{cp}$ are considered in absolute value, M_p and F_p are the static plastic bending moment and axial force capacities, respectively, and D_κ is a rate-sensitivity parameter for plastic bending that depends on the cross-section shape, as determined in Section 4.

It is noted that (3) assumes that the position of the neutral axis is not influenced by material rate sensitivity, which is valid for bending about an axis of symmetry. Although for asymmetric cross-sections the position of the neutral axis can vary with the plastic curvature rate, the influence of such variation on dynamic magnification of the plastic moment capacity can be realistically neglected, and hence (3) is also applicable to moderately asymmetric cross-sections.

Finally, the interaction between the dynamic plastic moment and axial force is realistically assumed to have the same shape as the static interaction curve (Figure B.5), where the transition between full plastic bending and plastic axial resistance is governed by:

$$(5): \quad \begin{cases} \dot{\epsilon}_{cp} < r_p \dot{\kappa}_p \Rightarrow M = M_d \\ \dot{\epsilon}_{cp} = r_p \dot{\kappa}_p \Rightarrow M + r_p F = M_d \end{cases}$$

with,

$$(6): \quad r_p = \frac{M_p}{F_p}$$

In view of the above, the principles used for formulating the previous rate-insensitive SDOF model [1] remain valid, provided the static cross-section capacities, M_p and F_p , are replaced by their dynamic equivalents, M_d and F_d , taking into account the deformation rate.

3.2 Bending Stage

The dynamic moment capacities at the member plastic hinges are obtained as the steady-state solution associated with a collapse mechanism subject to an average displacement rate. A number of cases arise depending on whether the plastic hinge at a member end is in the beam or in the support, as determined by the relative static plastic bending capacities of the support to that of the beam. The case of a plastic hinge in the beam at the left end but in the support at the right end is illustrated in Figure B.6. For a given dynamic plastic bending moment diagram, the plastic-hinge lengths in the beam can be determined where appropriate, and the rotation rate of these plastic hinges can be obtained.

Considering first the internal plastic hinge (Figure B.6), the rotation rate is determined as the integral of the plastic curvature rate over the plastic-hinge length:

$$(7) \quad \dot{\theta}_p = \int_{h_p} \dot{\kappa}_p dx = \int_{h_p} D_{\kappa} \left(\frac{M}{M_p} - 1 \right)^n dx = \Theta_p \left(\frac{M_d}{M_p}, h_p \right)$$

For the plastic hinge at the left end, the determination of the rotation rate depends on whether the plastic hinge is inside the beam (Figure B.6):

(8.a):

$$M_p^1 = M_p \Rightarrow \dot{\theta}_p^1 = \int_{h_p^1} \dot{\kappa}_p^1 = \int_{h_p^1} D_{\kappa} \left(\frac{M}{M_p} - 1 \right)^n dx = \Theta_p \left(\frac{M_d^1}{M_p^1}, h_p^1 \right)$$

or in the support, in which case the rotation rate is directly related to the dynamic plastic moment as determined by the support characteristics:

$$(8.b): \quad M_p^1 < M_p \Rightarrow \dot{\theta}_p^1 = \Theta_p^1 \left(\frac{M_d^1}{M_p^1} \right)$$

Similarly, for the plastic hinge at the right end, the determination of the rotation rate depends on whether the plastic hinge is inside the beam:

(9.a):

$$M_p^r = M_p \Rightarrow \dot{\theta}_p^r = \int_{h_p^r} \dot{\kappa}_p^r dx = \int_{h_p^r} D_{\kappa} \left(\frac{M}{M_p} - 1 \right)^n dx = \Theta_p^r \left(\frac{M_d^r}{M_p^r}, h_p^r \right)$$

or in the support (Figure B.6):

$$(9.b): \quad M_p^r < M_p \Rightarrow \dot{\theta}_p^r = \Theta_p^r \left(\frac{M_d^r}{M_p^r} \right)$$

In the above expressions, h_p^1 , h_p and h_p^r are the plastic-hinge lengths corresponding to the zones of the member over which the static plastic bending moment capacity (M_p) is exceeded (Figure B.6), and therefore these depend on the dynamic bending moment diagram as defined by M_d^1 , M_d , and M_d^r . Furthermore, Θ_p^1 , Θ_p , and Θ_p^r are highly nonlinear functions which depend on the variation of the bending moment over the corresponding plastic-hinge length. With each of $\dot{\theta}_p^1$, $\dot{\theta}_p$ and $\dot{\theta}_p^r$ related to the member displacement rate ($\dot{v}^m$), the nonlinear equations (7) to (9) can be solved for M_d^1 , M_d and M_d^r in terms of $\dot{v}^m$, though an exact solution can be very demanding, if not impossible. However, good solution accuracy can be achieved through appropriate simplifications, particularly with regard to relating the plastic-hinge lengths to the dynamic bending moments. Consequently, equations (7) to (9) can be expressed in the following general form:

$$(10): \quad \dot{\theta}_p^1 = D_{\theta}^1 \left(\frac{M_d^1}{M_p^1} - 1 \right)^{n_m^1}$$

$$(11): \quad \dot{\theta}_p = D_{\theta} \left(\frac{M_d}{M_p} - 1 \right)^{n_m}$$

$$(12): \dot{\theta}_p^r = D_{\theta}^r \left(\frac{M_d^r}{M_p^r} - 1 \right)^{n_m^r}$$

where (D_{θ}^1, n_m^1) , (D_{θ}, n_m) and (D_{θ}^r, n_m^r) are parameters that are either given (for an end plastic hinge in the support) or derived (for a plastic hinge in the beam).

With $\dot{\theta}_p^1$, $\dot{\theta}_p$ and $\dot{\theta}_p^r$ depending on $\dot{v}^m$ according to the plastic collapse mechanism, the dynamic plastic moment capacities can be determined from (10) to (12), as presented in Section 5.

Finally, it should be noted that for the case where an end plastic hinge is in the support ($M_p^1 < M_p$ or $M_p^r < M_p$), it is possible for the corresponding dynamic plastic bending moment (M_p^1 or M_p^r) to exceed the static plastic bending moment of the beam. Although in such a case, plastic deformation is also induced in the beam at the corresponding end, this would normally be small in comparison with the plastic deformation induced in the support, and is therefore neglected in the extended rate-sensitive SDOF model so as to maintain simplicity without significant compromise to accuracy.

3.3 Catenary Stage

With the assumed interaction between the dynamic plastic bending moment and axial force, as discussed in Section 3.1, the first catenary stage is initiated as for the rate-insensitive model when:

$$(13): v^m = r_p^t - v_0^m = \left(c^1 r_p^1 + r_p + c^r r_p^r \right) - v_0^m$$

with,

$$(14): r_p^1 = \frac{M_p^1}{F_p^1}; \quad r_p = \frac{M_p}{F_p}; \quad r_p^r = \frac{M_p^r}{F_p^r}$$

where c^1 and c^r are weighting parameters that depend on the location of the internal plastic hinge [1], and v_0^m is the reference displacement due to initial static loading. It is noted that, according to (14), the plastic radii are only

functions of the static bending and axial capacities of the beam and supports.

For a given dynamic magnification of the static bending strength, as determined in accordance with Section 3.2, the development of an axial force during the first catenary stage leads to a reduction in the bending moments but to an increase in the plastic-hinge lengths. This latter increase would be associated with an increased deformation rate, and hence, for a constant deformation rate, as assumed by the extended SDOF model, the dynamic magnification of the static strength should be reduced in the first catenary stage. However, this effect is considered to be negligible, and the complexities associated with its modelling are therefore not justified, particularly in view of the transient nature of the first catenary stage.

The transition between the first and second catenary stages is defined by a dynamic axial force capacity (F_d^m), dependent on the overall plastic axial deformation rate ($\dot{\Delta}_p$) and whether the axial plastic deformation is concentrated in any of the supports or spread over the length of the beam. Four cases can be identified as follows:

$$(15.a): F_p^1 < F_p^r \leq F_p \Rightarrow \dot{\Delta}_p^t - r_p \dot{\theta}_p - r_p^r \dot{\theta}_p^r = D_{\Delta}^1 \left(\frac{F_d^m}{F_p^1} - 1 \right)^{n_f^1}$$

$$(15.b): F_p^1 = F_p^r < F_p \Rightarrow \dot{\Delta}_p^t - r_p \dot{\theta}_p = 2 D_{\Delta}^1 \left(\frac{F_d^m}{F_p^1} - 1 \right)^{n_f^1}$$

$$(15.c): F_p^r < F_p^1 \leq F_p \Rightarrow \dot{\Delta}_p^t - r_p^1 \dot{\theta}_p^1 - r_p \dot{\theta}_p = D_{\Delta}^r \left(\frac{F_d^m}{F_p^r} - 1 \right)^{n_f^r}$$

$$(15.d): F_p^1 = F_p^r = F_p \Rightarrow \dot{\Delta}_p^t = L D \left(\frac{F_d^m}{F_p} - 1 \right)^n$$

where (D_{Δ}^l, n_f^l) and (D_{Δ}^r, n_f^r) represent axial rate-sensitivity parameters for the left and right supports, respectively.

With $\dot{\Delta}_p^l, \dot{\theta}_p^l, \dot{\theta}_p$ and $\dot{\theta}_p^r$ related to the reference displacement rate ($\dot{v}^m$), depending on the plastic collapse mechanism, the dynamic plastic axial capacity can be obtained from one of the applicable equations in (15), as presented for the individual blast loading configurations in Sections 5 to 7.

It is noted that the second case represented by (15.b) corresponds to identical plastic axial

response characteristics for the left and right supports, and hence axial plasticity is equally shared between the two supports. Furthermore, as for bending plasticity, the above expressions assume that the localisation of axial plasticity is related to the static rather than the dynamic relative axial capacities of the supports and the beam. This is considered to be a realistic assumption, which avoids major complications without significant compromise to accuracy in the determination of F_d^m .

4. CROSS-SECTIONAL RESPONSE

According to [3], the determination of the dynamic plastic bending moment capacity requires a rate-sensitivity parameter (D_κ) that depends on the cross-sectional shape and the axis of bending. In general, this can be related to the material rate-sensitivity parameter (D) by:

$$(16): D_\kappa = \frac{D}{d_e}$$

where d_e represents an effective distance from the neutral axis.

Two cross-sectional configurations are considered for the enhanced SDOF model, as depicted in Figure B.7, with bending about both the major and minor axes considered for the I-section.

4.1 Major-Axis Bending

With reference to Figure B.7a, for an asymmetric I-section subject to major-axis bending, d_e can be expressed as:

$$(17): d_e = \frac{d_w}{2} \left[\frac{\left(\frac{nw - (n+1)\delta}{2n+1} + 1 \right) \left(1 + \frac{\delta}{w} \right)^{\left(\frac{n+1}{n} \right)} + \left(\frac{nw + (n+1)\delta}{2n+1} + 1 \right) \left(1 - \frac{\delta}{w} \right)^{\left(\frac{n+1}{n} \right)}}{w \left(1 + \frac{\delta}{w} \right) \left(1 - \frac{\delta}{w} \right) + 2} \right]^n$$

where,

$$(18): w = \frac{A_w}{A_f^b + A_f^t}; \quad \delta = \frac{|A_f^b - A_f^t|}{A_f^b + A_f^t}$$

with ($\delta \leq w$) indicating a moderately asymmetric I-section with the neutral axis in the web.

The same expressions (17) and (18) can also be used for the out-of-plane one-way bending of a corrugated wall section (Figure B.7b).

For a symmetric I-section subject to major-axis bending, the above expression for d_e simplifies to:

$$(19): d_e = \frac{d_w}{2} \left[1 - \frac{w}{(2n+1)(w+2)} \right]^n \text{ such a cross-section being characterised with } (\delta = 0).$$

4.2 Minor-Axis Bending

With reference to Figure B.7a, for an asymmetric I-section subject to minor-axis bending, d_e can be expressed as:

$$(20): d_e = \frac{1}{2} \left[\frac{2n}{2n+1} \left(\beta (b_f^b)^{1/n} + (1-\beta) (b_f^t)^{1/n} \right) \right]^n$$

where,

$$(21): \beta = \frac{A_f^b b_f^b}{A_f^b b_f^b + A_f^t b_f^t}$$

For a symmetric I-section subject to minor-axis bending, the above expression for d_e simplifies to:

$$(22): d_e = \frac{b_f}{2} \left[\frac{2n}{2n+1} \right]^n$$

with b_f representing the flange width

($b_f = b_f^b = b_f^t$).