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**INTERACTIVE DESIGN OF FLEXURAL STEEL MEMBERS
SUBJECTED TO BENDING, AND
COMBINED BENDING AND TORSION**

by
Yuxiang He

A thesis submitted to
the Faculty of Graduate Studies and Research
in the partial fulfillment of the requirements
for the degree of
Master of Engineering*

Department of Civil and Environmental Engineering
Carleton University
Ottawa, Canada

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* The Civil Engineering Program is a joint program with University of Ottawa,
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**"Interactive Design of Steel Members Subjected to
Bending, and Combined Bending and Torsion"**

Submitted by Yuxiang He

**in partial fulfilment of the requirements for the degree of
Master of Engineering**

A handwritten signature in black ink, appearing to be 'S.J. Kennedy', written over a horizontal line.

Associate Professor S.J. Kennedy, Thesis Supervisor

A handwritten signature in black ink, appearing to be 'J.L. Humar', written over a horizontal line.

**Professor J.L. Humar, Chair
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**Carleton University
April 28, 1993**

Abstract

This thesis describes a state-of-the-art graphics-oriented computer program IDFSM for **I**nteractive **D**esign of **F**lexural **S**teel **M**embers Subjected to Bending, and Combined Bending and Torsion. Unlike existing computer software, which provide limited design rules with respect to lateral stability, IDFSM includes analytical and design procedures that take into account the effect of the type of lateral support, the type and point of application of the load, copes and the influence of interactive buckling on the lateral-torsional buckling capacity. Bearing stiffeners are automatically designed when required. IDFSM provides the structural engineer with solution strategies of different levels of sophistication to handle simple well defined problems and the most complex lateral stability problems as well. IDFSM has the capacity to analyze and design steel beams subjected to both flexural and torsional loads. IDFSM will either perform comprehensive design checks for a user specified beam, or an automatic design to obtain the least weight section that meets all the design constraints. An all mouse-driven menu and fully graphical input screen enable the structural engineer to produce, with little effort, 3D configurations of real members with realistic boundary conditions, lateral bracing and connections for systems like the Gerber system. These configurations, along with the loading conditions may be edited graphically as further refinements are required. High quality moment, shear and torque diagrams and deflection shapes along the member will be displayed graphically for each load combination. An inquiry system allows the user to obtain different levels of report, including intermediate calculations, design criterion and design strategies. IDFSM currently runs on Sun workstation and X-Window systems and has been designed to work on PC's and other system environments. IDFSM is programmed in C++, C and FORTRAN programming languages along with HOOPS graphics user interface package.

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Finally the author takes this opportunity to express his deepest appreciation to his wife June for her encouragement and understanding throughout my studies. This thesis is dedicated to her.

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List of Symbols

A	Area
B_f	Bearing force in a member or component under factored load
B_r	Factored bearing resistance of a member
b	Width of a section flange
C_w	Warping torsional constant
D	Dead load
d	Depth of beam
E	Elastic modulus of steel, 200 000 MPa
e	Eccentricity of a torsional load
F_s	Ultimate shear stress
F_y	Yield strength
F_u	Specified minimum tensile strength
G	Shear modulus of steel, 700 000 MPa
I_x	Moment of inertia of strong axis (X-axis)
I_y	Moment of inertia of weak axis (Y-axis)
J	St. Venant torsional constant
K	Effective length factor
KL	Effective length
k	Distance from outer face of flange to web-toe of fillet of I-shaped sections
L	Length; Live load
M_f	Bending moment in a member under factored load

M_p	Plastic moment
M_y	Yield moment
M_u	Ultimate moment of a unbraced beam
R	End reaction or concentrated transverse load applied to a flexural member
S	Elastic section modulus of a steel section
T_f	Torque in a member under factored load
T_r	Ultimate resistance torque of a member
T_y	Limiting torsional moment that causes first yield
T_{yp}	Plastic limiting torsional moment based on fully inelastic behaviour, but with maximum stresses taken at the yield level
T_u	Torsional moment based on fully inelastic behaviour with maximum stresses taken at the ultimate tensile strength level
t	Thickness of flange
V_f	Shear force in a member under factored load
V_r	Factored shear resistance of a member
w	Web thickness
Z	Plastic section modulus of a steel section
z	Distance from the left end of a member
α	Load factor
λ	Nondimensional slenderness ratio in column formula
ϕ	Resistance factor of a member; angle of twist
ω_2	Coefficient to account for increased moment resistance of a laterally unsupported beam segment when subject to a moment gradient

Note: The above symbols are general symbols used throughout this thesis.
Additional nomenclature will be noted where they appear.

Chapter 1

INTRODUCTION

1.1 General Background

In recent years the Civil Engineering profession has witnessed a broad acceptance of the concept of computer-aided structural engineering. Attractive advertisements describing the "state-of-the-art" programs claim to do wonderful things such as integrated analysis, design, detailing and shop drawing and are often illustrated in the professional magazines. Nevertheless, this is still a critical time for the software developers. As the evolution of hardware and underlying software is continuing, there is a need to develop better software on all platforms of operating systems and there is still a need to take advantages of continuing development of structural engineering knowledge to obtain correct estimates of member resistances and load effects by using a computer-aided approach.

This thesis addresses several important aspects of computer-aided structural engineering by presenting a comprehensive interactive computer program for the analysis and design of flexural steel members which demonstrates the trend of a new generation of software.

1.2 Steel Beam Design: Still A Challenge

Beams and girders are one of the most commonly used members in structural steel buildings. The design of these members as programmed by commercial software is generally inadequate or incomplete.

In some cases, software developers oversimplify some of the design parameters in order to claim increased scope and number of attributes of their analysis and design programs. Figure 1.1 shows a screen of one of the major commercial member design software currently on market, *Beam and Column Design*, by ECOM Associates, USA, (1991). It can be seen that **Braced Length** is the only parameter defined directly associated with the evaluation of the lateral-torsional buckling capacity. In this thesis, it is demonstrated that certain parameters such as the type of the lateral support, the shape of the moment diagram, the end coping of the member and other factors have to be considered to obtain a good estimation of the capacity of the member concerned. In other cases, the commercial software can not always perform the the function as described in the documentation or indicated by their title. The "Advanced Integrated Beam Design Program" by Engineering Software Company, can only analyze continuous beams for one load case, Rahimian (1992). The design capability of the program are limited and not clearly described.

Generally, most commercial software programs use the rules explicitly given in the design standard. These are minimum requirements and in some cases the standard refers to external references such as the Structural Stability Research Council's *Guide to Stability Design Criteria for Metal Structures*, Galambos (1988), for further guidance to solve more complex, often realistic problems. Such problems include Gerber system (Cantilever-link beam systems), see Clause 13.6 (c), CAN/CSA S16.1-M89; bending of monosymmetric shapes, see Clause 13.6(d), CAN/CSA S16.1-M89; and bending and torsion, see Clause 15.11, CAN/CSA S16.1-M89. The appropriate de-

S P A N D E F I N E		
Design Method: $\rightarrow$ E	Span Length: $\rightarrow$ 22.50000	
Initial Span Length	I Axis	F Axis
E Factor	1.00000	1.00000
Sliding Prevented	0	0
Span Length (SFD) $\rightarrow$ 22.50000		

Figure 1.1: Screen of design parameter definition, *Beam and Column Design* (ECOM 1991)

sign rules described in these references have also to be incorporated in member design programs.

Furthermore, it is risky to use some commercial software in which only limited technical explanation is given and thus there is no way to verify if the design procedures adopted are appropriate or not, i.e. “black box”. The authors of the structural analysis and design package, SODA, (Structural Optimization Design & Analysis), W.E.S., (1992), claim that the design generated is satisfactory according to CAN/CSA-S16.1-M84 and that the members are selected to be of least weight. A technical explanation of the algorithm for the optimization process for the least weight criteria is not given. It is not possible, except through hand computations, for the user to verify if the optimum solution has been determined. For beam design, the

program checks cross-sectional strength, lateral-torsional buckling capacity for one fixed braced length and live load deflection. Gerber system, beams subjected to load combinations that produce different unsupported lengths, beam with copes and/or different lateral supports, and beams that are subjected to torsion can not be designed by using this program. This severely limits its use in practical cases.

Therefore, it is still a challenge to develop a reliable and technically complete program in this area that addresses all the concerns as described.

1.3 An Innovative Approach in CAD Systems

Many CAD systems provide the basic functionality required by designers with little consideration of the development of graphics-oriented data structure and user friendly interfaces that model the design process, Anumba and Watson (1992). These must be considered in the development of the system to achieve an effective program.

The increasing and ultimately dominant use of the computers for all analysis, design and drafting process will demand radically new approaches to structural software design. One approach is to use interactive graphical methods for data input and output. The term "interactive graphics" is not clearly defined and often is used loosely when describing the attributes of a CAD systems. Some software described as interactive, actually consists of a graphics screen display for conventional numeric data input next to a representative figure (beam, column, structural frame or section) which does not respond to changes in the numbers. The reverse is more common, the program presents a figure with pertinent values noted, but does not have the capacity of changing the values on the screen, Brohn, (1992). An interactive graphics program is not just for ease of use, it should be designed to promote understanding of structural behaviour and it should feed back the information graphically required for verification and for checking the design, Brohn, (1992). Figure 1.2 shows a typical

Figure 1.2: A typical IDFSM screen of interactive user interface

user interface of the program IDFSM, which meets the requirements of interactive graphic CAD systems.

1.4 Objectives and Scope of Present Work

The present work serves as part an of effort to develop a state-of-the-art integrated system of modelling, analysis, design and detailing for steel structures. The interactive graphic program module, IDFSM, for **Interactive Design of Flexural Steel Members Subjected to Bending, and Combined Bending and Torsion**, performs a first-order elastic analysis and designs of single span beams and overhanging beams with any prescribed boundary conditions for any combination of in-plane bending and torsional

loadings. The beam is designed in accordance with CAN/CSA-S16.1-89 and the appropriate rules outlined in the Structural Stability Research Council's *Guide to Stability Design Criteria for Metal Structures*, Galambos (1988). Particular attention has been made to the detailed evaluation of lateral-torsional buckling capacity of the flexural members, taking account different in-plane and lateral supports, end coping, load patterns and torsional loadings. This has been coupled with a high level graphical user interface for defining, editing, interpreting and illustrating the design data. Scaled three dimensional structural member images are illustrated throughout the entire design process. The program IDFSM has been developed to function as an independent module and has also been designed to be integrated with a larger system for the analysis, design and detailing of steel structures. The program IDFSM can also be used as a research and teaching aid in structural engineering.

Chapter 2

COMPUTER AIDED MEMBER DESIGN PROCESS AND A DESCRIPTION OF THE CORRESPONDING USER INTERFACE

This chapter describes the member design process employed by the program IDFSM, which models that followed by structural engineers and gives the structural engineer the capacity to address strength, serviceability, architectural and economic limitations. Because of the graphics-oriented nature of the program IDFSM, each of these steps in the design process has its own representation in the form of a displayed screen or window, which is controlled by the buttons (menu items) of the same or higher levels. The design process, including limitations, will be described step by step along with the corresponding displayed screens or windows.

2.1 General

The member design process employed in program IDFSM consists of the following steps:

1. Selection of an existing job or creation of a new job.

The selection of an existing job implies that a file structure has been created to describe a flexural problem and demonstrates the program potential to be integrated subsequently into a general program for the design of steel structures.

2. Definition of the type of flexural member (Structural system, i.e. Gerber system, Beam to Girder/Column, OWSJ's, Plate Girder, Stub Girder or Floor).
3. Definition of section type and size, and member length.
4. Definition of in-plane and lateral supports, and stiffener and coping details.
5. Definition of loads and load combinations.
6. Selection of predefined design constraints (i.e. camber for dead load, deflection limitation, maximum member depth and minimum member width).
7. Selection of the appropriate solution strategy.
8. Elastic analysis and review of internal force distributions and deflected shapes.
9. Design check of an existing flexural member or an automatic design.
10. Review of design results and redesign with varied design parameters.
11. Production of engineering report (design notes and figures).

Member Description, Design Constraints and Design Options		Photo	Title	Date
Member Evaluation and Results		Return	Hardcopy name: mem_menu.ps Please wait	

FLEXURAL MEMBER DESCRIPTION

Structural System	Ok	Define/Check
Member Length, Section Type & Size	Ok	Define/Check
Support(s), Stiffener(s) & Cope(s)	Ok	Define/Check
Applied Loads	Ok	Define/Check
Internal Forces & Deflections	Ok	Check/Execute

DESIGN CONSTRAINTS

Camber for Dead Load:	No	Change
Deflection Limit(Live):	L/100	Change
Maximum Member Depth:	1000.0 (mm)	Change
Minimum Member Width:	100.0 (mm)	Change
Automatic Design	Check Member	

DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE

CAN/CSA-S16.1-M89	Yes	Ok	Default option (only for non-cantilever beams)
Modified SSRC Guide(1988)	Yes	Change	w2 value & load patterns (modifications (Kirby & Nethercot))
Schmitke and Kennedy(1985)	No	Change	Interactive buckling
Albert and Kennedy(1991)	No	Change	Finite element analysis

DEFAULT OPTIONS ARE HIGHLIGHTED. USE DEFAULT OPTIONS OR
MODIFY SELECTED OPTIONS BY PRESSING THE APPROPRIATE BUTTON

Figure 2.1: Main menu screen of the program IDFSM

The process is activated through buttons on the the program main menu, shown in Figure 2.1. A structural engineer should have no difficulty in using this program to design flexural members as each action results in instant, interactive and in most cases a graphical response.

2.2 Selection of An Existing Job or Creation of A New Job

The computer aided-design process begins with the job definition. Upon execution of the program, the following front menu page screen will be displayed:

New Design Problem	Photo	Date 18 Feb 1993
Read in Existing File	Exit Program	Hardcopy name 2_2.ps Please wait

IDFSM

Program for Interactive Design of Flexural Steel Members for Bending, Bending and Torsion

Version 1.0

by Yuxiang He

Thesis supervisor Stephen J. Kennedy

Department of Civil and Environmental Engineering
Carleton University
• February 1993

Figure 2.2: Front page of the program IDFSM

For starting a new design job, the **New Design Problem** option has to be selected from the front page screen and the user will be prompted to type in the job title and job description as shown in Figure 2.3.

New Design Problem	Photo	Title	Date 7-Jan 1993
Read in Existing File	Exit Program	Hardcopy name 2_3.ps	Please wait.

Job Title

Description

Figure 2.3: New job definition screen

To access an existing job, select the **Read in Existing File** option from the front page screen. Figure 2.4 shows the corresponding screen in which the program will read in the job catalog from the data base.

New Design Problem	Photo	Date: 7-Jan-1993
Read in Existing File	Exit Program	Hardcopy name: 2_4.ps Please wait...

JOB (FILE NAME) SELECTION TABLE

Job title	Description
verification_0	laterally supported beam (cantilever span of gerber system)
verification_4	overhang span (laterally supported along top flange)
cisc	Gerber System Design (cantilever span)
try7	4 lateral support types
example_5	Cantilever beam with different lateral supports
example_5_2	-----
example_5_3	-----
example_5_4	-----
example_5_5	-----
example_6	laterally unsupported beam(example 5.6 in text book page 139)
example_7	torsion (different load patterns)
cisc_2	gerber girder system, cantilever span
cisc_3	gerber girder system, cantilever span
cisc_4	beam with one overhang
example_7_1	torsion (different load patterns)

Figure 2.4: Job catalog listing

By selecting the **Accept** option, the existing file is read in or a new file is created and the program will return to the main menu as shown in Figure 2.1.

2.3 Structural System

Selecting the **Check/Define** button for **Structural System** from the main menu as shown in Figure 2.1, will activate the next step of the member design process and the screen shown in Figure 2.5 will be displayed.

Gerber System	Beam to Girder/Column	Photo	Title: unt	Date: 7-Jan-1993
MAXIMUM	ADD LATERAL SUPPORT	Return	Hardcopy name: 2_5.ps Please wait.	

Cantilever span

Suspended span

Noncomposite

	Laterally unsupported member	
	Laterally supported Member (along the top flange only)	
	Laterally supported member	

Figure 2.5: Structural system selection screen: Gerber Girder

The types of the flexural members that are designed by this program are clearly defined. The two options that are currently active are: **Gerber System** and **Beam to Girder/Column**. Future modules will be written to design OWSJ's, plate girders, stub girders and various floor systems. The Gerber system selection shown in Figure 2.5 gives the option to the structural engineer to design either the cantilever or suspended span and to define basic lateral support(s). This sets up the graphics

display for the remaining steps in the design process.

If the **Beam to Girder/Column** flexural member is selected then, various configuration of beams are displayed as shown in Figure 2.6. All possible framing patterns are illustrated. As before, the selection of any configuration sets up the graphics display for the remaining steps in the design process. Options under the **Composite** category are not currently active. The selection of the **Return** button returns to the main menu, displaying it on the computer screen. Once this design step is completed, the indicator on the main menu beside the structural system button will display **Ok**.

Girder System	Beam to Girder/Column	Photo	File Unit	Date 7 Jan 1988
Return	Beam to Girder/Column	Return	Hardcopy name: 2_5.ps Please wait.	

Beam to girder at both ends	Beam to column at both ends	Beam to column and on girder
Beam on girder at both ends	Beam to column at one end	Beam to column and to girder
Beam to girder and on girder	Beam to column and on column	Beam to girder and on column

Noncomposite <table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td style="background-color: #cccccc;">Laterally unsupported member</td><td style="width: 20px;"></td></tr> <tr><td style="background-color: #cccccc;">Laterally supported Member (along the top flange only)</td><td></td></tr> <tr><td style="background-color: #cccccc;">Laterally supported member</td><td></td></tr> </table>	Laterally unsupported member		Laterally supported Member (along the top flange only)		Laterally supported member		Composite <table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td style="background-color: #cccccc;">[Blank]</td><td style="width: 20px;"></td></tr> <tr><td style="background-color: #cccccc;">[Blank]</td><td></td></tr> <tr><td style="background-color: #cccccc;">[Blank]</td><td></td></tr> </table>	[Blank]		[Blank]		[Blank]	
Laterally unsupported member													
Laterally supported Member (along the top flange only)													
Laterally supported member													
[Blank]													
[Blank]													
[Blank]													

Figure 2.6: Structural system selection screen: Beam to Girder/Column

2.4 Definition of Member Length, and Section Type and Size

The next step in the design process, is the definition of member length, and section type and size, which is achieved by selecting corresponding **Check/Define** button in the main menu as shown in Figure 2.1. The program will display the following menu and image:

Member Length (mm)		Photo		File unit	Date 7 Jan 1988
Section Type and Size		Return		Hardcopy name 2.7.ps Please wait	

Current Section: W530x150 300W

	Member Section					
Depth	W	W	W	W	W	W
	Relative Weights					
W530x150	150	150	150	150	150	150
W530x140	140	140	140	140	140	140
W530x130	130	130	130	130	130	130
W530x120	120	120	120	120	120	120
W530x110	110	110	110	110	110	110
W530x100	100	100	100	100	100	100
W530x90	90	90	90	90	90	90
W530x80	80	80	80	80	80	80
W530x70	70	70	70	70	70	70
W530x60	60	60	60	60	60	60
W530x50	50	50	50	50	50	50
W530x40	40	40	40	40	40	40
W530x30	30	30	30	30	30	30
W530x20	20	20	20	20	20	20
W530x10	10	10	10	10	10	10

Depth
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10

	Member Section					
Depth	W	W	W	W	W	W
	Relative Weights					
W530x150	150	150	150	150	150	150
W530x140	140	140	140	140	140	140
W530x130	130	130	130	130	130	130
W530x120	120	120	120	120	120	120
W530x110	110	110	110	110	110	110
W530x100	100	100	100	100	100	100
W530x90	90	90	90	90	90	90
W530x80	80	80	80	80	80	80
W530x70	70	70	70	70	70	70
W530x60	60	60	60	60	60	60
W530x50	50	50	50	50	50	50
W530x40	40	40	40	40	40	40
W530x30	30	30	30	30	30	30
W530x20	20	20	20	20	20	20
W530x10	10	10	10	10	10	10

Depth
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10

	Member Section					
Depth	W	W	W	W	W	W
	Relative Weights					
W530x150	150	150	150	150	150	150
W530x140	140	140	140	140	140	140
W530x130	130	130	130	130	130	130
W530x120	120	120	120	120	120	120
W530x110	110	110	110	110	110	110
W530x100	100	100	100	100	100	100
W530x90	90	90	90	90	90	90
W530x80	80	80	80	80	80	80
W530x70	70	70	70	70	70	70
W530x60	60	60	60	60	60	60
W530x50	50	50	50	50	50	50
W530x40	40	40	40	40	40	40
W530x30	30	30	30	30	30	30
W530x20	20	20	20	20	20	20
W530x10	10	10	10	10	10	10

Depth
150
140
130
120
110
100
90
80

Figure 2.7: Member length, section type and size definition screen

With this screen, the member length, and the section type and size can be defined interactively.

Section type and size

Although all the standard shapes given in the CISC Handbook , CISC (1991) are tabulated in **Member Selection** subwindow, only the W and WWF sections are currently active. The section type and size is selected by activating the appropriate buttons within the subwindow. The structural engineer may scroll through the table to find the appropriate section. The geometric data associated with the sections shown in the **Member Section and Size** subwindow are stored in a data base that is accessed during the design process when:

1. a section's capacity is checked, or when
2. a auto-designed shape and size is not available under user situation. In this case, similar size may be selected and checked.

The section and an image of the member are displayed immediately after selection is made. Activating the **Return** button returns to the main menu screen.

The following screen will be displayed when the **Member length (mm)** button is selected:

Figure 2.8: Member length definition screen

17

2.5 Support, Stiffeners and End Coping Definition

2.5.1 In-plane support

Selecting the **Support(s), Stiffeners & Copes(s)** option in main menu will display the following window:

Figure 2.9: In-plane support definition screen

With this window, the supporting graphics for definition of in-plane support conditions is displayed automatically.

Definition of in-plane support includes a description of:

- the section (W or WWF) and size of in-plane support;

- the orientation of support column (column web parallel or perpendicular to the orientation of the member (screen), if applicable);
- the end conditions of support (simple or moment resistant connections, if applicable).

Note, no response will be given to selection of end conditions that are impossible for the structural system specified. For example, the selection of simple support condition for a cantilever will not be accepted. For a suspended span of Gerber girder, a fixed support is not allowed. All default conditions are highlighted in the corresponding buttons.

2.5.2 Lateral support

Selection the **Lateral Support(s)** option will result in either an image showing the lateral support conditions for a predefined problem, or for a new design problem, the following screen will be displayed. For predefined structural systems, the structural engineer may verify it visually and has the option to make modifications. For new problems the structural engineer must build the lateral support system according to the prompts given.

In-Plane Support(s)	Lateral Support(s)	Photo	Title Unit	Date 7-Jan-1993
Cope(s) and End Stiffener(s)	Return	Hardcopy name 2 10 ps Please wait		

Are you sure support is at 14000.0 mm? ☐

Figure 2.10: Lateral support definition screen 1

The structural engineer will be asked to specify the lateral supports in the main span and then the left and right overhanging spans if applicable. If the answer to the question displayed is yes, "y" for example, then the screen shown in Figure 2.11

In-Plane Support(s)	Lateral Support(s)	Photo	Title: unt	Date: 7-Jan-1993
Cope(s) and End Stiffener(s)		Return	Hardcopy name: 2.11.ps Please wait	

Lateral Support Options		<div style="display: flex; justify-content: space-around; font-size: 0.8em;"> 51015204560 </div> <div style="display: flex; justify-content: space-around; font-size: 0.8em;"> Rotate OverRotate UnderMove Right </div> <div style="display: flex; justify-content: space-around; font-size: 0.8em;"> Rotate RightRotate LeftMove Left </div> <div style="display: flex; justify-content: space-around; font-size: 0.8em;"> Rotate CWRotate CCWMove Up </div> <div style="display: flex; justify-content: space-around; font-size: 0.8em;"> Zoom InZoom OutWeld cap </div>
<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">W-Shape Beam-Joint</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ Beam to girder web </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ Beam on top of girder flange </div>	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">Open Web Steel Joists</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ Top and bottom chords of OWSJ's </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ Top chord of OWSJ's </div>	
<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ From far side of main member </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ From near side of main member </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> ☐ From both edges of main member </div>		

Figure 2.11: Lateral support definition screen 2

will appear, prompting for the location and then for the type as indicated in Figure 2.12. In this program, four typical lateral support types are identified (beam to girder web, beam on top of girder flange, top and bottom chord extension of OWSJ's, and top chord of OWSJ's), each of which has a different effect on lateral-torsional buckling capacity of the flexural member being designed. The correct estimation of the corresponding moment capacity for lateral segments with different lateral supports is described in Chapter 4. The structural engineer may select any one of the four different lateral supports shown.

The lateral support definition process described above is repeated until all the desired lateral supports have been added. It is possible to specify no lateral support. For the case of Gerber systems or overhanging beams, the program specifically recog-

In-Plane Support(s)	Lateral Support(s)	Phone	Title	Date
			unt	7 Jan 1993
Cope(s) and End Stiffener(s)		Return	Hardcopy name 2_12 ps Please wait	

Current lateral support location

Please select lateral support type

Done

Lateral Support Options			
W-Shape Beam/Joist		Open Web Steel Joists	
☐ Beam to girder web	☐ Top and bottom chords of OWSJ's		
☐ Beam on top of girder flange	☐ Top chord of OWSJ's		
☒ From far side of main member ☐ From near side of main member ☐ From both sides of main member			

5	10	15	20	45	60	Original Figure
Rein Over	Rein Under					More Right
Rein Right	Rein Left					More Left
Rein CW	Rein CCW					More Up
Zoom In	Zoom Out					More Near

Figure 2.12: Lateral support definition screen 3

nizes that some form of lateral support should be provided at the in-plane supports to eliminate potential stability problems. the minimum requirement must be some form of lateral support or a pair of bearing stiffeners over the supports. If these are not specified, then the program will automatically provide a pair of bearing stiffeners.

2.5.3 Definition of end coping details and bearing stiffeners

Selecting the **Cope(s) and Bearing Stiffener(s)** option generates the window for definition of coping and bearing stiffeners as shown below.

In-Plane Support(s)		Lateral Support(s)		Photo		Title: disc 4		Date: 21 Feb 1993	
Cope(s) and End Stiffener(s)				Return		Hardcopy name: 2_13.ra Please wait			

Cope Location	Top Flange Tip Copes	Bottom Flange Tip Copes	Top Flange Cope	Bottom Flange Cope

of Copes	Width = 0.00 mm	Change	Width = 0.00 mm	Change	Depth = 0.00 mm	Change	Depth = 0.00 mm	Change
Top Stiffener	Not Applicable	Change	Not Applicable	Change	Not Applicable	Change	Not Applicable	Change

Cope length along the beam = 100.00 mm (At each applicable location)	Change
--	--------

NOTE: COPING PATTERN AT EACH APPLICABLE BEAM END MUST BE THE SAME

<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="padding: 2px;">Stiffeners at left support: Not applicable</td> <td style="width: 10%;"></td> </tr> <tr> <td style="padding: 2px;">Right Support: Bearing Stiffener Added</td> <td style="padding: 2px;">Change</td> </tr> <tr> <td colspan="2" style="padding: 2px;">Depth x Width = 428 mm x 90 mm (a pair)</td> </tr> <tr> <td colspan="2" style="padding: 2px;">Thickness = 6 mm</td> </tr> </table>	Stiffeners at left support: Not applicable		Right Support: Bearing Stiffener Added	Change	Depth x Width = 428 mm x 90 mm (a pair)		Thickness = 6 mm
Stiffeners at left support: Not applicable									
Right Support: Bearing Stiffener Added	Change								
Depth x Width = 428 mm x 90 mm (a pair)									
Thickness = 6 mm									

Figure 2.13: Cope(s) and bearing stiffener(s) definition screen

End coping details

Copes in beams are made for fit and for ease of erection. These reduce the cross-section at the connections and reduce the lateral-torsional buckling capacity. Two types of coping details considered in the program, with the corresponding dimensions (width, length, and depth) are illustrated in Figure 2.13.

The default values, for the cope dimensions are 0.0 mm. To change these values,

simply select the corresponding **Change** buttons and enter the new value from the keyboard into the window provided. The following geometric restrictions are applied to the cope dimensions:

- for **Flange Tip Copes**, the

$$Width \leq \left(\frac{b}{2} - k \right)$$

- for **Flange cope's**, the

$$Depth \leq \frac{1}{5} \times d$$

$$Length \leq 2 \times d$$

where, d = section depth, mm

b = flange width, mm

k = the distance the distance from outer face of flange to web-toe of fillet of the member (I-shape), mm

If copes are made in both the top and bottom flanges , then the dimensions specified must be the same. Only one type of cope, either flange tip copes or flange cope, can be made for a given location, i.e. top flange cope.

Bearing stiffeners definition

Bearing stiffeners may be required to resist the local buckling of the web or to provide lateral-torsional support in the case where lateral support at top of the flange is missing. The program will automatically check through these two requirements to determine whether or not bearing stiffeners are necessary. The structural engineer may add stiffeners over the supports by selecting the **Change** button(s) for the left or right in-plane support location. The pair of bearing stiffeners have a length equal to

the full member web length and with a width not less than 10.0 mm and not beyond the tips of flanges. The program will determine the minimum thickness automatically ensuring Class 3 behaviour.

Return to main menu

Upon finishing up the definition of in-plane and lateral support, coping and stiffeners, select the **Return** button and the main menu screen shown in Figure 2.1 will be displayed. The indicator attached to the **Support(s), Stiffener(s) & Cope(s)** option, will read **Ok**.

2.6 Applied Load Description

2.6.1 General

The applied loads acting on a flexural member can be defined interactively and semi-automatically in the program IDFSM by selecting the **Applied Loads** option button in the main menu shown in Figure 2.1, displaying the following screen for new design problems:

Dead Load	Live Load 1	Live Load 3	Show All Loads	Photo	Title unit	Date 7 Jan 1993
Wind Up Lift	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name 2 14 ps Please wait	

Figure 2.14: Load definition screen 1

The program is capable of defining six load cases with a total of four load combinations. All load entries are defined as specified loads. Each load case may consist of any number of different load pattern types which include uniformly distributed loads.

concentrated loads and linearly varying distributed loads. In addition, torsional loads may be applied on any lateral unsupported segments provided that no adjacent such segments are subjected to torsional loadings for same load combination.

2.6.2 Semi-automatic load definition for lateral supported points

Upon selecting the load case from the menu as shown in Figure 2.14, the program will automatically show, one by one, the load types and locations. Where sub-members frame into the beam, the program will prompt for concentrated loads, as illustrated in Figure 2.15, and it will automatically apply a uniformly distributed dead load for self weight.

Figure 2.15: Load definition screen 2

2.6.3 Additional transverse/torsional load definition

When the semi-automatic load definition process is over, the following messages will appear on the screen.

Add additional transverse/torsional loads (y/n)?

Add load at main span (y/n)?

If the answers to these questions are all yes, "y", then additional windows will be displayed on the screen.

Dead Load	Live Load 1	Live Load 3	Show All Loads	Photo	File unit	Date 7-Jan-1993
Wind Up Lift	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name 2_16.ps Please wait	

Load Case 1: Dead Load

Please select load types

Done

Load Type	
<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">☐ Concentrated Load</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">☐ Uniformly Distributed Load</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">☐ Linearly Varying Dist. Load</div>	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">☐ Far side torsional loading</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">☐ Near side torsional loading</div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;">☐ Nontorsional loading</div>

Figure 2.16: Load definition screen 3: Load type definition

At this stage, one set of loads of any type including torsional loads can be added. The following parameters must be defined to describe each load type: load type, location, eccentricity of load (for torsional loads only) and the magnitude of the load.

With the graphical interface, the structural engineer should have no difficulty at all to define complicated load cases. The program does not use any cryptic data input nor does it require any prescribed format. The response to input is automatic and is shown graphically on the screen making verification easier. Various stages of the load description process are illustrated in Figure 2.16 through 2.19. Each load case can be reviewed by selecting the corresponding load case button or the **Show All Loads** option. Using the view control buttons located in the lower right hand corner of the screen, the structural engineer can scroll through and verify all of the service loads acting on the beam. An example summary for a complex set of loads for a dead load case is illustrated in Figure 2.20.

A positive load value corresponds to a load acting in the same direction as shown on the load diagram. A negative load value implies that the direction of the load is opposite to that illustrated on the screen. Similar procedures can be followed to change the loads or make corrections.

Dead Load	Live Load 1	Live Load 3	Show All Loads	Photo	Title unit	Date 7 Jan 1993
Wind Up Lift	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name 2.16 ps Please wait.	

Load Case 1 Dead Load

Load Type	
☐ Concentrated Load ☐ Uniformly Distributed Load ☐ Linearly Varying Dist. Load	☐ Far side torsional loading ☐ Near side torsional loading ☐ Nontorsional loading

Figure 2.18: Load definition screen 5: Load eccentricity

Dead Load	Live Load 1	Live Load 3	Show All Loads	Photo	File .xml	Date 7-Jan-1993
Wind Up Lift	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name 2_19.pl Please wait	

Load Case 1 Dead Load

Load Type

☐ Concentrated Load	☐ Far side torsional loading
☐ Uniformly Distributed Load	☐ Near side torsional loading
☐ Linearly Varying Dist. Load	☐ Nontorsional loading

Figure 2.19: Load definition screen 6: Load value

Dead Load	Live Load 1	Live Load 3	Show All Loads	Phase	Title: untitled	Date: 2 Feb 1993
Wind Up Lift	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name: 2_20.plt Please wait	

Load Case 1: Dead Load

Load Type				Display Figure	
☐ Concentrated Load	☐ Far side torsional loading	☐ Zoom in	☐ Zoom Out	☐ Move Right	☐ Move Left
☐ Uniformly Distributed Load	☐ Near side torsional loading	☐ Move Up	☐ Move Down	☐ Move Right	☐ Move Left
☐ Linearly Varying Dist. Load	☐ Nontorsional loading				

Figure 2.20: Load definition screen 7: Dead load summary

2.6.4 Load combinations

By selecting the **Load Factor** option in the load definition screen, the structural engineer will be able to define up to four different load combinations. Each load combination consists of a series of specified load sets which are multiplied by the appropriate load factor as defined in Clause 4.1.4 of the National Building Code of Canada, NBCC (1990). To change a load factor, the cursor is moved to the load factor to be changed and the mouse button is pressed. The program will then prompt with a small window as shown in Figure 2.21, for the new load factor value.

Dead Load	Live Load 1	Live Load 3	Show All Loads	Photo	File Print	Date 2 Feb 1993
Wind Up Lift	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name: 2.21.ps Please wait	

LOAD FACTOR

Load Description	Load Combination 1	Load Combination 2	Load Combination 3	Load Combination 4
Dead Load	1.00	Please type new load factor for Dead load		
Wind upward	0.00			
Live load 1	0.00	0.00	0.00	0.00
Live load 2	0.00	0.00	0.00	0.00
Live load 3	0.00	0.00	0.00	0.00
Live load 4	0.00	0.00	0.00	0.00

Figure 2.21: Load definition screen 8: Load factors

2.6.5 Return to main menu

Once the definition of all loads acting on the member are complete, select the **Return** option and the main menu, shown in Figure 2.1 will be displayed. The indicator attached to the **Applied Loads**, will read **Ok**.

2.7 Determination of Internal Forces and Deflections

If the **Internal Forces & Deflections** option on the main menu is selected, the program will execute the analysis modules and display the results with the bending moment diagrams being the default display, as shown in Figure 2.22. Selecting the options in the menu will display the corresponding internal force and deflection diagrams. By using the view control buttons located in the lower right hand corner of the screen, the structural engineer can review the diagrams for each load combination. The analysis modules incorporated into the program are described in Chapter 3. The selection of the **Return** option any time during the review process will return to the main menu screen.

Figure 2.22: Screen for displaying of internal force diagrams and deflected shapes

2.8 Design Constraints and Solution Strategies

The limitations or constraints imposed by the architect, fabricator and/or structural engineer, as well as the option of invoking different levels of sophistication of solutions should be explicitly incorporated into the design process. This is accomplished through two series of buttons in the programs main menu entitled, "DESIGN CONSTRAINTS" and "DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCES" as shown in Figure 2.1.

Under the category "DESIGN CONSTRAINTS", the structural engineer is able to specify:

1. **Camber for Dead Load** where the deflection for the specified dead load and sustained live load will be calculated and reported as a prescribed camber.
2. **Deflection Limit (Live)** where the limit for specified live load deflections are specified in terms of the span length "L". The term span refers to the length between in-plane supports or the length of the overhangs. Recommended values for the limits may be found in Appendix I in CAN/CSA S16.1-M89.
3. **Maximum Member Depth** sets the maximum depth allowable for the flexural member (generally an architectural constraint).
1. **Minimum Member Width** sets the minimum flange width allowable for the flexural member (generally a fabricator constraint).

A large number of beam design problems can be handled adequately using the rules specified in CAN/CSA S16.1-M89. However, for continuous beams and for special systems like the Gerber system, more sophisticated solution techniques are required to obtain the best possible design. The CAN/CSA S16.1-M89 option is always executed as a minimum requirement. The beam designed for this option can

be compared directly to the beam designed for the user specified solution. The option is both functional and educational. A detailed descriptions of the different solution strategies available are given in Chapter 4.

The structural engineer may conduct a member check for existing members or **Automatic Design**, in which the member will be designed to give a least weight section and to meet all design constraints by selecting the appropriate option. The results of the design can be obtained and viewed by selecting the **Member Evaluation and Results** option.

2.9 Design Status

Each step of the member design process has a small window which indicates whether or not the work within that step is complete with a corresponding **Ok** or **NotOk** response. If a design parameter or condition is changed in one step, others may be affected and their status might change if more work is required. For example, changing the applied loads would require the structural engineer to recompute the internal forces and deflections, and then redesign the member. This system helps to provide a simple, easy to follow interface for designing beams.

2.10 Representation of Design Results

2.10.1 On screen display

If all the design parameters under "Flexural Member Description" category have been defined, (with each of status indicator showing **Ok**) and other design criteria options decided, either by user actions or by default settings, the selection of the **Member Evaluation and Results** option in the upper part of screen for main menu will cause the program to execute member check or automatic design. Following the completion of this step, the screen illustrated in Figure 2.23 will be shown.

Member Description, Design Constraints and Design Options		Photo	File disc	Date 1 Jan 1993
Member Evaluation and Results		Return	Hardcopy name: disc_result_2.ps Please wait	

EVALUATION RESULTS		REPORT	
Moment: $M/M_r = 0.40$	Ok	Suggested Member Size: W460x158 300W	
Shear force: $V/V_r = 0.14$	Ok	Structural Image	
Bearing: $B/B_r = 0.40$	Ok	Summary Report Detailed Report	
Max Deflection: $L/2885$ (Dead, vertical) $L/262$ (Live, vertical)	Ok	CAN/CSA-S16.1-M89 Solution	
Max Depth Limit = 1000 mm, Min Width Limit = 100 mm	Ok	User Specified Solution	

ENGINEERING REPORT	
Date: 1-Jan-1993	
Job title: disc 1	
Job description: Gerber System Design (cantilever span)	
DESIGN CONSTRAINTS	
Camber for Dead Load: No	
Deflection Limit (Live) = $L/250$	
Maximum Member Depth = 1000.0 mm	
Minimum Member Width = 100.0 mm	
Design Type: Automatic Design	
DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE	
CAN/CSA S16.1-M89: Yes	
SSRC Guide: Yes	
Smitke and Kennedy (1985): No	
Albert and Kennedy (1991): No	

Figure 2.23: Screen for "Member Evaluation and Results"

This screen gives:

1. the section of the member checked or selected;
2. a very brief summary of the member capacity and whether or not it is satisfactory with respect to serviceability and geometric constraint criteria. The capacity of the member is expressed as a ratio of the maximum factored load to the factored resistance and has a value less than or equal to 1.0 if it is satisfactory. The corresponding indicator will read **Ok**;
3. a button entitled, **Structural Image**, which when activated will instruct the program to show the flexural member and in-plane and lateral supports in the window provided;
4. a button entitled, **Summary Report**, which when activated will display an engineering report in the window provided for review.
5. a button entitled, **Detailed Report**, which when activated will display a detailed engineering report for review.

The buttons entitled, **CAN/CSA-S16.1-M89**, and, **User Specified Solution**, specify the solution to be shown on screen. A description of the contents of the summary and detailed reports is given in the next section.

2.10.2 Output files

The program IDFSM is capable of producing both the summary and detailed reports, in the form of computer files. Each can be combined with optional graphic output specified by the user.

The summary report contains all user defined and/or default design parameters, with the exception of the applied loads which can be reported graphically; and gives

File description	File directory	File type	File prefix	File suffix
summary report	data2	ascii text	(Job name)	.sum
detailed report	data2	ascii text	(Job name)	.det
screen image	data2	PostScript	(Job name)	.ps

Table 2.1: Output file formats

the appropriate resistance values and the corresponding ratios. Example contents are given in Chapter 7 (Section 7.7). This report is available from the beginning of the design process, and its contents may vary depending upon the position of the user within the design process.

The detailed report provides all the intermediate design checks, for each load combination, as well as the results from the structural analysis. Example contents are given in Chapter 7 (Section 7.3 and 7.9).

A **Photo** button is included in each screen of the program IDFSM. The selection of this button at specific screen would generate a PostScript file of this window that may contain the non-menu part of the screen or entire screen as specified by the user. The user must specify the prefix file name for each PostScript file. This facility enables the structural engineer to obtain a hard copy of the structural image, load definitions, internal force diagrams and any other displays of the screen. All user-related output file formats are described in Table 2.1.

With these output files available, the design performed by the program IDFSM will not be a "black box", as is the case with most existing design software.

Chapter 3

ANALYSIS MODELLING

The two analysis modules in the program IDFSM are capable of analyzing the flexural members identified in the program for the internal forces – moments, shears, torques (where applicable), and for deflections. The first of the two modules, is based on PLFRAM, an independent plane frame analysis program developed by Murray (1988). Modifications have been made to this program for its use within the program IDFSM and are described in Section 3.1. The second module is for torsional analysis and consists of a number of subroutines from another independent program TORSTEEL. The analysis procedures, described in AISC (1983), are summarized in this chapter.

3.1 Module PLFRAM

The PLFRAM program module was developed for the analysis of plane frame structures and utilizes the stiffness method to perform first-order elastic analysis. The shear deformation of the flexural members are not included in the stiffness formulation. The analytical procedure is well document in the program code.

The program PLFRAM is integrated to main program by system calls from within the program IDFSM. The input and output data are exchanged between PLFRAM

and IDFSM by file transmission. The modifications have been made in the input data processing portion of the program PLFRAM to automate data input file generation from less cryptic graphical input and to automatically generate 100 submembers and the corresponding load definitions with any span. The second modification was required to obtain accurate descriptions of internal force distributions and of the deflected shape, as the original version of PLFRAM only gives the internal forces at member ends and the deflections at nodal points. The analytical procedures followed, input and output modifications made for IDFSM (dashed blocks) are shown in the block diagram in Figure 3.1.

The diagrams for shear force, bending moment and deflected shape can be viewed on the screen as shown in a typical display in Figure 2.22. The bending moments are plotted on the tension side of the member. The maximum internal force values and the maximum deflection, for each span, are shown on the diagrams. The deflected shape is proportional but not drawn to scale. The values associated with these diagrams are listed in the detailed report for each load combination.

Figure 3.1: Block diagram for incorporating PLFRAM module

3.2 Analysis for Torsion and Bending

3.2.1 General procedure

A beam will be subjected to combined bending and torsion when the transverse forces pass through any point other than the shear centre of the section. When the deformations caused by these loads are small (general structural engineering assumption and definition), then the bending and torsional loads can be evaluated separately. Bending moments and shear forces and the corresponding stresses due to the transverse load are calculated using the first order elastic analysis described in Section 3.1. The internal torque and the corresponding stresses are determined using a classic first order elastic analysis outlined in ASIC (1983) and summarized in Section 3.2.2. Once the internal forces due to transverse loads and torsional loads have been obtained, an evaluation of a beam and its redesign can be conducted using the method outlined in Driver and Kennedy (1989) as described in Section 4.6.

3.2.2 Torsional solution

The resistance of a cross section to a torsional moment T may be considered to be the sum of two components, Kollbrunner and Basler (1969). The first is the resistance to uniform torsion (St. Venant's torsion), T_1 , while the second is the non-uniform torsion (Warping torsion), T_2 .

Uniform torsion

The general orientation of a I-shape beam in torsional loading is illustrated in Figure 3.2. The term "I-shaped" means any doubly-symmetric shape having two flanges and one web. At any point along the length of the member subjected to torsional moment, the cross section will rotate through an angle of ϕ . For noncircular cross

sections, this rotation is accompanied by warping. Transverse sections do not remain plane after deformation. When the rate of change of the angle of twist is constant along the member, the longitudinal warping deflections are also constant along the member. It is in a state of uniform torsion or St. Venant torsion. The torsional moment, T_1 , resisted by the section is:

$$T_1 = GJ \frac{d\phi}{dZ} \quad (3.1)$$

where,

G = shear modulus of elasticity, (for steel, $G = 77\,000$ MPa)

J = torsional constant for the cross section, mm^4

Figure 3.2: General orientation of member in torsion. AISC (1983). p.6

Uniform torsion occurs when the torque is constant and the ends of the member are free to warp. In this case, the torque acting at any cross-section is resisted by a set of shear stresses distributed around the cross-section.

Non-uniform torsion

When the tendency for a cross section to warp freely is prevented or restrained, then the angle of twist varies along the member, causing a state of non-uniform torsion.

Kollbrunner and Basler (1969). In this case, the warping deflections vary along the member, and an additional set of shear stresses and warping normal stresses may be developed to form an additional torque T_2 for resisting the torque acted on the member in conjunction with T_1 due to uniform torsion. The T_2 and the angle of twist have following relationship:

$$T_2 = -EC_w \frac{d^3 \phi}{d^3 Z} \quad (3.2)$$

where

E = modulus of elasticity, (for steel, $E = 200\,000$ MPa)

C_w = warping torsional constant, mm^6

The total torsional resisting moment T for I-shaped beams is the sum of its St. Venant torsional capacity, T_1 and warping torsional capacity, T_2 , and is given as,

$$T = T_1 + T_2 = GJ \frac{d\phi}{dZ} - EC_w \frac{d^3 \phi}{d^3 Z} \quad (3.3)$$

Equation 3.3 can be rewritten as,

$$\frac{T}{EC_w} = \frac{1}{a^2} \frac{d\phi}{dZ} - \frac{d^3 \phi}{d^3 Z} \quad (3.4)$$

where, $a^2 = EC_w / GJ$

General solution

The general differential equation for a beam subjected to a concentrated torque, T_f , is

$$\frac{T_f}{EC_w} = \frac{1}{a^2} \frac{d\phi}{dZ} - \frac{d^3 \phi}{d^3 Z} \quad (3.5)$$

The general solution of which can be written as

$$\phi = A + B \cosh \frac{Z}{a} + C \sinh \frac{Z}{a} + \frac{MZ}{GJ} \quad (3.6)$$

where, the terms A , B and C are constants of integration which can be determined by evaluating the appropriate derivative of the general solution for the given boundary conditions. The torsional conditions and schematic representation of connections causing those conditions are illustrated in Figure 3.3. The corresponding physical and mathematical conditions are summarized in Table 3.1, where ϕ' and ϕ'' are the first and second derivatives of angle of twist, ϕ .

Mathematical Condition	Physical Condition	Torsional End Condition
$\phi = 0$	No rotation	Pinned or fixed end
$\phi' = 0$	Section cannot warp	Fixed end
$\phi'' = 0$	Section can warp freely	Pinned or free end

Table 3.1: Torsional boundary conditions, AISC (1983), p.80

For other torque distributions like uniformly and linearly varying torque moment distributions, similar solutions can be obtained by differentiating Equation 3.5 and analyzing the corresponding free body diagrams (see AISC 1983 for details). The twelve cases of different torsional boundary conditions and loading that have been incorporated into IDFSM are illustrated in Figure 3.4. The corresponding solutions, AISC (1983), are listed in Figure 3.5.

3.2.3 Program implementation

Subroutine **r123** (file: routines.torsteel.f) in the program IDFSM calculates the angle of twist ϕ , all its derivatives ϕ' , ϕ'' , ϕ''' and the corresponding internal torques for all cases identified in Figure 3.4. The block diagram and complete description, with examples, for the torsional analysis and design is given in section 4.6.

Figure 3.3: Torsional boundary conditions and schematic representation of the corresponding structural connection, AISC (1983), p.10

Note: The end restraints apply to torsional conditions only

Case	Torsional Loading	Torsional End Restraints		Remarks
		Left End	Right End	
1		Free $\phi = \phi' = 0$	Free $\phi' = 0$	Concentrated torques at ends of member with free ends
2		Fixed $\phi = \phi' = 0$	Fixed $\phi' = 0$	Concentrated torques at ends of member with fixed ends
3		Pinned $\phi = \phi' = 0$	Pinned $\phi = \phi' = 0$	Concentrated torque at $\alpha = 0.1, 0.3, \text{ or } 0.5$ on member with pinned ends
4		Pinned $\phi = \phi' = 0$	Pinned $\phi = \phi' = 0$	Uniformly distributed torque on member with pinned ends
5		Pinned $\phi = \phi' = 0$	Pinned $\phi = \phi' = 0$	Linearly varying torque on member with pinned ends
6		Fixed $\phi = \phi' = 0$	Fixed $\phi = \phi' = 0$	Concentrated torque at $\alpha = 0.1, 0.3, \text{ or } 0.5$ on member with fixed ends
7		Fixed $\phi = \phi' = 0$	Fixed $\phi = \phi' = 0$	Uniformly distributed torque on member with fixed ends
8		Fixed $\phi = \phi' = 0$	Fixed $\phi = \phi' = 0$	Linearly varying torque on member with fixed ends
9		Fixed $\phi = \phi' = 0$	Free $\phi' = 0$	Concentrated torque at $\alpha = 0.1, 0.3, 0.5, 0.7, 0.9, \text{ or } 1.0$ on member with fixed and free ends
10		Fixed $\phi = \phi' = 0$	Free $\phi' = 0$	Partial uniformly distributed torque along $\alpha = 0.1, 0.3, 0.5, 0.7, 0.9, \text{ or } 1.0$ with fixed end and free end
11		Free $\phi' = 0$	Fixed $\phi = \phi' = 0$	Linearly varying torque on member with free and fixed ends
12		Fixed $\phi = \phi' = 0$	Pinned $\phi = \phi' = 0$	Uniformly distributed torque on member with fixed and pinned ends

Figure 3.4: Various torsional loadings and end conditions. AISC (1983), p.26

SOLUTIONS TO DIFFERENTIAL EQUATIONS FOR VARIOUS LOADINGS AND BOUNDARY CONDITIONS

The following are the solutions of the differential equations using the proper boundary conditions. Take derivatives of ϕ equation to find ϕ' , ϕ'' , and ϕ''' .

CASE 1 $\phi = \frac{MZ}{GJ}$

CASE 2 $\phi = \frac{Ma}{GJ} \left(\tanh \frac{L}{2a} \cdot \cosh \frac{Z}{a} - \tanh \frac{L}{2a} + \frac{Z}{a} - \sinh \frac{Z}{a} \right)$

CASE 3 $0 \leq Z \leq aL$

$$\phi = \frac{ML}{GJ} \left[(1.0 - \alpha) \frac{Z}{L} + \left(\frac{\sinh \frac{\alpha L}{a}}{\tanh \frac{L}{a}} - \cosh \frac{\alpha L}{a} \right) \cdot \frac{a}{L} \cdot \sinh \frac{Z}{a} \right]$$

 $aL \leq Z \leq L$

$$\phi = \frac{ML}{GJ} \left[(L - Z) \frac{a}{L} + \frac{a}{L} \left(\frac{\sinh \frac{\alpha L}{a}}{\tanh \frac{L}{a}} \cdot \sinh \frac{Z}{a} - \sinh \frac{\alpha L}{a} \cdot \cosh \frac{Z}{a} \right) \right]$$

CASE 4 $\phi = \frac{ma^2}{GJ} \left[\frac{L^3}{2a^2} \left(\frac{Z}{L} - \frac{Z^3}{L^3} \right) + \cosh \frac{Z}{a} - \tanh \frac{L}{2a} \cdot \sinh \frac{Z}{a} - 1.0 \right]$

CASE 5 $\phi = \frac{mL}{GJ} \left[\frac{Z}{6L} - \frac{Z}{L} \cdot \frac{Z^3}{L^3} + \frac{a^2}{L^3} \cdot \frac{\sinh \frac{Z}{a}}{\sinh \frac{L}{a}} - \frac{Z^3}{6L^3} \right]$

CASE 6 $0 \leq Z \leq aL$

$$\phi = \frac{Ma}{(H+1)GJ} \left\{ \left[H \cdot \left(\frac{1}{\sinh \frac{L}{a}} + \sinh \frac{\alpha L}{a} - \frac{\cosh \frac{\alpha L}{a}}{\tanh \frac{L}{a}} \right) + \left(\sinh \frac{\alpha L}{a} - \frac{\cosh \frac{\alpha L}{a}}{\tanh \frac{L}{a}} + \frac{1}{\tanh \frac{L}{a}} \right) \right] \left[\cosh \frac{Z}{a} - 1.0 \right] - \sinh \frac{Z}{a} + \frac{Z}{a} \right\}$$

 $aL \leq Z \leq L$

$$\phi = \frac{Ma}{\left(1 + \frac{1}{H}\right)GJ} \left\{ \left[\frac{1}{H} \cdot \frac{1}{\sinh \frac{L}{a}} \left(\cosh \frac{\alpha L}{a} - 1.0 \right) + \frac{\left(\cosh \frac{\alpha L}{a} - \cosh \frac{L}{a} + \frac{L}{a} \cdot \sinh \frac{L}{a} \right)}{\sinh \frac{L}{a}} \right] + \cosh \frac{Z}{a} \left[\frac{1}{H} - \frac{1}{\tanh \frac{L}{a}} \left(1.0 - \cosh \frac{\alpha L}{a} \right) + \frac{\left(1.0 - \cosh \frac{\alpha L}{a} \cdot \cosh \frac{L}{a} \right)}{\sinh \frac{L}{a}} \right] + \sinh \frac{Z}{a} \left[\frac{1}{H} \left(\cosh \frac{\alpha L}{a} - 1.0 \right) + \cosh \frac{\alpha L}{a} \right] - \frac{Z}{a} \right\}$$

$$\text{Where: } H = \frac{\left[-\frac{1}{\sinh \frac{L}{a}} \left(\cosh \frac{L}{a} + \cosh \frac{\alpha L}{a} \cdot \cosh \frac{L}{a} - \cosh \frac{\alpha L}{a} - 1.0 \right) + \frac{L}{a} (\alpha - 1.0) - \sinh \frac{\alpha L}{a} \right]}{\left[-\frac{1}{\sinh \frac{L}{a}} \left(\cosh \frac{L}{a} + \cosh \frac{\alpha L}{a} \cdot \cosh \frac{L}{a} - \cosh \frac{\alpha L}{a} - 1.0 \right) + \frac{L}{a} (\alpha - 1.0) - \sinh \frac{\alpha L}{a} \right]}$$

Figure 3.5: Solutions for different torsional loadings and boundary conditions, AISC (1983), p.85

CASE 7 $\phi = \frac{mLa}{2GJ} \left[\left(\frac{1 + \cosh \frac{L}{a}}{\sinh \frac{L}{a}} \right) \left(\cosh \frac{Z}{a} - 1.0 \right) + \frac{Z}{a} \left(1 - \frac{Z}{L} \right) - \sinh \frac{Z}{a} \right]$

CASE 8 $\phi = \frac{mL^2}{GJ} \left\{ \left[\frac{a}{2L \sinh \frac{L}{a}} - S \cdot \tanh \frac{L}{2a} \right] \cdot \left(\cosh \frac{Z}{a} - 1.0 \right) + S \cdot \left(\sinh \frac{Z}{a} - \frac{Z}{a} \right) - \frac{Z^3}{6L^3} \right\}$

Where: $S = \frac{\left(\cosh \frac{L}{a} - 1.0 \right) \cdot \frac{a}{2L} - \frac{\sinh \frac{L}{a}}{6.0}}{\left(\frac{L}{a} \sinh \frac{L}{a} + 2.0 - 2 \cosh \frac{L}{a} \right)}$

CASE 9 $0 \leq Z \leq aL$
 $\phi = \frac{Ma}{GJ} \left[\left(\sinh \frac{aL}{a} - \tanh \frac{L}{a} \cdot \cosh \frac{aL}{a} + \tanh \frac{L}{a} \right) \left(\cosh \frac{Z}{a} - 1.0 \right) - \sinh \frac{Z}{a} + \frac{Z}{a} \right]$
 $aL \leq Z \leq L$
 $\phi = \frac{Ma}{GJ} \left[\left(\tanh \frac{L}{a} \cdot \cosh \frac{aL}{a} - \tanh \frac{L}{a} - \sinh \frac{aL}{a} \right) - \left(\cosh \frac{aL}{a} - 1.0 \right) \right.$
 $\left. \left(\tanh \frac{L}{a} \cdot \cosh \frac{Z}{a} \right) + \left(\cosh \frac{aL}{a} - 1.0 \right) \cdot \sinh \frac{Z}{a} + \frac{aL}{a} \right]$

CASE 10 $0 \leq Z \leq aL$
 $\phi = \frac{Ma^2}{GJ} \left\{ \left[\tanh \frac{L}{a} \left(\frac{aL}{a} - \sinh \frac{aL}{a} \right) + \cosh \frac{aL}{a} \right] \left[\cosh \frac{Z}{a} - 1.0 \right] - \right.$
 $\left. \frac{aL}{a} \cdot \sinh \frac{Z}{a} + \frac{Z}{a} \left(\frac{aL}{a} - \frac{Z}{2a} \right) \right\}$
 $aL \leq Z \leq L$
 $\phi = \frac{Ma^2}{GJ} \left[\tanh \frac{L}{a} \cdot \sinh \frac{aL}{a} - \cosh \frac{aL}{a} - \frac{aL}{a} \cdot \tanh \frac{L}{a} + 1.0 + \frac{a^2 L^2}{2a^3} - \right.$
 $\left. \left(\sinh \frac{aL}{a} - \frac{aL}{a} \right) \cdot \tanh \frac{L}{a} \cdot \cosh \frac{Z}{a} + \left(\sinh \frac{aL}{a} - \frac{aL}{a} \right) \cdot \sinh \frac{Z}{a} \right]$

CASE 11 $\phi = \frac{Ma^2}{GJ} \left\{ \left[-\frac{5L^2}{6a^2} - \left(\frac{a}{L} - \frac{L}{2a} \right) \cdot \tanh \frac{L}{a} + 1.0 \right] + \left[-\frac{Z}{L} + \frac{ZL}{a^2} \right] + \left[\frac{a}{L} - \frac{L}{2a} \right] \right.$
 $\left. \left(\frac{\sinh \frac{Z}{a}}{\cosh \frac{L}{a}} \right) - \frac{Z^2}{6a^2} \cdot \frac{Z}{L} \right\}$

CASE 12 $\phi = \frac{ma^2}{GJ} \left[H \cdot \left(\tanh \frac{L}{a} - \frac{Z}{a} - \tanh \frac{L}{a} \cdot \cosh \frac{Z}{a} + \sinh \frac{Z}{a} \right) + \right.$
 $\left. \frac{\cosh \frac{Z}{a}}{\cosh \frac{L}{a}} - \frac{1}{\cosh \frac{L}{a}} - \frac{Z^2}{2a^2} \right]$

Where: $H = \left(\frac{L^3}{2a^3} - 1.0 + \frac{1}{\cosh \frac{L}{a}} \right) \cdot \frac{1}{\left(\tanh \frac{L}{a} - \frac{L}{a} \right)}$

Figure 3.5: Solutions for different torsional loadings and boundary conditions (Continued), AISC (1983), p.86

Chapter 4

MEMBER DESIGN

4.1 Introduction

This Chapter describes the structural design methodology adopted in the program IDFSM. The focus is given to methods concerning the analysis and design of flexural steel members that are referred in CAN/CSA-S16.1-M89 in Clause 6, 11.1, 13.6, 15.3.1 and 15.11, and to recent research yet to be incorporated into CAN/CSA-S16.1-M89 and into existing structural software.

4.2 Classification of Sections

Overall member behaviour is a function of the local buckling behaviour of the plate elements that make up the section and are categorized as Class 1, 2, 3 or 4 type sections. The limits between each class are defined in terms of the slenderness of the plate elements and are a function of the boundary conditions, applied stress distribution, yield strength and residual stresses. The limits given in CAN/CSA-

S16.1-M89 in Clause 11.1 for I-shapes subject to bending have been incorporated into the program IDFSM and are summarized in Table 4.1.

Section Class	Flange	Web
Class 1	$b/t \leq 145/\sqrt{F_y}$	$h/w \leq 1100/\sqrt{F_y}$
Class 2	$b/t \leq 170/\sqrt{F_y}$	$h/w \leq 1700/\sqrt{F_y}$
Class 3	$b/t \leq 200/\sqrt{F_y}$	$h/w \leq 1900/\sqrt{F_y}$

Table 4.1: Width-thickness ratios for section classification

Sections are defined as Class 4 if they fail to meet requirements listed in Table 4.1. Currently, the program IDFSM does not design or check the capacity of Class 4 sections. It excludes only one section if grade 300 W steel is specified (WWF500×197) and 8 others if grade 350 W steel is specified.

4.3 Cross-Section Strength

The cross-section strength of members subjected to bending can be determined from Clause 13.5 of CAN/CSA-S16.1-M89 as:

- for Class 1 and Class 2 sections,

$$M_r = \phi Z F_y = \phi M_p \quad (4.1)$$

- and for Class 3 sections,

$$M_r = \phi S F_y = \phi M_y \quad (4.2)$$

where, Z = plastic section modulus

M_p = plastic moment

S = elastic section modulus

M_y = yield moment

The moment capacity of flexural members with continuous lateral support along the compression flanges is given by its cross-section strength.

4.4 Shear Capacity for Beam

In accordance with the clause 13.4 of CAN/CSA-S16.1-M89 standard, for a uncoped I-shaped beam or a coped beam with I-shape, the factored shear resistance, V_r , developed by the web of beam is,

$$V_r = \phi A_w F_s \quad (4.3)$$

where,

A_w = shear area (d_w for rolled shapes and h_w for girders)

F_s = the ultimate shear stress, depending upon the width-thickness ratio of web as defined in Clause 13.4.1

For a coped beam, with T or Rectangular shape, it is assumed that the connection assembly is capable of preventing the shear buckling of the web and that the factored shear resistance can be taken as,

$$V_r = \phi A_w (0.66 F_y) \quad (4.4)$$

4.5 Lateral-Torsional Buckling Strength

4.5.1 General

The determination of the lateral-torsional buckling capacity of a steel beam is relatively complex and is one of the prime concerns in the development of the program IDFSM. The complexity of evaluating and obtaining a good estimation of the lateral-torsional buckling capacity of a beam lies in the difficulty of assessing the influence on capacity due to the load distribution, the location of the load along the length of the member and with respect to the shear center and of the lateral restraint (restraint against lateral displacements, rotation, warping and shear distortions of the web) provided to the beams by OWSJ's, beam, columns and structural steel connections.

Extensive research in this field has been conducted by Johnston (1976), Trahair (1977), Kirby and Nethercot (1977,1983), Schmitke and Kennedy (1984), Albert and Kennedy (1991) and others. Closed-form analytical solutions exist for most simple cases and are summarized in the "Guide to Structural Stability Design Criteria for Metal Structures", Galambos (1988). Since current design standards give only limited design rules with regard to the design of laterally unsupported members, there is a need to provide a comprehensive set of design guidelines to solve most common design problems and there is also a need to develop the corresponding computer software to facilitate the process.

In this section, appropriate lateral-torsional buckling capacity solution strategies are discussed, and the design approaches employed by program IDFSM in accordance with these strategies are presented.

4.5.2 Assumptions

The following general assumptions have been made in the procedures employed by the program IDFSM for evaluating the lateral-torsional buckling problems.

1. The beam is geometrically perfect.
2. The applied loads act solely in the plane of the weak axis.
3. The deflection of the member is small.
4. The shape of the cross section does not change during buckling.
5. The prebuckling deflection either in-plane or out-of-plane have no effect on the lateral-torsional buckling behaviour of the beam.

The first four above assumptions are common assumptions for beam stability problems. The last assumption is considered to be valid when the ratios of the minor axis flexural stiffness and torsional stiffness to the major axis flexural stiffness is small, Yong and Trahair (1992). The I-shaped members produced in Canadian mills and considered in this thesis fall into this category.

4.5.3 Lateral-torsional buckling behaviour

Members that are loaded in the plane of the weak axis and not continuously laterally supported along the compression flange may fail by lateral-torsional buckling. This type of failure is a bifurcation problem and occurs when the critical moment is reached.

(a) Uniform bending case

A perfectly straight elastic beam loaded by equal and opposite end moments applied about the x-axis is shown in Figure 4.1(p.322, Chen and Lui 1987).

By equating the corresponding external and internal moments, the governing differential equations can be written as

$$EI_x \frac{d^2 v}{dz^2} + M_0 = 0 \quad (4.5)$$

$$EI_y \frac{d^2 u}{dz^2} + \gamma M_0 = 0 \quad (4.6)$$

$$GJ \frac{d\gamma}{dz} - EC_w \frac{d^3 \gamma}{dz^3} - \frac{du}{dz} M_0 = 0 \quad (4.7)$$

where,

I_x, I_y — moments of inertia about the X and Y axis respectively

u, v — displacements in the x and y direction respectively

γ — angle of twist about the Z axis

M_0 — applied moment

J — St. Venant torsional constant

C_w — warping torsional constant

Figure 4.1: Lateral buckling of an I-section under uniform moment

The solution to above three equations given by Timoshenko (1961) is,

$$M_{0cr} = (\pi/L) \sqrt{EI_y GJ} \sqrt{1 + \frac{\pi^2 EC_w}{L^2 GJ}} \quad (4.8)$$

where,

- L length of the unbraced portion of the beam
- M_{cr} minimum (critical) moment at which lateral-torsional buckling occurs

(b) Nonuniform bending case

In the case of a beam subjected to unequal moments at ends (i.e. a moment gradient), the general solution can be written as,

$$M_{cr} = \omega_2 M_{0,cr} \quad (4.9)$$

where ω_2 is defined as equivalent uniform moment factor. Equation 4.9 is identical to the expression given in Clause 13.6 of CAN/CSA-S16.1-M89 for critical elastic moment capacity, M_{cr} .

The maximum moment resistance of a beam is its cross-sectional strength as defined in Clause 13.5(a) in CAN/CSA-S16.1-M89 as the plastic moment capacity for Class 1 and Class 2 sections and in Clause 13.5(b) as the elastic moment capacity for Class 3 sections. The inelastic lateral-torsion buckling capacity is obtained from a straight-line interaction equation given in Clause 13.6. The focus of this section on solution strategies is in determining the correct values for ω_2 and L and hence M_{cr} or M_r directly. The major factors influencing the elastic lateral-torsional buckling capacity of a beam and its design are:

- member geometry, cross-sectional properties and length of laterally unsupported segment;
- type of in-plane support;
- type and location of lateral support and stiffness of lateral support;

- load patterns and location of applied load;
- geometric imperfections (out-of-straightness);
- magnitude and distribution of the residual stresses.

The latter two can only be incorporated into solutions using sophisticated finite element models such as the one presented by Albert and Kennedy (1991).

4.5.4 Review of different solution strategies

As shown in Figure 2.1, the program IDFSM gives the user four options with respect to the evaluation of lateral-torsional buckling capacity of flexural members. At this time, only the first three are implemented. The strategies related to each of these options are described in the following sections.

CAN/CSA-S16.1-M89 solution

The equations and design rules in CAN/CSA-S16.1-M89 Clause 13.6, which is entitled "*Bending-Laterally Unsupported Members*", form the core part of the design rules implemented in the program IDFSM as they embody the limit states design philosophy, describe probable failure modes, and by law are the minimum design requirements. Hence all members are either checked or designed according to these rules. The general guidelines given in CAN/CSA-S16.1-M89 make reference to and encompass other methods of evaluating the elastic critical moment capacity of flexural members that are not explicitly covered by the standard, such as cantilever beams and continuous beams with overhangs.

If the **Modified SSRC Guide (1988)** option is not activated, then ω_2 in Equation 4.9 will be evaluated according to Clause 13.6.1, in CAN/CSA-S16.1-M89.

$$\omega_2 = 1.75 + 1.05\kappa + 0.3\kappa^2 \leq 2.5 \quad (4.10)$$

where,

κ = ratio of the smaller factored moment to the larger factored moment at opposite ends of the unbraced length; the value is positive for double curvature and negative for single curvature

$\omega_2 = 1.0$ when the bending moment at any point within the unbraced length is larger than the large end moment or when there is no effective lateral support for the compression flange at one of the ends of the unsupported length

The following rules for elastic and inelastic lateral-torsional buckling capacity and cross-sectional strength as given in Clause 13.6 of CAN/CSA-S16.1-M89 apply to all the lateral-torsional buckling solution strategies implemented in the program IDFSM.

1. Elastic lateral-torsional buckling

$$M_r = \phi M_{cr} \quad (4.11)$$

where, M_r = the factored moment resistance

$$\phi = 0.9$$

2. Inelastic lateral-torsional buckling

- for doubly symmetric Class 1 and 2 sections, where

$$M_{cr} \geq 0.67 M_p, \text{ then}$$

$$M_r = 1.15 \phi M_p \left(1 - \frac{0.28 M_p}{M_{cr}} \right) \leq \phi M_p \quad (4.12)$$

- for doubly symmetric Class 3 sections, where

$$M_{cr} \geq 0.67 M_y, \text{ then}$$

$$M_r = 1.15 \phi M_y \left(1 - \frac{0.28 M_y}{M_{cr}} \right) \leq \phi M_y \quad (4.13)$$

3. cross-sectional strength

- for Class 1 and 2 sections,

$$M_r = \phi M_p \quad (4.14)$$

- for Class 3 sections,

$$M_r = \phi M_y \quad (4.15)$$

Modified SSRC Guide

If the **Modified SSRC Guide (1988)** option is activated, for beams without overhangs or the main spans of a continuous beam, the value ω_2 is calculated using the formula proposed by Kirby and Nethercot (1979).

$$\omega_2 = \frac{3M_2 + 4M_3 + 3M_4 + 2M_{max}}{12M_{max}} \quad (4.16)$$

where, M_2 , M_3 , M_4 , represent the moment values indicated in Figure 4.2. M_{max} is the maximum moment value on the span under consideration.

Figure 4.2: Moment diagram between two laterally supported points for determination of ω_2 value, CISC (1989), p.34

All moment values are taken as absolute values. If the compression flange is laterally supported at the location where M_2 , M_3 or M_4 is evaluated, use a moment value of zero in Equation 4.16.

In the situation in which continuous lateral support is provided to the entire length (main span) of the tension flange of a beam, the expression proposed by Roeder and Assadi (1982) is used to obtain the critical buckling moment.

$$M_{cr} = \omega_2 \left[\frac{GJ}{d'} + \frac{\pi^2 EI_y d'}{2L^2} \right] \quad (4.17)$$

where d' = centre to centre distance between flanges.

The basic equation for calculating the elastic lateral-torsional buckling capacity given in CAN/CSA-S16.1-M89 (Equation 4.10), Kirby and Nethercot (1979) (Equation 4.16) and Roeder and Assadi (1982) (Equation 4.17) cannot be applied to cantilever beams. Galambos (1988) recommends the approach described in the SSRC Guide, Galambos (1988), proposed by Nethercot (1983), for a variety of loading conditions (top flange loading, load applied through the shear centre or the bottom flange) and boundary conditions (lateral support) at the root and tip of the cantilever. The M_{cr} expression proposed is as follows:

$$M_{cr} = \frac{\pi}{KL} \sqrt{EI_y GJ} \sqrt{1 + \frac{\pi^2 EC_w}{(KL)^2 GJ}} \quad (4.18)$$

where, K is the effective length factor, its value can be obtained by using Table 4.2.

The rules may also be applied to the overhanging portion of a continuous beams, such as in a Gerber girder system.

For Equation 4.18, the following restrictions outlined in Nethercot (1973) and Kirby and Nethercot have been inadvertently omitted from the description given in Nethercot (1983) and the SSRC Guide, Galambos (1988).

Restraint Conditions		Effective length	
At root	At tip	Top flange loading	All other cases
1.4 L	0.8 L
	1.4 L	0.7 L
	0.6 L	0.6 L
2.5 L	1.0 L
	2.5 L	0.9 L
	1.5 L	0.8 L
7.5 L	3.0 L
	7.5 L	2.7 L
	4.5 L	2.4 L

Table 4.2: Effective length factors K for cantilevers, Galambos(1988), p.168

1. For the beam parameter, X

$$0 < X < 1.57$$

where,

$$X = \sqrt{\frac{\pi^2 E C_w}{G J L^2}}$$

2. For a overhanging beam, the effective length of the overhanging span should not be less than the back span.

These restrictions have not yet been incorporated into IDFSM as there is no recent literature that suggests that the solutions generated are incorrect. These may severely restrict the application of the effective length factors. Future incorporation of the Albert and Kennedy (1991) finite element solution may render this portion of the program code obsolete.

Schmitke and Kennedy: interactive buckling of adjacent spans of a continuous member

The laterally unsupported spans of a continuous beam with discrete lateral supports, as shown in Figure 4.3, do not buckle independently. Restricting the capacity of the beam to the lowest critical buckling moment capacity of one of the lateral unsupported spans calculated independently would be conservative. Schmitke and Kennedy (1984) have proposed a method for determining the interactive buckling capacity of the entire beam and is called the equivalent beam method. This method has been incorporated into the program IDFSM and is summarized as follows.

1. Compute M_x for the non-uniform moment on each segment, $L_1, L_2, \dots, L_n$ of the beam. Use the appropriate ω_2 value as calculated by either Equation 4.10 or 4.16.

(a) Structural image

(b) Lateral span layout

Figure 4.3: Beam with discrete lateral supports

2. Compute the corresponding equivalent length of each segment for a beam with uniform moments, i.e. $\omega_2 = 1.0$.

$$L_e = \frac{\pi(EI_y GJ)^{1/2}}{\sqrt{2}M_{cr}} \left\{ 1 + \left[1 + \frac{4M_{cr}^2 C_w}{I_y (GJ)^2} \right]^{1/2} \right\}^{1/2} \quad (4.19)$$

3. Replace the beam by an equivalent beam (with uniform moment) of length $L = \sum L_e$.
4. Calculate the effective length for each segment of the equivalent beam such that they have the same critical moment (beam buckles interactively).

$$L' = \sum L_e / n$$

where, n = number of segments.

5. Calculate the corresponding critical moment capacity of that segment ($\omega_2 = 1.0$ - uniform moment).
6. Modify M_{cr} to reflect inelastic behaviour as required, refer to Equation 4.12 and 4.13.

4.5.5 Lateral support types

The type of lateral support has a pronounced effect on the lateral-torsional buckling resistance of beams, as to how and where the lateral supports are connected to the beams; and to the restraint they provide to the beam through their flexural and axial stiffness. Four typical types of lateral supports have been included for in the program IDFSM, shown in Figure 4.4.

The evaluation of the effect of the lateral support on M_{cr} is based on the following assumptions:

1. The lateral supports shown in Figure 4.4, are capable to provide adequate support to prevent lateral and torsional displacements of the beam at the locations of the support. Note: Calculations for the required stiffness of lateral supports are not included in IDFSM.
2. Discrete lateral support provided to the compression flange of a beam has capacity to restrain both lateral displacements and twisting of the cross section of the beam at the location of the lateral support.
3. Lateral supports provided to the tension flange of a beam have little or no impact on the lateral-torsional buckling resistance, therefore their contribution is ignored.

(a) Beam to beam web connection

(b) Beam connected to the top flange of a beam

(c) OWSJ's connected to the top flange of a beam

(d) OWSJ's connected to both the top and bottom flanges of a beam

Figure 4.4: Lateral support types

Based on these and other assumptions stated previously, the effectiveness of the lateral restraints for each lateral support type defined in IDFSM can be estimated.

Beam to beam web connections, as shown in Figure 4.4 (a), are generally made with standard end plates, back-to-back angles, or with single angles, bolted and/or welded depending on the construction. The shape of the cross-section at the point of lateral support will be maintained (no web distortion). The compression flange is effectively braced from lateral displacements and the member restrained from twisting. Similar restraint is provided by an OWSJ framing onto the top and bottom flange of a beam, Figure 4.4 (d).

Beams or OWSJ's connected to the top flange of a beam, as shown in Figures 4.4 (b) and (c) respectively, prevents lateral displacement of that flange and provides limited restraint against rotation of the beam at that location. The web may still distort.

If the top flange is in compression then it is assumed that effective lateral support is provided for lateral displacements and twisting. If the top flange is in tension then the relative effectiveness of the lateral support is small, Trahair (1988), and is ignored in the calculation of M_{cr} . The program IDFSM gives a slightly conservative design for this latter case.

The effects of these lateral supports is more closely modelled with the finite element solution proposed by Albert and Kennedy (1991).

4.5.6 Laterally unsupported length determination

A major factor affecting the lateral-torsional buckling resistance of a beam is the distance between two effective lateral supports. Effective lateral supports are those that provide effective lateral restraint to compression flange at locations of lateral support (bracing points). For cases where lateral support is provided only to the top flange of a beam, it is crucial to determine whether or not the flange is in compression or in tension and hence whether or not the lateral support is effective.

The laterally unsupported length is a function of the bending moment diagram (defines which flange or where it is acting in compression) and the type and location of lateral support.

As illustrated in Figure 4.5 for a typical gerber girder roof system with equally spaced OWSJ's, the lengths of unsupported segments may be different for different load combinations. The program IDFSM calculates the unsupported lengths for each load case and used these values along with the appropriate solution strategy to determine the elastic lateral-torsional buckling strength, M_{cr} . A serious shortcoming of most commercial software is that they use a predefined laterally unsupported length throughout the design process.

(a) Gerber girder system image

(b) Original length of lateral unsupported segment

(c) Length of lateral unsupported segment unchanged

(d) Length of lateral unsupported segment changed

Figure 4.5: Laterally unsupported length and load configurations

4.5.7 Special treatment for cantilever beams and the cantilever portion of overhanging beams

The design approach for determining the effectiveness of a lateral support, presented in preceding section can only be applied to a beam between vertical supports (columns or beams)

The design approach proposed by Nethercot (1983), as described in Section 4.5.4 has to be used for build-in cantilever beams or for the cantilever portion of overhanging beams. The Nethercot approach provides a good estimation of the lateral-torsional buckling capacity due to different types of lateral support at the root and tip of the cantilever segments. This approach cannot be applied directly when more than one lateral support is present along a cantilever beam or along the cantilever portion of overhanging beams. The following design rules presented here are an extension of that approach.

- The lengths of all laterally unsupported segments within the cantilever are defined by the structural configuration and are independent of the loads and the resulting bending moment;
- Each laterally unsupported segment is treated as an independent cantilever with the bracing point closer to the in-plane support taken as the root point.
- The elastic lateral-torsional buckling capacity of each segment is calculated independently using Equation 4.18, in which the effective length factor K is determined from the value given in Table 4.2.
- Lateral support provided to the compression flange prevents lateral displacement and twisting of the beam at that location.

(a) Structural image

(b) Locations of lateral supports along the beam length

(c) Moment diagram for different load combinations

Figure 4.6: Laterally unsupported cantilever beam with different load combinations

Load Case	Segment No	Node No.	Lateral Restraint Location	Lateral Restraint Type	Effective Length KL
	1-2	1	Root		5000 mm $K = 2.5$
		2	Tip
Load Combination 1	2-3	2	Root		6750 mm $k = 4.5$
		3	Tip
	3-4	3	Root		2500 mm $k = 2.5$
		4	Tip
Load Combination 2	1-2	1	Root		3000 mm $k = 1.5$
		2	Tip
	2-3	2	Root		2250 mm $k = 1.5$
		3	Tip
	3-4	3	Root		1250 mm $k = 2.5$
		4	Tip

Table 4.3: Determination of lateral restraints and effective lengths for cantilever beam with more than one lateral support

Figures 4.6(a), (b) and (c) show a cantilever beam with two different lateral support systems and the corresponding bending moment diagrams for load combinations that produce compression in the bottom and top flanges respectively. The relative effectiveness of the lateral support on the moment resistance is dependent on which flange is being laterally supported and how it is being supported. This is illustrated by the figures and values in Table 4.3 for lateral restraint types and effective lengths. The effective length for load combination 1 exceeds that for load combination 2. As expected, the moment resistance of the member was governed by load combination 1 where the M_t/M_r ratios for load combination 1 and 2 are 0.53 and 0.43 respectively. For this particular case the design was controlled by the deflection limit.

1.5.8 Effect of end coping

The ends of flexural members are frequently coped for fit and for ease of construction. The type, location and dimensions of these copes can be defined in IDFSM using the menu shown in Figure 4.7

The effect of coping at the end of the beam are:

1. to reduce the cross-section, the coped region of an I-shaped beam may become singly symmetric (generally one plane of symmetry, about the weak axis), and
2. to give rise to two possible local failure modes – shear buckling of the web and fatigue cracking (not implemented into the program), and
3. to reduce the torsional and lateral stiffness of the beam reducing its lateral-torsional buckling strength (Cheng, Yura and Johnson (1984)).

Clause 15.3.1 of CAN/CSA-S16.1-M89 specifically recognizes the latter and specifies that the effect of copes on the lateral-torsional buckling resistance of a beam or girder be taken into account. The design approach incorporated into IDFSM is that

In-Plane Support(s)	Lateral Support(s)	Photo	Title : doc 4	Date : 21 Feb 1993
Cope(s) and End Stiffener(s)	Return	Hardcopy name : 2_13 ps Please wait		

Cope Location	Top Flange Top Copes	Bottom Flange Top Copes	Top Flange Cope	Bottom Flange Cope

Left Support	Width = 0.00 mm Change	Width = 0.00 mm Change	Depth = 0.00 mm Change	Depth = 0.00 mm Change
Right Support	Not Applicable Change	Not Applicable Change	Not Applicable Change	Not Applicable Change
Cope length along the beam = 100.00 mm (At each applicable location)				Change
NOTE : COPING PATTERN AT EACH APPLICABLE BEAM END MUST BE THE SAME				

Stiffeners at left support : Not applicable
Right Support : Bearing Stiffener Added Change	
Depth x Width = 426 mm x 90 mm (a pair)	
Thickness = 6 mm	

Figure 4.7: Copes and stiffeners definition menu

proposed by Cheng (1992). Two interaction formula, based on theoretical parametric studies and experimental evidence, were developed: Equation 4.20 for beams with copes at both ends of the unbraced length and Equation 4.21 for beams coped at one end of the unbraced length.

$$\left[\frac{1}{M_{unbraced}} \right] + \left[\frac{1}{(L_u/2C)M_{cr}} \right] = \left[\frac{1}{M_{cr}} \right] \quad (4.20)$$

$$\left[\frac{1}{M_{unbraced}} \right]^2 + \left[\frac{1}{(L_u/2C)M_{cr}} \right]^2 = \left[\frac{1}{M_{cr}} \right]^2 \quad (4.21)$$

where,

$M_{unbraced}$ = the elastic lateral-torsional buckling strength of the uncoped section determined by Equation 4.9

M_{coped} = the elastic lateral-torsional buckling strength of the coped section (calculated for a reduced I-shaped for flange tip copes or for a T-shaped section using Equation 4.9)

M_{cr} = the elastic lateral-torsional buckling strength for the beam which accounts for the interaction between coped and uncoped regions

L_b = the unbraced length

C = the cope length

These equations are applicable only to cases where the cope length is less than twice the beam depth and the cope depth is less than one-fifth the beam depth. The same restrictions are applied within IDFSM. For T-shaped sections (Singly symmetric about weak axis), the value for M_{coped} is given in the SSRC Guide, Galambos (1988) as,

$$M_{coped} = \frac{\omega_2 \pi^2 E I_y \beta_x}{2(K_y L)^2} \left\{ 1 + \sqrt{1 + \frac{1}{\beta_x^2} \left[\frac{C_y K_y^2}{I_y K_y^2} + \frac{GJ(K_y L)^2}{\pi^2 E I_y} \right]} \right\} \quad (4.22)$$

where β_x is a geometric coefficient for singly symmetric sections and is defined as,

$$\beta_x = 0.9d' \left(\frac{2I_{yc}}{I_y} - 1 \right) \left[1 - \left(\frac{I_y}{I_x} \right)^2 \right] \quad (4.23)$$

where,

d' = the distance between the centroids of the two flanges

I_{yc} = the moment of inertia of the compression flange about the weak axis

I_y = the moment of inertia of the section about the weak axis

For a T-shaped section, I_{yc} is equal to I_y if the flange is in compression and is equal to zero if the web is in compression. For simply supported end condition the effective length factors K_y and K_x is set to one. In applying Equation 4.23, the relevant sectional properties (I_x , I_y , I_{yc} , C_y and J) for the coped section are calculated in IDFSM. The value M_{cr} is then checked against the limits for inelastic

2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

lateral-torsional buckling given in CAN/CSA-S16.1-M89 and the appropriate moment resistance is calculated.

The in-plane bending and shear strengths are calculated as for uncoped beams. The program IDFSM does not calculate the reduced torsional stiffness of the beam due to copes. Consequently, torsional loads cannot be placed with the coped regions of a laterally unsupported beam.

4.5.9 Applications of different solution strategies

The descriptions of the different design solutions and solution strategies available in the program IDFSM are given in Table 4.4 and 4.5 respectively.

Many design problems are well defined and the solutions produced by CAN/CSA-S16.1-M89 are satisfactory. However, there are classes of buckling problems that lie outside the limitations of the design rules given in CAN/CSA-S16.1-M89, which require a more sophisticated solution. The program IDFSM provides this option. Each solution produced is valid, some are more conservative than others. The solution using CAN/CSA-S16.1-M89 is always produced in conjunction with the user specified solution. The system is informative and educational.

Solution	Button names	Descriptions
1	CAN/CSA-S16.1-M89	Minimum design requirement; end coping effects; may automatically invoke SSRC rules as they are referenced within the standard; design for bending and torsion, Clause 15.11, Driver and Kennedy (1989); always applied
2	Modified SSRC Guide (1988)	Alternative ω_2 values for different load patterns; M_{cr} for tension flange support; effective length factor K concept for cantilever beam segments
3	Schmitke & Kennedy (1989)	Interactive buckling of laterally unsupported segments of continuous beams
4	Albert and Kennedy (1991)	Finite element analysis of beam; includes web distortion, general loading and boundary conditions; and residual stress patterns

Table 1.1: Design options

Solution Strategies	Scope and Limitations
1	beam without cantilever segment(s)
1+2	build-in cantilever and beam with cantilever segment(s)
1+2	beam without cantilever segment(s)
1+2+3	same as 1+2, interactive buckling considered
1+3	same as 1, interactive buckling considered
2+3	same as 2, interactive buckling considered
1+4	Yet to be implemented

Table 4.5: Solution strategies available in the program IDFSM

4.6 Limit States Design for Beams Subjected to Combined Bending and Torsion

Flexural members may be subjected to combined bending and torsion if the section is not loaded through its shear centre. Examples are spandrel beams and girders that support cladding. Clause 15.11.1 of CAN/CSA-S16.1-M89 gives a general statement that instructs the structural engineer to provide a beam or girder with sufficient strength and rigidity to resist the torsional moment and forces in addition to bending moments and forces. The rational approach selected for design and inclusion into IDFSM was developed by Driver and Kennedy (1989). Based on test results and research conducted by others, Driver and Kennedy developed moment-torque ultimate strength interaction diagrams for I-shaped, Class 1, 2 and 3 sections, for flexural members with different torsional and bending boundary conditions and for different bending and torsional load cases. Serviceability limit states have also been developed and generally govern the design.

4.6.1 Description of moment-torque interaction diagrams —ultimate limit state

The proposed moment-torque interaction diagram for Class 1,2 and Class 3 sections are shown in Figures 4.8 and 4.9 respectively. The bases for determining the limiting values of moments and torques, which are used in constructing the interaction diagrams are given in Table 4.6, Driver and Kennedy (1989).

Class of section	Maximum bending moment	Bending moment on web, M_w	Maximum total torque	Warping torque, T_w	St. Venant torque, T_v
1	$M_m = M_p = \sigma_y Z$	$M_w = M_{pw} = \sigma_y Z_w$	$T_m = T_w = T_{tw} + T_{vw}$	Rectangular stress block, $\sigma_m = \sigma_u^*$	Sand heap, $T_{vw}^\dagger$ $\tau_m = \tau_v = \sigma_u/\sqrt{3}$
2	$M_m = M_p = \sigma_y Z$	$M_w = M_{pw} = \sigma_y Z_w$	$T_m = T_{yp} = T_{wy} + T_{wp}$	Rectangular stress block, $\sigma_m = \sigma_y^*$	Sand heap, $T_{wy}^\dagger$ $\tau_m = \tau_v = \sigma_y/\sqrt{3}$
3	$M_m = M_y = \sigma_y S$	$M_w = M_{yw} = \sigma_y S_w$	$T_m \leq T_y = T_{wy} + T_{vw}$	Linear stress distribution, $\sigma_m = \sigma_y$	Soap film, $T_{wy}^\ddagger$ $\tau_m = \tau_v = \sigma_y/\sqrt{3}$

*See Table 3.

$^\dagger T_{vw} = \tau_m [4t^3 + 6(h - t)t^2 + 3(d - 2t)t^2 + w^3]$.

‡ See Heins and Seaburg (1963)

Table 4.6: Bases for determining limiting values of moments and torques, Table 4, Driver and Kennedy (1989)

The steps for determining the limiting values for drawing the interaction diagrams are:

1. Calculate of the maximum resistance moment M_m

- For class 1 and 2 sections, the maximum resistance bending moment M_m , with zero torque is the plastic moment capacity indicated by point E in Figure 4.8 and is given by

$$M_m = M_p = \sigma_y Z \quad (4.24)$$

- For class 3 sections the maximum resistance bending moment M_m , is the yield moment (point E in Figure 4.9), and is given by

$$M_m = M_p = \sigma_y S \quad (4.25)$$

If the flexural capacity is limited by lateral-torsional buckling, as was the case in the tests conducted by Razzaq and Galambos (1979), then the maximum

Figure 4.8: Moment-torque interaction diagram for Class 1, 2 sections, Fig. 17, Driver and Kennedy (1989)

Figure 4.9: Moment-torque interaction diagram for Class 3 sections, Fig. 18, Driver and Kennedy (1989)

moment would correspond to lateral-torsional buckling capacity (elastic or inelastic).

2. Calculate the maximum torque T_m , with zero moment (point F in Figures 4.8 and 4.9).

- For class 1 sections, maximum torque T_m , is taken to be the sand heap torque plus the plastic warping torque with both quantities based on the ultimate tensile strength of the material.

The sand heap torque T_{shu} , is a function of the ultimate shear stress τ_u ($\sigma_u\sqrt{3}$) and is given by Driver and Kennedy (1987) as,

$$T_{shu} = \frac{1}{6}[4t^3 + 6(b-t)t^2 + 3(d-2t)w^2 + w^3]\frac{\sigma_u}{\sqrt{3}} \quad (4.26)$$

The plastic warping torque T_{wu} at ultimate is based on a warping normal stress distribution consisting of opposite rectangular stress blocks in the flanges of intensity equal to the ultimate tensile strength and is given by Driver and Kennedy (1987) as,

$$T_{wu} = [Kb^2t(d-t)/L]\sigma_u \quad (4.27)$$

where K is a factor based on torsional end and loading conditions taken from Table 4.7.

- For class 2 sections, the limiting torques are based on fully inelastic stress distributions, but with maximum stresses taken at the yield level instead of ultimate level. Hence,

$$T_{shy} = \frac{1}{6}[4t^3 + 6(b-t)t^2 + 3(d-2t)w^2 + w^3]\frac{\sigma_y}{\sqrt{3}} \quad (4.28)$$

$$T_{wy} = [Kb^2t(d-t)/L]\sigma_y \quad (4.29)$$

Load condition	Torsional end conditions			
	Pinned-pinned*	Fixed-fixed*	Fixed-free†	Fixed-pinned†
Uniformly distributed torque	1	3/2	1/2	5/4
Concentrated torque at midspan	1/2	1	—	11/12
Concentrated torque at free end	—	—	1/4	—
Concentrated torque at z	$\frac{1}{4(z/L)}$	$\frac{2(z/L) + 1}{4(z/L)}$	$\frac{1}{4(z/L)}$	$\frac{2 + 2(z/L) - (z/L)^2}{4(z/L)(2 - z/L)}$ for $z/L < 0.586$ $\frac{2 + 2(z/L) - (z/L)^2}{4(z/L)(3 - z/L)}$ for $0.586 < z/L < 0.653$ $\frac{1}{4(1 - z/L)}$ for $z/L > 0.653$

* z measured from the closer end

† z measured from the fixed end

Table 4.7: Warping factor, K . Table 3. Driver and Kennedy (1989)

where,

T_{shy} = shear torsional moment evaluated using $\tau_u = \sigma_u \sqrt{3}$

T_{up} = plastic warping torsional moment evaluated using σ_y

- For class 3 section, limiting torques are based on linear elastic analyses. The total yield torque, T_y , is calculated as the sum of the St. Venant torque, T_{svy} , and the warping torque, T_{wy} , based on an elastic analysis with the maximum stress taken as the yield stress. The maximum torque,

T_m , is likely to be less than the yield torque, T_y , as normal yield stresses due to warping and shear yield stresses due to St. Venant torsion are unlikely to be reached simultaneously.

3. Because the web does not contribute to the warping torque, point G is established directly above point F at a moment corresponding to the fully plastic moment of the web (M_{pw} , for bending moment and T_m for torsional moment), for Class 1 and 2 sections; and to the yield moment of the web (M_{yw} , for bending moment and T_m for torsional moment), for a Class 3 section.
4. Point H, as shown in Figures 4.8 and 4.9 can be established from the corresponding values of T_{shu} , T_{sv} and T_m .

The curve EHGF as shown in Figures 4.8 and 4.9 forms a moment torque interaction diagram that defines the ultimate limit state for a given load combination. The factored moment resistance can be obtained by multiplying the curve EHGF by the resistance factor $\phi = 0.90$. The beam is considered satisfactory for strength if a series of points represented on these figures by a point J (ratio of the factored moment to factored torque at any location along the beam) lie within the factored resistance curve.

4.6.2 Serviceability limit state

The serviceability criteria applicable for beams subject to combined bending and torsion are:

- A vertical deflection limit may be imposed as for beams in flexure.
- A similar limit may be placed on the maximum angle of rotation so that the nonstructural elements are not damaged. (see Section 4.8.2)

- In addition, Driver and Kennedy (1989) propose that a serviceability limit state based on first yield of the cross section due to normal stresses, with the analysis carried out on the undeformed shape. This guards against inelastic deformations at specified loads. The interaction diagrams for this serviceability limit state are plotted in Figure 4.8 by connecting points $K(0, M_y/M_p)$ and $L(T_{wy}/T_m, 0)$ and in Figure 4.9 by connecting points $E(0, M_y/M_y)$ and $F(T_m/T_m, 0)$. The beam is considered satisfactory for serviceability if the series of points represented by point J lie within the curve.

4.6.3 Application of the Driver and Kennedy approach

The Driver and Kennedy (1989) limit state design approach has been incorporated in the program IDFSM with some interpretation and modifications as required to apply it to common load cases and structural framing systems.

• **Warping torque factor, K**

The K values in Table 1.7, used to obtain the ordinate T_{wu} for moment-torque diagrams of Class 1 and 2 sections, are given for two unique load cases,

- uniformly distributed torque and,
- a concentrated torque at any location along length of the beam.

Practical design cases include members that are subjected to load combinations in which the K value has not been explicitly derived as for those cases given in Table 4.7. The program IDFSM uses the smallest K value possible. For the main span, the K value corresponds to a concentrated load acting at midspan, and for cantilever beams or the overhanging segment of a continuous beam a concentrated load acting at the free end. This in turn gives a smaller value of T_{wu} , slightly shrinking the

moment-torque interaction diagram, providing a lower bound ultimate limit state. Although this interpretation is conservative, it will not likely govern the design, as serviceability limitations generally control the design.

Calculation of T_m

For Class 3 sections the maximum torque, T_m , is likely to be less than the yield torque, T_y , given in Table 4.6, as the maximum normal yield stresses due to warping and the maximum shear yield stresses due to St. Venant torsion are unlikely to be reached simultaneously. The value of T_m is given as,

$$T_m = T_{suy} + T_{wy} \leq T_y \quad (4.30)$$

which can be expressed in terms of ϕ' and ϕ''' as.

$$T_m = GJ\phi' + EC_w\phi''' \quad (4.31)$$

The limiting value of T_m may be reached when either the normal stress due to warping reached F_y , Case 1, or the St. Venant shear stress reached $\tau_u = F_y\sqrt{3}$, Case 2. The relationship for ϕ , ϕ' , ϕ'' , ϕ''' and the torsional loads and the relationships between the normal warping stress, σ_{ws} , and functions of ϕ must be determined.

The relationship between the angle of twist ϕ and the warping normal stresses σ_{ws} as determined from the governing differential equation, Equation 3.2, is

$$\sigma_{ws} = EW_{ns}\phi'' \quad (4.32)$$

where, W_{ns} is the normalized warping function at any point on the cross section.

The relationship between the angle of twist ϕ and the uniform torsional stresses, St. Venant torsional stresses, τ_t as determined from the governing differential equation, Equation 3.1, is

$$\tau_t = Gt\phi' \quad (4.33)$$

where t represents the flange or web thickness as appropriate.

a. Determination of T_m for Case 1

1. set $\sigma_{us} = F_y$ in Equation 4.32 and rearrange the expression to determine the corresponding ϕ'' value.

$$\phi''_{max} = \frac{F_y}{EW_{ns}} \quad (4.34)$$

where,

$W_{ns} = hb/4$ for I-shaped sections, AISC (1983)

$h =$ depth of the beam

$b =$ flange width

2. substitute ϕ''_{max} into the function ϕ'' to determine the maximum value for the torsional load.
3. given the function for ϕ' and ϕ'' for the torsional loading and corresponding maximum load, calculate the values of ϕ' and ϕ''' at the same location along the beam where ϕ''_{max} occurs.

1. substitute these values into Equation 4.31 to determine T_{m1} .

b. Determination of T_m for Case 2

1. set $\tau_t = \tau_y = F_y\sqrt{3}$ in Equation 4.33 and rearrange the expression to determine the corresponding ϕ' value.

$$\phi'_{max} = \frac{F_y/\sqrt{3}}{Gt} \quad (4.35)$$

2. substitute ϕ'_{max} into the function ϕ' to determine the maximum value for the torsional load.

3. calculate the corresponding value of ϕ'' at the same location along the beam.
4. substitute these values into Equation 4.31 to determine T_{m2} .

The value for T_m is the lesser of T_{m1} and T_{m2} and cannot be greater than T_y . The value of T_y can be obtained from Equation 4.31 by using corresponding ϕ''' value for ϕ''_{max} , as given in Equation 4.34, and ϕ'_{max} as obtained from Equation 4.35.

Torsional restraints at in-plane and lateral supports

Currently, only 12 cases of different torsional load and boundary conditions (torsional restraints) have been programmed into IDFSM, see Section 3.2. Complete sets of solutions are given for uniformly distributed load, linearly varying distributed load and concentrated load for torsionally fixed-fixed, pinned-pinned, and fixed-free boundary conditions at the ends of a beam segment.

The fixed-fixed torsional boundary conditions are applied to cantilever beams and to overhangings of continuous beams. Fixed-fixed and pinned-pinned torsional boundary conditions are applied directly to beams where the corresponding flexural boundary conditions have been specified. For continuous beams over supports or for fixed-pinned or for pinned-fixed flexural boundary conditions, the pinned-pinned torsional boundary conditions are applied. This leads to slightly conservative results as some warping restraint does occur in a continuous member over the support or at the fixed end.

Design of lateral unsupported segments subjected to bending and torsion

The design of laterally unsupported segments subjected to bending and torsion is a relatively complex design problem and requires answers to the following questions.

1. What is the distribution and the magnitude of torsional loads introduced into a beam from the loads acting on member framing into it?

2. What is the torsional restraint provided to the ends of a laterally unsupported segment by the lateral support and the continuity of the beam?
3. What is a rational design approach for laterally unsupported segments subjected to bending and torsion? Are there any assumptions and/or limitations?

The first question can be answered by comparing the torsional stiffness of the beam (I-shaped) with the flexural stiffness of the members framing into the beam (also lateral support) which contributes to the torsional stiffness of system at the lateral support location. The following comparisons were made for two typical lateral support members (beams, OWSJ's) to illustrate the proportioning of the torsional loads.

Beam to Beam:

The structural layout is shown in Figure 4.10.

Figure 4.10: Beam to beam configuration

Lateral support member:

The lateral support member frames into the main member from one side and connected through shear type connection at both ends

Section size: W250 $\times$ 33

$$I_x = 48.9 \times 10^6 \text{ mm}^4$$

$$L = 4000 \text{ mm}$$

Assume that rotational stiffness of the shear connection is as low as 2% of that for a rigid connection, then the torsional stiffness provided the the beam is,

$$\frac{T}{\phi} = \frac{3EI}{L} \cdot 2\% = \frac{3 \times 200000 \times 48.9 \times 10^6}{4000} \cdot 2\% = 146.7 \times 10^6 \text{ Nmm/radian}$$

where, T is the internal torque at corresponding braced point.

Main member:

Section size: $W460 \times 74$

$$J = 0.517 \times 10^6 \text{ mm}^3$$

$$G = 77000 \text{ MPa}$$

$$L = 6000 \text{ mm}$$

The torsional stiffness of the beam for a concentrated torque at midspan (assuming simply supported boundary conditions for bending and torsion), can be obtained from the corresponding solution to this torsion problem. Case 3, $\alpha = 0.5$. AISC (1983), where

$$\frac{\phi GJ}{T} \cdot \frac{1}{L} = 0.105$$

and,

$$\frac{T}{\phi} = \frac{GJ}{L} = \frac{77000 \times 0.517 \times 10^6}{6000} = 6.6 \times 10^6 \text{ Nmm/radian}$$

The portion of the total torque resisted by the lateral support is

$$\frac{146.7}{146.7 + 6.6} = 96\%$$

and the corresponding portion of the total torque resisted by the main member (beam) is

$$\frac{6.6}{146.7 + 6.6} = 4\%$$

OWSJ's to beam:

The structural layout is shown in Figure 4.11

Figure 4.11: OWSJ's to beam configuration

Lateral support members:

2 back-to-back angles, $L40 \times 40 \times 4$

$I_x = 0.091 \times 10^6 \text{ mm}^4$ (each)

$L = 850 \text{ mm}$

The flexural bending stiffness of the top chord of the OWSJ's at laterally braced point is

$$\frac{T}{\phi} = \frac{3EI}{L} \times 2 = \left(\frac{3 \times 200000 \times 2 \times 0.091 \times 10^6}{850} \right) = 183.0 \times 10^6 \text{ Nmm/radian}$$

where, T is the internal torque at corresponding braced point.

Main member:

The section is a $W460 \times 74$ and the rest of the parameters are the same as the previous example. The portion of the total torque resisted by the lateral support is

$$\frac{183}{183 + 6.6} = 96.5\%$$

The portion of the total torque resisted by main member (beam) is

$$\frac{6.6}{183 + 6.6} = 3.5\%$$

Based on these and other examples it was concluded that if a torsional load was introduced at the lateral support point that the torsional load on the main member could be neglected.

The answers to the second and third question are coupled. The Driver and Kennedy (1989) design approach can be used for laterally unsupported segments subjected to bending and torsion by limiting the moment resistance to its lateral torsional-buckling capacity. The torsional restraints at the ends are assumed to be simply supported. The resulting design would be slightly conservative as it neglects the effects of warping restraint due to continuity and any possible increase in capacity. To eliminate any negative impact that might result from warping distortions from one segment on another, the program restricts the user from applying torsional loads on adjacent laterally unsupported segments for any given load combinations.

Examples

Examples illustrating the design limitations and torsional boundary conditions for beams with laterally unsupported segments are given in Figure 4.12. The torsional boundary conditions that have been applied are limited to the solutions currently provided in IDFSM. These approximations must be verified when the analytical tools have been developed.

Beam Configuration	Description of Limitations	Torsional Boundary Conditions
<p style="text-align: center;">Continuous beam</p>	<p>Segments 1-2, 2-3, 3-4, 4-5 and 5-6 can be considered as individual members for torsional analysis provided no adjacent segment is subjected to torsional loads simultaneously</p>	<p>Segments 1-2, 2-3 and 3-4 are considered pinned-pinned torsionally. Segments 4-5 and 5-6 are considered fixed-free if the torsional loads occur within that segment.</p>
<p style="text-align: center;">Cantilever beam</p>	<p>Segments 1-2 and 2-3 can be considered as individual members for torsional analysis provided that the other segment is not subjected to torsional loads simultaneously</p>	<p>Segments 1-2 and 2-3 are considered fixed-free if the torsional loads occur within that segment.</p>

Figure 4.12: Examples illustrating design limitations and boundary conditions for beams with laterally unsupported segments

4.6.4 Implementation of torsion evaluation into IDFSM

The program block diagram for the design of beams subjected to combined bending and torsion is shown in Figure 4.13.

Figure 4.13: Program block diagram for design of beams subjected to combined bending and torsion

4.7 Bearing Stiffeners

Bearing stiffeners are automatically designed in the program IDFSM to ensure local web stability and to enhance the overall stability of the member by preventing web distortions of continuous beams over supports. If effective lateral support is not provided to both flanges of overhanging beams at the locations of vertical support (beam on column or beam on girder) in the definition of the flexural design problem, then IDFSM will automatically insert and design a pair of bearing stiffeners at these locations. The minimum thickness will be 5 mm.

4.7.1 Local web stability

In program IDFSM, four types of in-plane support configurations are identified as shown in Figure 4.14. Under these situations, it is assumed that the reaction is distributed uniformly over the entire length of the bearing plate (column depth or width as shown in Figures 4.14(a), (b) respectively); and over the width of the supporting beam as indicated in Figures 4.14(c),(d). For end bearing, the end of the beam coincides with the edge of the supporting member.

Under a concentrated load or reaction, the beam web may fail locally by yielding or by inelastic web buckling (crippling). The corresponding resistances for interior loads or reaction and for end reactions are given in Clause 15.9 of CAN/CSA-S16.1-M89, sentences (a) and (b), respectively,

- For interior reactions as shown in Figures 4.14(b),(c)

$$B_r = 1.10w(N + 5k)F_y \quad (\text{web yielding}) \quad (4.36)$$

$$B_r = 300w^2 \left[1 + 3 \left(\frac{N}{d} \right) \left(\frac{w}{t} \right)^{1.5} \right] \sqrt{F_y t / w} \quad (\text{crippling}) \quad (4.37)$$

(a) End bearing (Beam on Column)

(b) Interior bearing (Beam on Column)

(c) Interior bearing (Beam on Beam)

(d) End bearing (Beam on Beam)

Figure 4.14: Definitions of bearing lengths and types

- For end reactions as shown in Figures 4.14(a),(d)

$$B_r = 1.10w(N + 2.5k)F_y \quad (\text{web yielding}) \quad (4.38)$$

$$B_r = 150w^2 \left[1 + 3 \left(\frac{N}{d} \right) \left(\frac{w}{t} \right)^{1.5} \right] \sqrt{F_y t / w} \quad (\text{crippling}) \quad (4.39)$$

where,

w = web thickness

N = length of bearing as defined in Figure 4.14, (N shall be not less than k for end reactions)

k = distance from outer face of flange to the toe of flange-to-web fillet or the web

t = flange thickness

Bearing stiffeners are also required at the unframed ends of beams (beam on a beam flange), with a web depth to thickness ratio greater than $1100/\sqrt{F_y}$, to prevent overall instability.

4.7.2 Automatic design for bearing stiffeners

If bearing stiffeners are required, IDFSM will automatically design a pair of bearing stiffeners for the full height of the web. Plate thicknesses incorporated into a data base for stiffener design include thickness region from 5 mm through to 12 mm, 14 mm through to 20 mm, 22 mm, 25 mm, 28 mm, 30 mm and 35mm as listed in the table for flat metal products on page G-135 of the CISC Handbook, CISC (1990). The automatic design procedure for bearing stiffeners is as follows:

1. Determine the range of stiffener widths (geometric requirement):

$$\text{width} \geq 10 \text{ mm} \quad (\text{minimum width requirement})$$

$$\text{width} \leq 0.5[(\text{flange width of the beam}) - (\text{web thickness})]$$

$$\text{width} \leq 200(t/\sqrt{F_y}) \quad (\text{Class 3 behaviour requirement})$$

where, t = thickness of bearing stiffener

2. Select the smallest plate thickness, $t = 5$ mm and calculate the corresponding stiffener width.
3. The axial compressive resistance of the stiffeners and corresponding web is calculated in accordance with Clause 15.6.2 of CAN/CSA-S16.1-M89. The column section consists of the pair of stiffeners and a centrally located length of the web equal to not more than 25 times its thickness at interior stiffeners, or a length equal to not more than 12 times its thickness when the stiffeners are located at the end of the web. The effective column length, KL , is taken as three-fourths of the length of the stiffeners in calculating the ratio KL/r . The compressive resistance of column, C_r , with the cross-section and slenderness defined by Clause 15.6.2 is then calculated from Clause 13.3.1 of CAN/CSA-S16.1-M89.
4. The bearing resistance of the contact area of the stiffeners is calculated according to Clause 13.10.1(a) of CAN/CSA-S16.1-M89 standard.

$$Br = 1.50\phi F_y A \quad (4.40)$$

where, A = the contact area of a pair of bearing stiffeners which is equal to $2(\text{width} + t/2 - k)t$

$$\phi = 0.90$$

5. If the capacity of the bearing stiffeners is less than the factored reaction, then the next larger thickness is selected and the process repeated until the largest plate thickness, 35 mm, is exceeded. For this case (stiffener design is unrealistic).

the program will print the following warning in the "Engineering report":

Further reinforcement of support for bearing is required

4.8 Deflection and Camber Requirements

4.8.1 Vertical deflections

The program IDFSM automatically calculates the vertical deflections due to both the specified dead and live loads for each load combination.

The dead load deflection may be offset by cambering the beam and will be given in the engineering report if the camber option is activated in the main menu, refer to Figure 2.1. The structural engineering is required to enter the appropriate live load deflection limit for the given application, otherwise, the default option of 1/300 of the beam span will be used. Recommended values are given in Appendix I of CAN/CSA-S16.1-M89. The program IDFSM will either automatically select the appropriate section to satisfy the deflection limit specified for the automatic design option, or it will calculate and report the deflection as a function of the span and indicate whether or not it is satisfactory for the design check option.

4.8.2 Lateral deflections

The lateral deflections identified by the program IDFSM are caused by both the specified dead and live torsional loads. Driver and Kennedy (1989), proposed as serviceability criteria that these deflections should be compared to the live load deflection limit specified for the gravity live loads. The lateral deflection at any location along the length of the member is given as

$$\Delta_t = \frac{\phi h}{2} \quad (4.41)$$

where, Δ_l = lateral deflection due to specified dead and live torsional loads

ϕ = the angle of rotation of the cross-section

h = section depth, for I-shapes

4.9 Determination of the Optimum Section Size

The automatic design option of IDFSM will determine the optimum section size, minimum weight (hence minimum cost), that will satisfy all the design requirements (serviceability and strength) and geometric constraints specified; using a modified constraint direct search method.

The objective function for minimum weight is discrete and mathematically can be expressed as,

$$W_{min} = Fn(x_1, x_2, \dots, x_n) \quad (4.42)$$

where,

W_{min} = minimum section weight, kN/m

$x_1, x_2, \dots, x_n$ = design variables which are the geometric properties of the section; $I_x, S_x, Z_x, I_y, S_y, Z_y, J, C_w, d, b, t, w$ and k

The constraints imposed on the solution are related to ultimate and serviceability limit state criteria for flexural members, as well as two architectural constraints restricting the outer dimension of the section. These are:

1. $M_f/M_r \leq 1.0$ and/or $T_f/T_r \leq 1.0$

(compared with the moment-torque interaction diagram, when applicable)

2. $V_f/V_r \leq 1.0$
3. $B_f/B_r \leq 1.0$
4. (maximum deflection due to live load)/(maximum deflection limit) ≤ 1.0
5. (maximum depth)/(maximum specified depth) ≤ 1.0
6. (member flange width)/(minimum specified flange width) ≥ 1.0

Optimization by using a direct search method means that the objective function is evaluated and conclusions are drawn from the values of the function for various combinations of the independent design variables. The effectiveness of the optimization procedure is dependent on the search method which describes the logic behind those conclusions.

The CISC geometric data for W and WWF shapes are given as a function of the nominal depth and within that section group, i.e. W200's, the sections are listed in descending order by mass or weight. Examination of the geometric properties for the section with the largest mass with each section group indicates that there are two shape groups for W and WWF sections where the geometric properties increase with increasing mass. Large values for geometric properties is synonymous with increased capacity. These shape groups are:

- for W-shapes, shown in Figure 4.15

Shape group 1 — W100 through W300

Shape group 2 — W410 through W1000 with the exceptions of sections W920×1072, W920×1188 and W920×1262

- for WWF-shapes,

Shape group 1 — WWF350 through WWF650

Shape group 2 — WWF700 through WWF2000

Figure 4.15: Shape and section groupings for the optimization procedure

The first step of the automatic design procedure is to apply the direct search algorithm to determine the least weight section group within **Shape group 1**, which consists of the set of sections with the largest mass within each **Section group** and satisfies all the constraints, i.e. limit states design requirements. As illustrated in the example given in Figure 4.16, W250×167 were the least weight sections from **Shape group 1** of W shape.

The second step is to apply the direct search algorithm to determine the least weight section within each Section group obtained by step one and to a subset of each Section group deeper than the least weight section group selected, which also satisfies all the constraints. As illustrated in Figure 4.16, the optimum section with the W250's was W250×167. Only the subset of sections with weights less than 167 for the next deeper Section group, W310, needs to be searched. The optimum section within that subset was a W310×129. Similarly only the subset of sections with weights less than 129 for W360's needs to be searched. The optimum section within that subset was a W360×101.

The process is repeated, as illustrated for the next shape group, section groups and all subsets (when applicable) to determine the optimum section. Each search within a list of sections determines the new maximum lightest weight section which satisfies all the design requirements. Any section with weights above this value need not be examined. For this particular example a W530×66 was found to be the optimum section. The search path showing the optimum section size for each section group is shown in Figure 4.15.

Notes of the Application of the Direct Search Method

A section check is performed on the section closest to the middle of any given group of sections. If the section satisfies all the constraints then the group of sections is reduced by half ($n/2$) to the smaller mass sections only. Another section check is

STEP 1: DETERMINATION OF THE LEAST WEIGHT SECTION GROUP WITHIN SHAPE GROUP 1

STEP 2: SECTION GROUP SEARCH WITHIN SHAPE GROUP 1

Figure 4.16: Illustration of logic of direct search method

STEP 3: DETERMINATION OF THE LEAST WEIGHT SECTION GROUP WITHIN SHAPE GROUP 2

STEP 4: SECTION GROUP SEARCH WITHIN SHAPE GROUP 2

Figure 4.16: Illustration of logic of direct search method (Continued)

performed on the section closest to the middle of this reduced group and one half of that will be eliminated. This reduces the total number of sections to be evaluated to $n/4$. By performing $\log_2(n + 1)$ section checks, the section of minimum weight within that section group will be determined. Practically however, this number is quite a bit less as the search starts with lightest section groups and reduces the data set with each optimum section found, and needn't proceed if the maximum lightest section found is smaller than the lightest section of next available Section group.

It is estimated that the maximum number of section checks that would need to be conducted for one automatic design with the above search constraints, including a search of all W and WWF shapes, would be 30.

4.10 Design Module Structure

The member design module BEAM_DESIGN has been designed so that it can be maintained and executed separately from the user-interface module. This facilitates the option of incorporating this flexural member design module into an integrated system for the analysis, design fabrication and erection of steel buildings. A block diagram illustrating the basic is shown in Figure 4.18. The BEAM_DESIGN module is also an integrated program module consisting of multi-language (programming) sub-routines and two individual programs TORSTEEL and PLFRAM. The block diagram for TORSTEEL is given in Figure 4.17 and for PLFRAM in Figure 3.1.

Figure 4.17: Block diagram for the module TORSTEEL

Figure 4.18: Block diagram for the module BEAM-DESIGN

Chapter 5

INTERACTIVE CAD SYSTEM FOR FLEXURAL MEMBER DESIGN

A good member design program should:

1. determine the section size based on all possible failure modes (according to the limit states design philosophy; and
2. provide a good user interface that is simple, comprehensive, easy to use, graphics oriented, and models the design process; and
3. be capable of being integrated with other programs; and
4. be capable of being ported to different operating systems.

The first of these has been discussed in detail in chapter 3 and 4. The remainder will be discussed in the following sections.

5.1 User Interface

A good user interface should be simple, comprehensive, flexible, easy to use, provide as much information as requested, illustrate data through scaled images as well as numbers, and model the design process.

Unlike most other existing member design software, which at most provide a spreadsheet for input entries and limited structural information displays, the program IDFSM has uniquely designed graphics-oriented user interface which has following features:

- Each structural geometrical or load data entry is illustrated by three-dimensional scaled structural image displays as shown in Figure 5.1. For example, the type of lateral support is specified by the highlighted button at the bottom of the screen and its location by the indicator shown.
- Each successful data entry is instantly illustrated on an updated image as indicated in Figure 5.2, where an additional lateral support has been added.

With these features, and the implementation of grouped menus, arranged in accordance with design process, the designer should have no difficulty in using the program IDFSM, even without help facility menus. Errors resulting from incorrect data input are more easily detected through scaled images, hence the probability of any incorrect data being entered is diminished. This approach is a significant improvement on existing systems where the data structure is shielded or partially shielded from the designer.

Loads, scaled internal force and deflection diagrams are shown along with the structural system. This allows the structural engineer to clearly visualize whether or not the lateral supports are effective in supporting the compression flange. A summary of member resistances and detailed engineering reports can be viewed on

In-Plane Support(s)	Lateral Support(s)	Photo	Title: untitled	Date: 19 Mar 1993
Cape(s) and End Brackets(s)		Return	Handcopy name: 5.1 ps Please wait.	

Current lateral support location

Please select lateral support type
Done

Lateral Support Options

W-Shape Beam Joist

Beam to girder web

Beam on top of girder flange

Open Web Steel Joist

Top and bottom chords of OWSJ's

Top chord of OWSJ's

From far side of main member

From near side of main member

From both sides of main member

5	10	15	20	45	60	Original Figure
Rotate Over	Rotate Under	Rotate Right				
Rotate Right	Rotate Left	Rotate Left				
Rotate Over	Rotate Over	Rotate Left				
Rotate 0°	Rotate 0°	Rotate 0°				

Figure 5.1: Graphics-assisted entry

In-Plane Support(s)	Lateral Support(s)	Photo	Title: untitled
Copies(s) and End Stiffener(s)	Return	Hardcopy Name: 5_2.pdf Please wait

Draw with member length (ft)?: ☐

Lateral Support Options

W-Shape Beam/Joint

Beam to girder web

Beam on top of girder flange

Open Web Steel Joist

Top and bottom chords of OWSJ's

Top chord of OWSJ's

From far side of main member

From near side of main member

From both sides of main member

5	10	15	20	45	60	Original Figure
Rotate View	Rotate View	Rotate View	Rotate View	Rotate View	Rotate View	Rotate View
Rotate Right	Rotate Right	Rotate Left	Rotate Left	Rotate Left	Rotate Left	Rotate Left
Rotate Off	Rotate Off	Rotate Off	Rotate Off	Rotate Off	Rotate Off	Rotate Off
Zoom In	Zoom In	Zoom Out	Zoom Out	Zoom Out	Zoom Out	Zoom Out

Figure 5.2: Instant response to the data entry

the screen. Hardcopies of all images are easily obtained by executing the **photo** option and printing the appropriate PostScript file.

A graphics-oriented user interface such as this leads to a better understanding of the structural system and the design process. The program IDFSM will serve as both a design tool and an educational tool.

5.2 Integration

There are basically two levels of integration related to the member design step of the whole design process. The higher lever integrates the stand alone program like IDFSM, into an integrated system for the design of steel buildings. The lower lever integrates existing third party programs to perform one portion of IDFSM functions.

5.2.1 Design of stand alone program for an integrated system

The program IDFSM has been designed to be integrated into a complete design (integrated) system for steel buildings, which would include other member design modules, a load determination module, a geometric modeling module, analysis modules, and connection and fabrication modules.

In the integrated module, member definition, boundary conditions and loads would be determined by using general load determination and a geometric modeller module for the whole structure and data for each flexural member would be automatically generated. Current member definition screens would not be used. Within the integrated program, IDFSM would be a sub-program, and would be activated by a flexural member design button.

To make it possible to integrate the flexural member design module, the user

interface code and member design code were designed and written to function independently. The flexural member design module is a stand alone sub-program and can be utilized in both IDFSM and for integrated steel building design program. The flexural member design module would simply be executed by system calls.

When implemented as a sub-program within the integrated program, add-on control routines will be written to execute the stand-alone design module multiple times. At this stage, the user interface module of IDFSM would be modified to act as a viewing tool for the design results of each individual member. The user would retrieve detailed graphical and non-graphical information about a member geometry, loads, internal forces, design constraints, design options, member resistance and deflections. Current member definition screens would be used to allow changes in the design parameters for specific members and the redesign of those members. The corresponding results would be stored in the **general database**.

The **general database** is defined as a comprehensive database created for entire integrated system to facilitate communication between the modules (sub-programs, like IDFSM) of the system. All modules would be capable of reading from and writing to this database with the information required for or created by their process, Duchesne and Thomson (1992). The format of the flexural member design portion of this general database has been developed and is a communication file with extension **.in**. Both user interface and design module are linked to **.in** files. The user interface module will be able to perform its viewing functions, given a **.in** file for a specific job even if the design module was missing.

5.2.2 Flexural member design program as an integrated application

The stand alone program IDFSM in itself is an integrated application. IDFSM is composed of two independent modules, one for user interface and one for flexural member design, which communicate through a common data base. Other third party or new modules could easily be incorporated into the system provided that proper communication routines are written to read and write information to the database. This is exemplified in the BEAMDESIGN module which integrates the program TORSTEEL and PLFRAM. This modular format allows:

1. the programmer to make use of existing programs, and
2. each program to be maintained separately, which is desirable for future updating; and
3. for the integration of programs written in FORTRAN, C, C++; and
4. for possible enhancement of the application environment (from FORTRAN to C, and to C++).

When only a portion of an existing program is useful and the source code of the program is available, and multi-language codes in a single application are supported by the operating system, it is productive to simply copy required routines to the module under development. Data will be transferred in and out of these copied routines by its arguments.

5.3 Portability

The program, IDFSM, has been designed so that it may be ported to other operating systems. To ensure the portability of IDFSM to other operating systems:

1. the primary program modules were written in C language using common (system independent) functions; and
2. the program was modularized making it convenient to be divided into several blocks to accommodate memory management for PC applications.

HOOPS, the graphics tool system adopted in the program IDFSM, is capable of producing advanced graphics applications across the entire spectrum of workstations and personal computers. Among these computer systems, which HOOPS provides 100% source-code compatibility are SUN, VAX, X Windows, DOS, Machintosh and OS/2.

Integrated FORTRAN programs or routine should be converted to C or C++ using FORTRAN to C or C++ converter programs before they are ported to a new environment. The result is likely to be less hardware dependent. The original code should be retained for maintenance and translation when required.

With a small amount of source code modifications, the program IDFSM could be ported to other workstations and personal computers.

Chapter 6

PROGRAM STRUCTURE

This chapter describes the program, file and database structures, and system requirements, and gives information on installing, executing and maintaining the program.

6.1 General Information

The program IDFSM, developed on the SUN workstation environment, consists of the following four individual executable programs:

IDFSM is the main program, written primarily in the C programming language, has its main function written in C++ and contains several FORTRAN routines that have been extracted from the program TORSTEEL. The program IDFSM can be divided into two major components according to their function – a user interface program in which the computer graphics software package HOOPS is embedded and called extensively to produce graphics-oriented windows, buttons, images and text; and an analysis and design program called **BEAM_DESIGN**.

BEAM_DESIGN is a program for analysis and design flexural steel members for bending and torsion, that can be executed on its own or from within the program

IDFSM. It is written in both C and FORTRAN, and contains two individual programs called TORSTEEL and PLFRAM.

TORSTEEL is an executable program for calculating moment and torsion resistance for both laterally supported and unsupported beams. It is integrated with BEAM-DESIGN by file transmission and system calls from within BEAM-DESIGN. TORSTEEL is written in FORTRAN.

PLFRAM is an existing executable program for plane frame analysis, which was modified for IDFSM and is integrated with IDFSM by file transmission and system calls from within BEAM-DESIGN. PLFRAM is written in FORTRAN.

6.2 System Requirements

Currently, the program IDFSM runs on SUN workstations with SPARC microprocessor architecture (SPARC station SLC and better models), under the Sun Operating System (SunOS 4.0), and through network support, the screen display can be opened on all other workstation and personal computer environments running the X Window network-transparent system. The SunOS is the basic level of device independence, and X11 and either OpenWindow or SunView/XView graphics libraries are required to open user interface display.

The source code of the program IDFSM package uses approximately 3008 tape blocks or 3.0 MBytes of static memory. The memory management of Sun Systems is handled at the operating system level under Sun virtual memory operating system, which ensures that for even the minimum memory installation of low end SPARC stations, the program IDFSM has sufficient memory available.

6.3 Program Installation and File Structure

All source files and the executable version of the program IDFSM are stored in one single tar file archive, named **idfsm.tar**. These files (including sub-directories) can be extracted from **idfsm.tar** to user defined working directory by typing the following command from the system prompt in that directory:

```
tar xvf idfsm.tar
```

All executable files are kept in a top level directory (working directory) of directory trees. These files are: **idfsm**, **beam_design**, **torsteel**, and **plfram**. Along these are the four subdirectories - **data2**, **cisc**, **design** and **window**, and a **README** and a **Makefile** files.

The program reads and writes the data files other than sectional data-base files needed in the process of execution from and to the **data2** directory. These data files have following extensions:

.in	files containing geometric, load data, design constraints and results for any given member (individual design job)
.sum	files that contain the summary design report and have the same prefix job name as the .in files
.det	files that contain the detailed report and have the same prefix job name as the .in files
.data	files containing default design data
.ps	PostScript files created in the execution process by using the Photo option

Other files that might be created in the execution process are:

torsteel.input	— input file for TORSTEEL which is created automatically by the program when evaluating the moment capacity.
torsteel.output	-- output file of TORSTEEL
torsteel.idfsm_specified	--- output file of TORSTEEL (user specified solution), to be read by IDFSM (internal use only)
torsteel.idfsm_s16	output file of TORSTEEL (default solution), to be read by IDFSM (internal use only)
DATA	- input file for PLFRAM which is created automatically by the module IDFSM
OUTPUT	- output file of PLFRAM to be read by IDFSM which contains the results from the analysis

The **cisc** directory houses the CISC sectional data files which have **.dat** extensions. The prefix of **.dat** files represents the corresponding sectional shapes (W shapes, w.dat; WWF shapes, wwf.dat; WRF shapes, wrf.dat; HSS, hss.dat; C shapes, c.dat; angles, angles.dat; HP shapes, hp.dat; M shapes, m.dat; and S shapes, s.dat;).

The **design** and **window** directories house the source files for design and user interface module of the program IDFSM respectively. Files in these two directories have the following extensions:

- .c** -- C program text files
- .cc** -- C++ program text files
- .f** -- FORTRAN program text files

`.h` --- header text files for C program text
`.o` --- the object files for equivalent source files

6.4 Program Execution

The first step is to login to the host machine where the program is stored (X terminal emulator is required, for remote connection to the host machine). Go to the working directory that houses IDFSM and type:

```
idfsm
```

The following will appear on the screen:

```
-----IDFSM version 1.0-----  
Copyright ©Carleton University, 1993  
Please select the desired type of display:  
monochrome =1, colour=2
```

Select the desired type of display and press the **Return** key, the front page of the program will be displayed, as shown in Figure 2.2. System environment variables will not be required to be set up for executing the program, regardless whether or not the program is run locally or remotely. The executable version has non-shared linkage with the C, C++ and FORTRAN run time libraries.

If the design job is completely defined (all the input requirements are met), either by using the user interface screens or even by modifying the input file using a text editing tool, then the member design can be executed directly from the system prompt by typing:

```
beam_design JobName
```

where, **JobName** is the prefix of the file with the extension **.in**. The summary and detailed reports are created during the execution of the program **BEAM.DESIGN**. This feature has been developed for the future versions that will incorporate IDFSM into a comprehensive integrated system for the design of steel buildings.

6.5 User Interface

A typical IDFSM screen page, shown in Figure 6.1, consists of five regions:

1. Major menu
2. Message display window
3. Structural image display window
4. Additional member definition menu
5. View control menu

Each menu item within one of the window regions on the screen is called a "button". The selection of various buttons controls the flow of screens. Some buttons generate sub-windows, specific to the design task, that either appear as a different screen or only a small window within the current screen. The user is prompted to type in a numeric value using the keyboard. Generally, type the number desired and press the **Return** or **Enter** key. The Units for the input data are indicated within the same window. The units are used throughout and are **mm** for distance, **kN**, **kN/m**, or **kNm** for loads and/or internal forces.

For most of the screens, activating the **Return** button will either return the user to the main menu, as shown in Figure 2.1, or when in the main menu, cause the display of first page of IDFSM as shown in Figure 2.2. New or existing jobs can be created or retrieved using the menu on the first page.

Figure 6.1: Typical IDFSM screen regions and the corresponding HOOPS segments

When the **Photo** button is activated, a portion of or all of the image displayed on the screen will be written to a PostScript file with user specified name and will be stored in **data2** directory.

6.6 Updating IDFSM

To make changes to the source code and to debug the program, SUN C, C++, FORTRAN compiler and corresponding run time libraries are required, and **HOOPS** graphics package (version 2.20 or up) has to be installed on the host machine, in which the program is located. C, C++ or FORTRAN codes can be added to modify, revise and update the program. It is recommended that new code would be written in C or C++.

To compile and link the modified program, simply type the system command **make** in the top level directory. A corresponding **Makefile** is included with the program IDFSM to perform all the compiling, updating and regeneration tasks. The **make** command will activate the make functions for the two subdirectories, **design** and **window**, where source files of the program IDFSM are being held. **Makefiles** in these sub-directories contain all the commands that are executed during the **make** process. The **make** command can be executed within either the design or window directory to update any changes to the source code within. If the additional source files are created during the program updating process, the file **makefile** in the corresponding directory has to be modified accordingly.

The C function and FORTRAN subroutine source files ending with **.c** and **.f** suffixes, respectively. The associated prefix file name is representative of the task it performs. Any C function being called, which is not declared in a local file, is global function and is declared in the header file **id_gfun.h**. The C language defines all FORTRAN subroutines as global functions. All global variables used in program are

being declared in the header file `id_var.h`. These header files are included at the “head” (beginning) of each `.c` files.

6.7 Program Modules

6.7.1 Major modules

The program IDFSM is designed to house specific structural design and graphic interface functions within specific software modules. The combinations of these modules form various levels of the integrated program modules. The flow of the program is controlled by the menu buttons which represent these modules. Figure 6.2 illustrates the higher level modules within the program IDFSM and their relationship to each other. Solid blocks represent individual modules while dashed blocks represent their parent module.

6.7.2 Corresponding programming routines for modules

Figure 6.3 lists the major routines within each modules illustrated in Figure 6.2, where “routines” are defined as “functions” in C language or “subroutines” in FORTRAN language. In Figure 6.3, All routines are C functions unless otherwise noted by the letter (F) after the routine name. The files in which these routines reside are also listed.

6.7.3 Structure of graphic data

The program IDFSM utilizes the **Hoops** graphics package for creating interactive graphic user interface. The **Hoops** graphics database (a series of graphics macros) is organized into a tree-shaped hierarchy, resembling a file directory tree. Graphics macros are given or have been developed for geometrical primitives, cameras, lights,

rendering and modeling attributes, and application-specific information. Related elements are grouped together in *segments* which are the units of organization within the database. Each segment can contain other segments, forming a tree structure.

In each stage of member design process, as described in Chapter 2, the input data will be interpreted into both executable design data and executable data for graphical display. The data for graphical displays will be stored in appropriate *segments*, in **HOOPS**, HOOPS Reference Manual (1992). The "segment tree" for IDFSM, shown in Figure 6.4 defines the relationship among the segments developed. The "?Picture" is the top level segment, required by **HOOPS** and is used to open a display screen. The next level of segments define different regions on the screen. Lower level segments define the contents (in the form of text data and/or image data) of each region. The typical window regions corresponding to the highest level of segments are illustrated in Figure 6.1. Lower level of segments are defined in the program in routines as **HC_Open_Segment**, and can easily be traced through out the program C' functions.

Figure 6.2: Program module blocks

Upper level module (Routine name)	Module name	Major lower level routine names	File name
<div>Program front page</div> <div>(run_menu_main)</div> <div>file: main_c.c</div>	Read in existing file	run_files_read	front.c
		build_read_display_window	front.c
		run_prob_definition	main_c.c
	New design Problem	run_files_new	front.c
		build_new_prob_display_window	front.c
		run_prob_definition	main_c.c
	Photo	print_screen	util1.c
		screen_dump	util1.c
	Exit program	exit_program	main_c.c
		build_main_cover	front.c
		build_menu_main	front.c

Figure 6.3: Module related routines

Upper level module (Routine name)	Module name	Major lower level routine Names	File name
Member description, design constraints and design options (run_prob_definition) file: main_c.c	Camber for Dead Load	change_camber_status	prob_defi.c
	Deflection Limit (Live)	change_deflection_limit	prob_defi.c
	Maximum Member Depth	change_depth_limit	prob_defi.c
	Minimum Member Width	change_width_limit	prob_defi.c
	Automatic Design	change_to_auto_design	prob_defi.c
	Check Member	change_to_design_check	prob_defi.c
	CAN/CSA-S16.1-M89	default_s16	prob_defi.c
	Modified SSRC Guide (1988)	change_ssrc	prob_defi.c
	Smitke & Kennedy (1989)	change_interactive_buckling	prob_defi.c
	Albert & Kennedy (1991)	change_finite_element (to be implemented)	prob_defi.c

Figure 6.3: Module related routines (Continued)

Upper level module (Routine name)	Module name	Major lower level routine names	File name
Member description, design constraints and design options (run_prob_definition) file: main_c.c	Structural System	run_menu_structure_type	structure.c
		run_gerber_system	structure.c
		run_beam_column_system	structure.c
	Support(s), Stiffer(s) & Cope(s)	run_menu_flexmemb_defi	memb_defi.c
		run_member_length	memb_defi.c
		run_member_display	memb_defi.c
	Member Length, Type and Size	run_menu_connection	support.c
		run_cope_stiffener_defi	support.c
		run_lateralsupp_defi	support.c
	Applied Load	run_menu_load	load_1.c
		run_load_defi	load_2.c
		run_display_load_diagram	load_2.c
	Internal Forces & Deflection	run_menu_analysis	analysis.c
		PLFREM (stand alone program)	plframe.f
		run_display_diagram	analysis.c
	Structural Image	run_menu_image	prob_defi.c
		build_menu_show_structure	prob_defi.c
		build_viewsel_window	prob_defi.c
		build_lateralsupp_display	prob_defi.c
		build_menu_prob_definition	main_c.c
		run_prob_definition	main_c.c
		run_menu_main	main_c.c
		print_screen	util1.c

Figure 6.3: Module related routines (Continued)

Upper level module (Routine name)	Module name	Major lower level routine names	File name
Member evaluation and results (run_design) file: main.c	design	TORSTEEL (stand alone)	design/*.f
		BEAM_DESIGN (stand alone)	design/*.c, *.f
		select_memb_size_auto	auto_design.c
		design_check_ for_one_shape	auto_design.c
		write_data	read_write.c
		read_data	read_write.c
		write_engineering_ report	read_write.c
	result	build_menu_evaluation_ in_display_window	evaluation.c
		build_moment_resistance_ result_window	evaluation.c
		build_shear_resistance_ result_window	evaluation.c
		build_deflection_check_ result_window	evaluation.c
		build_depth_width_ limits_report_window	evaluation.c
		build_member_size report_window	evaluation.c
		build_structural_image report_window	evaluation.c
		build_detailed_ report_window	evaluation.c
		build_summary report_window	evaluation.c
		build_CAN_S16_ report_window	evaluation.c
		build_user_specified_ solution_window	evaluation.c
		build_report_ show_window	evaluation.c
		run_show_structure for_evaluation	evaluation.c
		read_in_report_ for_evaluation	read_write.c
		build_menu_description_ evaluation	main.c

Figure 6.3: Module related routines (Continued)

Level	1	2	3	4	Description
	?Picture				
		menu			Major menu buttons
			main		First page
			structure system		Structural system definition
			Length size		Length, section type and size
			Support		Supports, stiffeners & copes definition
			load		Load definition screen
			internal force		View screen of the internal forces and deflection
		display			Displays of the structural image and additional menu options
			member display		Displays of the structural image
			menu 2		Additional menu options
				str defi	Additional menu options for member description
				view	Image view control buttons
			prob definition		Main menu screen
			evaluation		View and design results check screen
			cofes stiff		Definition of cofes and suffeners
			structure system		Definition of structural system
		info			Message display window
			title		Job title display text
			date		Date display text
			message		Messages for all design steps

Figure 6.4: HOOPS segment tree within IDFSM

Chapter 7

ILLUSTRATED EXAMPLE PROBLEMS

This Chapter contains ten example problems which illustrate the features (user interface, graphic displays and reports) and versatility (the ability to handle a large number of different design problems) of the program IDFSM. As verification, these examples are compared to existing solutions whenever they exist.

7.1 Moment Capacity for Laterally Supported Beam

Structure Type: Simply supported beam (laterally supported)

Reference: Kulak G.L., Adams, P.F. and Gilmor M.I. 1990. Limit States Design in Structural Steel, CISC, p.122-124.

Problem Definition: Design check for a simply supported W310x52 beam, 7300 mm long, subjected to a uniformly distributed factored load of 33.9 kN/m. The

beam is connected to the flanges of columns at both ends by standard web angle connections (single or back-to-back angles, bolted and /or welded), as shown in Figure 7.1. The steel grade is specified as CAN/CSA G40.21-M87 Grade 300W.

Figure 7.1: Loads and geometry: Example problem 1

Solution: The solution screen corresponding to the design check is shown in Figure 7.2.

Member Description, Design Constraints and Design Options		Photo	File: verification_1	Date: 21 Mar 1993
Member Evaluation and Results		Return	Hardcopy name: 7_2.ps Please wait	

EVALUATION RESULTS <table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td>Moment: (M/M_r) = 1.00</td><td style="text-align: center;">Ok</td></tr> <tr><td>Shear force: V/V_r = 0.29</td><td style="text-align: center;">Ok</td></tr> <tr><td>Bearing resistance is not applicable</td><td></td></tr> <tr><td>MaxDeflection: L/308(Dead,vertical) L/465(Live, vertical)</td><td style="text-align: center;">Ok</td></tr> <tr><td>MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm</td><td style="text-align: center;">Ok</td></tr> </table>	Moment: (M/M _r) = 1.00	Ok	Shear force: V/V _r = 0.29	Ok	Bearing resistance is not applicable		MaxDeflection: L/308(Dead,vertical) L/465(Live, vertical)	Ok	MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	Ok	REPORT <table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td colspan="2" style="text-align: center;">User Specified Member Size: W310x52 300W</td></tr> <tr><td colspan="2" style="text-align: center;">Structural Image</td></tr> <tr><td style="text-align: center;">Summary Report</td><td style="text-align: center;">Detailed Report</td></tr> <tr><td colspan="2" style="text-align: center;">CAN/CSA-S16.1-M89 Solution</td></tr> <tr><td colspan="2" style="text-align: center;">User Specified Solution</td></tr> </table>	User Specified Member Size: W310x52 300W		Structural Image		Summary Report	Detailed Report	CAN/CSA-S16.1-M89 Solution		User Specified Solution	
Moment: (M/M _r) = 1.00	Ok																				
Shear force: V/V _r = 0.29	Ok																				
Bearing resistance is not applicable																					
MaxDeflection: L/308(Dead,vertical) L/465(Live, vertical)	Ok																				
MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	Ok																				
User Specified Member Size: W310x52 300W																					
Structural Image																					
Summary Report	Detailed Report																				
CAN/CSA-S16.1-M89 Solution																					
User Specified Solution																					

ENGINEERING REPORT

Date: 21-Mar-1993
 Job title: verification_1
 Job description: laterally supported beam

DESIGN CONSTRAINTS:

Camber for Dead Load: No
 Deflection Limit (Live) = L/300
 Maximum Member Depth = 1000.0 mm
 Minimum Member Width = 100.0 mm
 Design Type: Check User Specified Member Size

DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE:

CAN/CSA-S16.1-M89: Yes
 SSRC Guide: No
 Smitke and Kennedy (1985): No
 Albert and Kennedy (1991): No

Figure 7.2: Design result screen: Example problem 1

Solution Comparison:

	Factored Moment (kN-m)	Factored Moment Resistance (kN-m)
IDFSM	226	226
Kulak, Adams, and Gilmor (1990)	226	226
Difference	None	None

Table 7.1: Solution comparison: Example problem 1

7.2 Moment Capacity for Laterally Unsupported Beam

Structure Type: Simply supported beam (laterally unsupported)

Reference: Kulak G.L., Adams, P.F. and Gilmor M.I. 1990. Limit States Design in Structural Steel, CISC, p.139-141.

Problem Definition: Design check for a simply supported W310x52 beam, 7300mm long, subjected to an uniformly distributed factored dead load of 15.0 kN/m, as shown in Figure 7.3. The beam is connected to the flanges of columns at both ends by standard web angle connections. The steel grade is specified as G40.21-M87 Grade 300W steel.

Figure 7.3: Loads and geometry: Example problem 2

Solution: The solution screen corresponding to the design check is shown in Figure 7.4

Member Description, Design Constraints and Design Options		Photo	Title: verification_2	Date: 7 Jan 1995
Member Evaluation and Results		Return	Hardcopy name: ver_2_2.ps Please wait.	

<p style="text-align: center;">EVALUATION RESULTS</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td>Moment: (M/Mr) = 1.00</td> <td style="text-align: center;">Ok</td> </tr> <tr> <td>Shear force: V/Vr = 0.13</td> <td style="text-align: center;">Ok</td> </tr> <tr> <td>Bearing resistance is not applicable</td> <td></td> </tr> <tr> <td>MaxDeflection: L/311(Dead,vertical)</td> <td style="text-align: center;">Ok</td> </tr> <tr> <td>MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm</td> <td style="text-align: center;">Ok</td> </tr> </table>	Moment: (M/Mr) = 1.00	Ok	Shear force: V/Vr = 0.13	Ok	Bearing resistance is not applicable		MaxDeflection: L/311(Dead,vertical)	Ok	MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	Ok	<p style="text-align: center;">REPORT</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="2" style="text-align: center;">User Specified Member Size: W310x52 300W</td> </tr> <tr> <td colspan="2" style="text-align: center;">Structural Image</td> </tr> <tr> <td style="text-align: center;">Summary Report</td> <td style="text-align: center;">Detailed Report</td> </tr> <tr> <td colspan="2" style="text-align: center;">CAN/CAS-S16.1-M89 Solution</td> </tr> <tr> <td colspan="2" style="text-align: center;">User Specified Solution</td> </tr> </table>	User Specified Member Size: W310x52 300W		Structural Image		Summary Report	Detailed Report	CAN/CAS-S16.1-M89 Solution		User Specified Solution	
Moment: (M/Mr) = 1.00	Ok																				
Shear force: V/Vr = 0.13	Ok																				
Bearing resistance is not applicable																					
MaxDeflection: L/311(Dead,vertical)	Ok																				
MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	Ok																				
User Specified Member Size: W310x52 300W																					
Structural Image																					
Summary Report	Detailed Report																				
CAN/CAS-S16.1-M89 Solution																					
User Specified Solution																					

Distance along the main span measured from the left end of main span:

End Copie Description:

Number of copies at left support: 0

Number of copies at right support: 0

.....DESIGN RESULTS.....

Resistance Factor = 0.9

Moment Resistance: Ok

CAN/CAS-S16.1-M89 Solution:

Factored Moment/Resistance Moment = 1.00 (maximum ratio)

Corresponding Factored Moment = 99.9 kNm

Corresponding Resistance Moment = 100.2 kNm

In Main span, (Load Combination 1)

User Specified Solution: None

Figure 7.4: Design result screen: Example problem 2

Solution Comparison:

	Factored Moment (kN-m)	Factored Moment Resistance (kN-m)
IDFSM	100	100
Kulak, Adams, and Gilmor (1990)	100	100
Difference	None	None

Table 7.2: Solution comparison: Example problem 2

7.3 Laterally Unsupported Beam Using Different Solution Strategies for Evaluation of Moment Resistance

Structure Type: Simply supported beam (laterally unsupported)

Problem Definition: Design check for a simply supported W410x39 beam, 12000mm long, subjected to the total factored concentrated loads as shown in Figure 7.5. The beam is connected to the web of supporting girders at both ends by standard web angle connections. The steel grade is specified as G40.21-M87 Grade 300W steel.

Figure 7.5: Loads and geometry: Example problem 3 — Illustration of different solution strategy options for evaluating the moment capacity

CAN/CSA-S16.1-M89	Yes	Ok	Default option (only for non-cantilever beams)
Modified SSRC Guide(1988)	Yes	Change	w2 value & load patterns (modifications (Kirby and Nethercot))
Schmitke and Kennedy(1988)	Yes	Change	Interactive buckling
Albert and Kennedy(1991)	No	Change	Finite element analysis

Figure 7.6: Different solution strategy options for evaluating moment capacity (extracted from the main menu screen)

Solution: The solution screen for the user specified solution is shown in Figure 7.7.

Member Description, Design Constraints and Design Options		Photo	Title: verification_3	Date: 26 Dec 1997
Member Evaluation and Results		Return	Hardcopy name: ver_3_2.ps Please wait.	

EVALUATION RESULTS		REPORT	
Moment, $M/M_r = 0.47$	Ok	User Specified Member Size: W410x39 300W	
Shear force: $V/V_r = 0.03$	Ok	Structural Image	
Bearing resistance is not applicable		Summary Report Detailed Report	
MaxDeflection: $L/328$ (Live,vertical)	Ok	CAN/CSA-S16.1-M89 Solution	
MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	Ok	User Specified Solution	

Structural Image

Figure 7.7: Design result: User specified solution

Solution Comparison:

The following is a portion of the detailed report produced, from which the evaluation results using three different solution strategies are shown. The text, data and strengths given for each span and solution strategy has the following format:

- Span identification number relative to the left-hand end,
- Effective length or equivalent length for a beam with uniform moment, Schmitke and Kennedy (1985),
- Describing whether or not the span is satisfactory,
- Factored moment capacity, and
- Maximum factored moment occurring within the span

CAN/CSA-S16 1-M89 SOLUTION

Laterally unsupported segment number = 1
 $W2 = 1.75$
 Effective length = 2632.6 mm
 The span under investigation is satisfactory under the load given.
 The factored moment capacity = 170.1 kN-m
 The maximum factored moment = 54.0 kN-m

**NETHERCOT (1983) AND KIRBY AND NETHERCOT (1978) SOLUTION
 (USER SPECIFIED SOLUTION)**

Laterally unsupported segment number = 1
 $W2 = 1.71$
 Effective length = 2662.3 mm
 The span under investigation is satisfactory under the load given.
 The factored moment capacity = 168.9 kN-m
 The maximum factored moment = 54.0 kN-m

CAN/CSA-S16 1-M89 SOLUTION

Laterally unsupported segment number = 2
 $W2 = 1.00$
 Effective length = 4800.0 mm
 The span under investigation is satisfactory under the load given.
 The factored moment capacity = 78.1 kN-m
 The maximum factored moment = 66.0 kN-m

**NETHERCOT (1983) AND KIRBY AND NETHERCOT (1978) SOLUTION
 (USER SPECIFIED SOLUTION)**

Laterally unsupported segment number = 2
 $W2 = 1.05$
 Effective length = 4663.6 mm

The span under investigation is satisfactory under the load given.

The factored moment capacity = 81.8 kN-m

The maximum factored moment = 66.0 kN-m

CAN/CSA-S16.1-M89 SOLUTION

Laterally unsupported segment number = 2

$W_2 = 1.75$

Effective length = 2632.6 mm

The span under investigation is satisfactory under the load given.

The factored moment capacity = 170.1 kN-m

The maximum factored moment = 54.0 kN-m

NETHERCOT (1982) AND KIRBY AND NETHERCOT (1978) SOLUTION (USER SPECIFIED SOLUTION)

Laterally unsupported segment number = 2

$W_2 = 1.71$

Effective length = 2662.2 mm

The span under investigation is satisfactory under the load given.

The factored moment capacity = 168.9 kN-m

The maximum factored moment = 54.0 kN-m

RESULTS USING SCHMITKE AND KENNEDY (1985) SOLUTION (INTERACTIVE BUCKLING)

Effective length = 2329.4 mm

The beam under investigation is satisfactory under the load given.

The factored moment capacity = 140.3 kN-m

The maximum factored moment = 66.0 kN-m

The results for using each of three solution strategies is summarized in Table 7.3

Discussion: The relative difference between the CAN/CSA-S16.1-M89 solution and the modified SSRC Guide (1988) solution is small for this particular case with the first being slightly more conservative. In both cases the capacity of the beam was governed by segment 2 and is limited to 81.8 kNm. If the interactive buckling capacity of the beam is recognized, then the beam has approximately 72% more moment capacity (140.3 kNm), that can be utilized.

Solution Option	ω_2 value		Ratio M_f/M_r	
	Left end span	Midspan	Left end segment	Midsegment
CAN/CSA-S16.1-M89	1.75	1.0	0.32	0.85
Modified SSRC Guide(1988)	1.64	1.05	0.33	0.81
Schmitke and Kennedy(1985)	N/A	N/A	0.47	

Table 7.3: Solution comparison: Different solution strategy options

7.4 Laterally Unsupported Coped Beam

Structure Type: Simply supported beam (laterally unsupported)

Reference: Kulak G.L., Adams, P.F. and Gilmor M.I. 1990. Limit States Design in Structural Steel, CISC, p.139-141.

Problem Definition: Design for a simply supported W310x52 beam, 7300 mm long, subjected to an uniformly distributed factored dead load of 15.0 kN/m. The beam is connected to the web of supporting girders at both ends by standard web angle connections. The ends are coped to fit around the top flange of the girders and are defined (location and dimensions using the screen shown in Figure 7.9. The steel is specified as G40.21-M87 Grade 300W.

Solution: A typical solution screen is shown in Figure 7.10.

Solution Comparison: The effects of various coping conditions for cope length of 150mm and 300 mm on the the moment and shear resistances have been investigated and are given in Table 7.4 and 7.5, respectively. The relative capacities

Dead Load	Live Load 1	Live Load 2	Show All Loads	Print	Top example 9	Date 4 Jan 1993
Wind Up 1/4	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy name: ex_9_1.ps Please wait

Load Case 1: Dead Load

JOB TITLE: example 9	HARDCOPY NAME: ex_9_1.ps	DATE: 4 Jan 1993
----------------------	--------------------------	------------------

Figure 7.8: Loads and geometry: Example problem 4

In Plane Supports	Lateral Supports	Print	Top example 9
Copies and End Stiffness		Return	Hardcopy name: ex_9_1.ps Please wait

Cope Location	Top Flange Top Copes	Bottom Flange Top Copes	Top Flange Cope	Bottom Flange Cope

	Width : 0.00 mm Change	Width : 0.00 mm Change	Depth : 0.00 mm Change	Depth : 30.00 mm Change
	Width : 0.00 mm Change	Width : 0.00 mm Change	Depth : 0.00 mm Change	Depth : 30.00 mm Change
Cope length along the beam : 150.00 mm (At each applicable location)				Change
NOTE: COPIING PATTERN AT EACH APPLICABLE BEAM END HAS TO BE THE SAME				

Stiffeners at left support: Not applicable	Change
Stiffeners at right support: Not applicable	Change	
Depth x Width : 0 mm x 0 mm (a pair)		
Thickness : 12 mm		

Figure 7.9: Coping definition screen

Member Description, Design Constraints and Design Options		Print	Yes	EndPage 1	Date	4-Jun-1988
Stored Calculations and Results		Return	Hardcopy name as: 0 - .ps	Please wait.		
EVALUATION RESULTS		REPORT				
Moment: (M _{max}) = 1.18	Not OK	User Specified Member Size: W310x52 300W				
Shear force: V _{max} = 0.16	OK	Standard Image				
Bearing resistance is not applicable		Summary Report				
MaxDeflection: L/211 (Dead, vertical)	OK	Detailed Report				
MaxDepthLimit: 1000 mm, MinWidthLimit: 100 mm	OK	CAN/CAS S16.1 1989 Solution				
		User Specified Solution				
<p>One page description:</p> <p>Number of copes at left support: 2 Top Web Cope, Depth = 30.00 mm Bottom Web Cope, Depth = 30.00 mm Cope length along the member: 150.000000 mm</p> <p>Number of copes at right support: 2 Top Web Cope, Depth = 30.00 mm Bottom Web Cope, Depth = 30.00 mm Cope length along the member: 150.000000 mm</p> <p>.....DESIGN RESULTS.....</p> <p>Resistance Factor = 0.9</p> <p>Moment Resistance: Not OK</p> <p>CAN/CAS S16.1 1989 Solution</p> <p>Factored Moment/Resistance Moment = 1.18 (maximum ratio) Corresponding Factored Moment = 99.8 kNm Corresponding Resistance Moment = 84.6 kNm</p>						

Figure 7.10: Design results: Laterally unsupported coped beam

are given as a function of the capacity of the beam without copes. The subscript *nc* is a short form for no copes.

Discussion:

As indicated by the relative moment capacities given in Table 7.4 and 7.5, the lateral-torsional buckling strength of the beams with coped compression flanges are reduced and significantly reduced if both flanges are coped. Coping of just the tension flange has no effect. Even though there is a relative decrease in the shear capacity for coped beams, the overall capacity being utilized is still quite small, less than 16% for the worst case.

It may be practical to reinforce the coped area with stiffeners to obtain the full moment capacity of the beam. For this case, the structural engineer should design the beam as though there are no copes.

Coping Type	Support Location	Cope Depth	$M_r/M_{r_{nc}}$	$V_r/V_{r_{nc}}$
No copes	N/A	N/A	1.00	1.00
Bottom Flange Cope only	Left and Right	30.0 (mm)	1.00	0.93
Top Flange Cope only	Left and Right	30.0 (mm)	0.96	0.93
Top and Bottom Flange Copes	Left and Right	30.0 (mm)	0.85	0.81

Table 7.4: Solution comparison: Effect of end coping conditions with a cope length of 150 mm

Coping Type	Support Location	Cope Depth	$M_r/M_{r_{nc}}$	$V_r/V_{r_{nc}}$
No copes	N/A	N/A	1.00	1.00
Bottom Flange Cope only	Left and Right	30.0 (mm)	1.00	0.93
Top Flange Cope only	Left and Right	30.0 (mm)	0.91	0.93
Top and Bottom Flange Copes	Left and Right	30.0 (mm)	0.57	0.81

Table 7.5: Solution comparison: Effect of end coping conditions with a cope length of 300 mm

7.5 Cantilever Beam

Problem Definition: Design of a cantilever beam, 3000 mm long, with and without lateral support, and subjected to factored concentrated loads. The steel grade is specified as G40.21-M89 Grade 300W. The loads and basic geometry are shown in Figure 7.11.

Figure 7.11: Loads and basic geometry: Cantilever beam

Solution: The solution screens for different lateral support conditions, using the CAN/CSA-S16.1-M89 solution in conjunction with the Modified SSRC Guide(1988) solution are shown in Figures 7.12 to 7.14.

Member Description, Design Constraints and Design Options		Photo	File: m_3.mbr 3	Date: 10/02/1993
Member Evaluation and Results		Return	Hardcopy name: m_3_1.pl Printed out:	

EVALUATION RESULTS		REPORT	
Moment $M/M_b = 0.65$	Ok	Suggested Member Size W310x45 300W	
Shear force $V/V_b = 0.12$	Ok	Structural Image	
Bearing resistance is not applicable		Summary Report Detailed Report	
Max Deflection $L/233$ (Dead, vertical) $L/464$ (Live, vertical)	Ok	CAN/CSA-S16 1-1989 Solution	
MaxDepthLimit- 1000 mm, MinWidthLimit- 100 mm	Ok	User Specified Solution	

Structural image

Figure 7.12: Lateral support provided to the top flange at the load point

Member Description, Design Constraints and Design Options		Photo	File: m_3.mbr 7	Date: 10/02/1993
Member Evaluation and Results		Return	Hardcopy name: m_3_2.pl Printed out:	

EVALUATION RESULTS		REPORT	
Moment $M/M_b = 0.79$	Ok	Suggested Member Size W310x45 300W	
Shear force $V/V_b = 0.14$	Ok	Structural Image	
Bearing resistance is not applicable		Summary Report Detailed Report	
Max Deflection $L/198$ (Dead, vertical) $L/398$ (Live, vertical)	Ok	CAN/CSA-S16 1-1989 Solution	
MaxDepthLimit- 1000 mm, MinWidthLimit- 100 mm	Ok	User Specified Solution	

Structural image

Figure 7.13: Lateral support provided to both the top and bottom flanges at the load point (OWSJ's with a bottom chord extension)

Member Description, Design Constraints and Design Options		Photo	Title: 01_01_01_1	Date: 01/01/01
Member Evaluation and Results		Return	Hardcopy name: 01_01_01_1.ppt	
EVALUATION RESULTS		REPORT		
Moment (M _{Ed}) = 0.79	Ok	Suggested Member Size: W310x39 300W		
Shear force: V _{Ed} = 0.14	Ok	Structural Image		
Bearing resistance is not applicable		Summary Report		
Max Deflection: L/160 (Dead, vertical) L/300 (Live, vertical)	Ok	Detailed Report		
MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	Ok	CANCSA-S15.1-MSB Solution		
		User Specified Solution		
Structural Image

Figure 7.14: Lateral support provided along the beam length (both top and bottom flanges)

Solution Comparison: The design results for different lateral support conditions are summarized in Table 7.6

Discussion: The cantilever beam was automatically designed by IDFSM for each set of lateral support conditions. The corresponding sections given in Table 7.6 show a general increase in size as the relative effectiveness of the lateral support to compression flange diminishes.

The moment capacity for continuous lateral support to both flanges was calculated to be 164.7 kNm for W310x39 as is denoted by the symbol M_{rLs} . The corresponding moment capacity of the same section but for other lateral support conditions is given by the ratio M_r/M_{rLs} in Table 7.6. The ratio M_r/M_{rLs} decreases as the relative effectiveness of the lateral support to compression flange diminishes.

Lateral Support Conditions	M_r/M_{r1s}	Section Obtained from Automatic design
Top flange at braced point	0.78	W310x45
Top and bottom flanges at braced point	1.0	W310x39
Top and bottom flanges along the length	1.0	W310x39

Table 7.6: Solution comparison: Different lateral support conditions

7.6 Beam Laterally Supported Along Entire length of the Top Flange

Problem Definition: Design check for a W360x39 overhanging beam, 12000 mm long for main span with two overhang segments of 2000 mm each, laterally supported along entire length of the top flange, subjected to the in-plane factored load shown in Figure 7.15. The steel grade is specified as G40.21-M87 grade 300W steel.

Solution: The solution screen for the user specified solution is shown in Figure 7.16.

Engineering Report:

The following is a portion of the summary report produced:

Figure 7.15: Load and geometry: Beam laterally supported along top flange only

*****DESIGN RESULTS*****

Resistance Factor = 0.9

Moment Resistance : Ok

CAN/CSA-S16.1-M89 Solution (For reference only)

Factored Moment/Resistance Moment = 1.05 (maximum ratio)

Corresponding Factored Moment = 100.0 kNm

Corresponding Resistance Moment = 94.9 kNm

In Main span (Load Combination 1)

User Specified Solution (Applied Solution)

Factored Moment/Resistance Moment = 0.76 (maximum ratio)

Corresponding Factored Moment = 100.0 kNm

Corresponding Resistance Moment = 132.3 kNm

In Main span (Load Combination 1)

Shear Resistance : Ok

Factored Shear/Resistance Shear = 0.13 (maximum ratio)

Corresponding Factored Shear Force = 55.0 kN

Corresponding Resistance Shear Force = 408.9 kN

In Right overhang (Load Combination 1)

Deflection : Ok

No Live Load Defined

Deflection ratio due to dead load = L/77 (maximum ratio)

Corresponding Deflection = 26.0 mm

In Right overhang

Bearing Resistance : Ok

Factored Concentrated load/Factored Bearing Resistance

= 0.36 (maximum ratio)

Corresponding Factored Bearing Force = 173.3 kN

Corresponding Resistance Bearing Force = 474.6 kN

In Right support (Load Combination 1)

Bearing Stiffener Description

Left support : Yes

Length = 331.9 mm

Width = 60.0 mm (a pair)

Thickness = 6.0 mm

Right support : Yes

Length = 331.9 mm

Width = 60.0 mm (a pair)

Thickness = 6.0 mm

Member Depth Limit : Ok

Member Depth = 252.0 mm

Maximum Depth Limit = 1950.9 mm

Member Width = 128.0 mm

Minimum Width Limit = 150.0 mm

Section $W 90.9 \times 79.0$ (W 9) : satisfactory

Member Description, Design Constraints and Design Options		Photo	File: verification_4	Date: 07-Sep-1993
Member Evaluation and Results		Return	Hardcopy name: ver_4_1.pl Please exit.	

EVALUATION RESULTS		REPORT	
Moment: MRb = 0.76	OK	User Specified Member Size W360x39 300W	
Shear force: VPr = 0.13	OK	Structural Image	
Bearing: BRb = 0.36	OK	Summary Report Detailed Report	
MaxDeflection: L/77(Dead,vertical)	OK	CAN3-CSA-S16.1-M89 Solution	
MaxDepthLimit= 1000 mm, MinWidthLimit= 100 mm	OK	User Specified Solution	

ENGINEERING REPORT	
Date: 27-Apr-1993 Job No: verification_4 Job description: overhang span (laterally supported along top flange)	
DESIGN CONSTRAINTS	
Camber for Dead Load: No Deflection Limit (Live) = L/300 Maximum Member Depth = 1000 mm Minimum Member Width = 100 mm Design Type: Check User Specified Member Size	
DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE	
CANCSA-S16.1-M89: Yes SSRC Guide: Yes Smith and Kennedy (1985): No Albert and Kennedy (1991): No	

Figure 7.16: Design result: User specified solution

Discussion:

The beam shown in Figure 7.17, can be divided into five lateral braced segments according to the locations of points of inflections and the in-plane supports. Each end of these segments is marked by node number 1 through 6. In evaluating the moment capacity, segment 3-4 is considered to be laterally supported; segment 2-3 and 4-5 are identified to be laterally supported only at ends; and segments 1-2 and 5-6 are evaluated as individual cantilevers with continuous lateral support provided to the top flange only. The corresponding laterally unsupported lengths, factored moments, moment resistances and applicable solution are listed in Table 7.7

Moment Diagram (kN-m) (Load combination 1)

Figure 7.17: Moment diagram showing points of moment inflections

Segment	M_f (kNm)	M_r (kNm)	M_f/M_r	Laterally Unsupported Length (mm)	Applicable Solution
1-2	80.0	178.7	0.45	2000	SSRC (1988)
2-3	80.0	112.2	0.56	5400.0	SSRC and S16.1
3-4	0.28	178.7	0.01	600.0	SSRC and S16.1
4-5	70.0	132.3	0.53	6000.0	SSRC and S16.1
5-6	100.0	178.7	0.53	2000.0	SSRC

Table 7.7: Design results and applicable solution strategies

7.7 Laterally Unsupported Overhang Beam with Various Load Combinations

Structure Type: Cantilever Girder

Reference: Roof Framing with Cantilever (Gerber) Girders & Open Web Steel Joists, CISC (1989)

Problem Definition: Design check W460X74 section for the Gerber System and loads defined in example 6 -- CISC (1989), as shown in Figure 7.18; and if necessary, a redesign using the automatic design procedure in IDFSM. The steel grade is specified as G40.21-M87 Grade 300W steel.

Load conditions: The load combinations are defined in Table 7.8 and the corresponding load factors are given in Figure 7.19. Detailed load values and locations as given in IDFSM are shown in Figures 7.20 to 7.22.

Load Combination	Cantilevers and Drop Span	Main Span
1	Dead plus Full Snow	Dead plus Full Snow
2	Dead plus Full Snow	Dead plus Half Snow
3	Dead plus Half Snow	Dead plus Full Snow
4	Dead Plus wind uplift	Dead plus wind uplift

Table 7.8: Load combinations and the corresponding Load conditions

Lateral support conditions:
 x = bottom chord extension (BCE)
 T = BCE and acting as tie joist

Unfactored girder loads from joist lines:

Joist line location	Dead load ¹ kN	100% snow ² kN	Wind uplift ³ kN
1-5, 25-29	18.1	33.6	27.6
8 - 10	18.1	33.6	22.4
6, 24	18.1	33.6	23.9
7, 11-23	18.1	33.6	20.3

Notes:

- including steel weight
- roof snow
- wind loads for strength design are computed using Commentary B, Supplement to the National Building Code of Canada, 1985.

Figure 7.18: General design conditions, CISC (1989), p.8

Dead Load	Live Load 1	Live Load 2	Show All Loads	Print	File Edit View Help
Wind Up 0.0	Live Load 2	Live Load 4	Load Factors	Return	Hardcopy format: pdf, html, jpg Please wait.

LOAD FACTOR

Load Type	Load Combination 1	Load Combination 2	Load Combination 3	Load Combination 4
Dead Load	1.25	1.25	1.25	0.62
Wind upward	0.00	0.00	0.00	1.50
Live load 1	1.50	0.00	0.00	0.00
Live load 2	0.00	1.50	0.00	0.00
Live load 3	0.00	0.00	1.50	0.00
Live load 4	0.00	0.00	0.00	0.00

Figure 7.19: Load combinations

Figure 7.20: Specified dead loads (Load Case 1)

Figure 7.21: Specified wind and snow load (Load Case 2 and 3)

Figure 7.22: Load Case 4: Full snow load on cantilevers and half load on main span
Load Case 5: Half snow load on cantilevers and full load on main span

Solution: The design option screen for this problem is illustrated in Figure 7.23.

The internal bending moment, shear forces and deflections for all load combinations are shown in Figures 7.24 and 7.25, Figures 7.26 and 7.27, Figures 7.28 to 7.30, respectively. The results from the design check of the W460x74 section are shown in Figure 7.31. As indicated, the section is unsatisfactory as the live load deflection limit is exceeded and a redesign is necessary. The results from the automatic design shown in Figure 7.32 is followed by corresponding engineering report.

Member Development, Design Constraints and Design Options		Photo	Title: 1000 0	Date: 1/01/1997
Member Evaluation and Results		Return	Hardcopy Name: 000: main.pr Please wait	

FLEXURAL MEMBER DESCRIPTION			DESIGN CONSTRAINTS		
Structural System	Ok	Define/Check	Camber for Dead Load	No	Change
Member Length, Section Type and Size	Ok	Define/Check	Deflection Limit(Live)	L/240	Change
Support(s), Stiffener(s) & Cope(s)	Ok	Define/Check	Maximum Member Depth	1000.0 (mm)	Change
Applied Loads	Ok	Define/Check	Minimum Member Width	100.0 (mm)	Change
Internal Forces & Deflections	Ok	Check/Execute	Automatic Design	Check Member	

DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE			
CAN/CSA-S16 1-M89	Yes	Ok	Default option (only for non-cantilever beams)
Modified SSRC Guide(1988)	Yes	Change	w2 value & load patterns (modifications (Easa & Kennedy))
Schmidt and Kennedy(1985)	No	Change	Interactive buckling
Albert and Kennedy(1991)	No	Change	Finite element analysis

DEFAULT OPTIONS ARE HIGHLIGHTED USE DEFAULT OPTIONS OR
 MODIFY SELECTED OPTIONS BY PRESSING THE APPROPRIATE BUTTON

Figure 7.23: Design option screen

Figure 7.24: Bending moment diagrams, for load combinations 1 and 2

Figure 7.25: Bending moment diagrams, for load combinations 3 and 4

Figure 7.26: Shear force diagrams, for load combinations 1 and 2

Figure 7.27: Shear force diagrams, for load combinations 3 and 4

Figure 7.28: Deflected shapes, for the specified dead and live loads from load combination 1

Figure 7.29: Deflected shapes, for the specified live loads from load combinations 2 and 3

Figure 7.30: Deflected shapes, for the specified live loads from load combination 4

Figure 7.31: Design check: W410x74 section

Member Description, Design Constraints and Design Options		Photo	File name	Date	Jan 1993
Member Evaluation and Results		Return	Hardcopy name: csc_result_1.pr Please wait		

EVALUATION RESULTS		REPORT	
Moment $M/M_r = 0.52$	Ok	Suggested Member Size W810x 101 300W	
Shear force $V/V_r = 0.16$	Ok	Structural Image	
Bearing $B/B_r = 0.73$	Ok	Summary Report Detailed Report	
Max Deflection $L/2885$ (Dead,vertical) $L/262$ (Live, vertical)	Ok	CANCSA-S16 1-M89 Solution	
MaxDepthLimit: 1000 mm MinWidthLimit: 100 mm	Ok	User Specified Solution	

<p align="center">ENGINEERING REPORT</p> <p>Date: 1-Jan-1993 Job title: csc.1 Job description: Gerber System Design (cantilever span)</p> <p>DESIGN CONSTRAINTS</p> <p>Camber for Dead Load: No Deflection Limit (Live) = $L/240$ Maximum Member Depth = 1000.0 mm Minimum Member Width = 100.0 mm Design Type: Automatic Design</p> <p>DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE</p> <p>CANCSA-S16 1-M89: Yes SSRC Guide: Yes Smith and Kennedy (1985): No Albert and Kennedy (1991): No</p>

Figure 7.32: Automatic redesign

Engineering Report: (summary report)

ENGINEERING REPORT

Date: 28-Mar-1993
Job title: csc.1
Job description: Gerber System Design (cantilever span)

DESIGN CONSTRAINTS

Camber for Dead Load: No
Deflection Limit (Live) = $L/240$
Maximum Member Depth = 1000.0 mm
Minimum Member Width = 100.0 mm
Design Type: Automatic Design

DESIGN OPTIONS FOR EVALUATING MOMENT RESISTANCE

CANCSA-S16 1-M89: Yes
SSRC Guide: Yes
Smith and Kennedy (1985): No
Albert and Kennedy (1991): No

STRUCTURAL SYSTEM INFORMATION

Structural System Type: Noncomposite Gerber system

(Cantilever span)

Member Length

Main span = 12000 0 mm

Left overhang = 2200 0 mm

Right overhang = 2200 0 mm

Member Sections

Flexural Member (default) W610 x 101 300W

(Class 1 section)

Support Member (left) W610 x 140 300W

Support Member (right) W610 x 140 300W

Lateral Support Description

Number of Laterally supported point(s) in main span = 7

Distance along the main span measured from the left end of main span

2000 00 (m) (Top chord of OWSJ's, From both sides of main member)

4000 00 (m) (Top chord of OWSJ's, From both sides of main member)

6000 00 (m) (Top chord of OWSJ's, From both sides of main member)

8000 00 (m) (Top chord of OWSJ's, From both sides of main member)

10000 00 (m) (Top chord of OWSJ's, From both sides of main member)

0 00 (m) (Top and bottom chords of OWSJ's, From both sides of main member)

12000 00 (m) (Top and bottom chords of OWSJ's, From both sides of main member)

Number of Laterally supported point(s) in left overhang = 1

Distance along the left overhang measured from the left end of main span

2000 00 (m) (Top and bottom chords of OWSJ's, From both sides of main member)

Number of Laterally supported point(s) in right overhang = 1

Distance along the right overhang measured from the right end of main span

2000 00 (m) (Top and bottom chords of OWSJ's, From both sides of main member)

*****DESIGN RESULTS*****

Resistance Factor = 0.9

Moment Resistance Ok

CAN/CSA-S16.1-M89 Solution (For reference only)

Factored Moment/Resistance Moment = 0.52 (maximum ratio)

Corresponding Factored Moment = 403.8 kNm

Corresponding Resistance Moment = 783.0 kNm

In Main span, (Load Combination 3)

User Specified Solution (Applied Solution)

Factored Moment/Resistance Moment = 0.52 (maximum ratio)

Corresponding Factored Moment = 403.8 kNm

Corresponding Resistance Moment = 783.0 kNm

In Main span, (Load Combination 3)

Shear Resistance Ok

Factored Shear/Resistance Shear = 0.16 (maximum ratio)

Corresponding Factored Shear Force = 182.6 kN

Corresponding Resistance Shear Force = 1128.3 kN

In Main span, (Load Combination 3)

Deflection Ok

Deflection ratio due to live load = $L/251$ (maximum ratio)
 Corresponding Deflection = 8.8 mm
 In Right overhang. (Load Combination 2)
 Deflection ratio due to dead load = $L/2765$ (maximum ratio)
 Corresponding Deflection = 4.3 mm
 In Main span

Bearing Resistance : Ok
 Factored Concentrated load/Factored Bearing Resistance
 = 0.73 (maximum ratio)

Corresponding Factored Bearing Force = 730.2 kN
 Corresponding Resistance Bearing Force = 1005.6 kN

In Right Support (Load Combination 1)

Bearing stiffener at support

Left support : Yes

Length = 573.0 mm

Width = 70.0 mm (a pair)

Thickness = 6.0 mm

Right support : Yes

Length = 573.0 mm

Width = 70.0 mm (a pair)

Thickness = 6.0 mm

Member Geometry Limit : Ok

Member Depth = 602.0 mm

Maximum Depth Limit = 1000.0 mm

Member Width = 228.0 mm

Minimum Width Limit = 100.0 mm

The section has been resized to a W610x101 700W
 section W610x101 300W is satisfactory

Discussion: The moment capacity determined by the design check using IDFSM was consistent with those given in (ISC) (1989). The section was found to be unsatisfactory with respect to serviceability limit states. The deflection at the tip of the cantilever for load combination 2 exceeded the specified limit of $L/240$. The deflection at the tip of cantilever span also governed the automatic design, where the optimum section was found to be W610x101. Information on the number of effective lateral supports, the length of laterally braced segments and the corresponding moment capacities for each load combination can be traced in the detailed engineering report housed in .det file. A summary is given in Table 7.9

	Load Combination	1	2	3	4
Segment 1	Length (mm)	2000	4000	2000	2000
	Location	Main Span	Main Span	Main Span	Main Span
	M _r (kN-m)	783.0	783.0	783.0	783.0
Segment 2	Length (mm)	2000	2000	2000	8000
	Location	Main Span	Main Span	Main Span	Main Span
	M _r (kN-m)	783.0	783.0	783.0	370.3
Segment 3	Length (mm)	2000	2000	2000	2000
	Location	Main Span	Main Span	Main Span	Main Span
	M _r (kN-m)	783.0	783.0	783.0	783.0
Segment 4	Length (mm)	2000	4000	2000	2000
	Location	Main Span	Main Span	Main Span	Left Overh.
	M _r (kN-m)	783.0	783.0	783.0	783.0
Segment 5	Length (mm)	2000	2000	2000	2000
	Location	Main Span	Left Overh.	Main Span	Right Overh.
	M _r (kN-m)	783.0	783.0	783.0	783.0
Segment 6	Length (mm)	2000	2000	2000	200
	Location	Main Span	Right Overh.	Main Span	Left Overh.
	M _r (kN-m)	783.0	783.0	783.0	783.0
Segment 7	Length (mm)	2000	200	2000	200
	Location	Left Overh.	Left Overh.	Left Overh.	Right Overh.
	M _r (kN-m)	783.0	783.0	783.0	783.0
Segment 8	Length (mm)	2000	200	2000	
	Location	Right Overh.	Right Overh.	Right Overh.	
	M _r (kN-m)	783.0	783.0	783.0	
Segment 9	Length (mm)	200		200	
	Location	Left Overh.		Left Overh.	
	M _r (kN-m)	783.0		783.0	
Segment 10	Length (mm)	200		200	
	Location	Right Overh.		Right Overh.	
	M _r (kN-m)	783.0		783.0	

Table 7.9: Summary of design results

7.8 Laterally Unsupported Beam with Combined Bending and Torsional Loads

Structure Type: Simply supported beam (laterally unsupported)

Reference: AISC 1983. Torsional Analysis of Steel Members. American Institute of Steel Construction.

Problem Definition: Design check for a W250X80 (W10X54) beam, 4572 mm (15 ft) long, connected to the columns at either end by standard web angle connections, and subjected to a factored concentrated load of 40.04 kN (9 kips), with an eccentricity of 152.4 mm (6 in) at midspan, as shown in Figure 7.33. The steel grade was specified as G40.21-M87 Grade 300W steel ($F_y=43.51$ ksi).

Figure 7.33: Loads and geometry: Combined bending and torsion

Solution: The torque diagram and the corresponding design results are shown in Figure 7.34 and 7.35, respectively.

Figure 7.34: Torque diagram

Figure 7.35: Design results: Combined bending and torsion

Discussion:

The indices for moment torque diagram, calculated by IDFSM and given in Figure 7.35, are shown non-dimensionally in Figure 7.36. The ultimate limit state and serviceability limit state curves are given by curves EHGF and KL, respectively. Point *P* represents the maximum combination of torque and bending moment which occurs at midspan. The torque is directly proportional to the bending moment. The intersection of the line through *P* and the origin, and the serviceability limit state curve KL represents the maximum combination of torque and moment that can be applied to the beam (58% of the beams capacity is being utilized). This corresponding to the AISC (1983) evaluation where the maximum combined normal stress due to bending and warping is limited to F_y . For this case, the combined normal stress was calculated to be 21.4 ksi, approximately 19% of the yield stress.

Figure 7.36: Moment-torque diagram for class 1 sections

7.9 Laterally Unsupported Beam with Combined Bending and Torsional Load of Different Patterns

Structure Type: Simply supported beam (laterally unsupported)

Problem Definition: Automatic design of a beam, 4000 mm long, connected to columns at either end by standard web angle connections, and subjected to a factored concentrated load and an uniformly distributed load, as shown in Figure 7.37. The steel grade was specified as G40.21-M87 Grade 300W steel.

Figure 7.37: Load and geometry: Combined bending and torsion with different load patterns

Solution: The torque diagrams for each load case and the combination (superimposed) are shown in Figure 7.38. The corresponding design results are shown in Figure 7.39.

Figure 7.38: Torque diagrams

Figure 7.39: Design result: Combined bending and torsion with different load patterns

Discussion:

The modified strategy for constructing the moment-torque diagram described in Chapter 4 for beams subjected to more than one torsional load pattern was used to determine the indices (critical moments and torques) given in Figure 7.39. As indicated for the W250x80 section specified, the moment/torque capacity was "Not Ok" even though the ratio's of M_t/M_r and T_t/T_r of 0.21 and 0.35 are less than one. An examination of the torsion part of the detailed report, reproduced below, shows that the serviceability limit state (S.L.S) has been exceeded at either end of the member. Note, comparisons of moment and torque values with limit state design criteria were made at 100 equally spaced locations along the beam. A redesign of the beam by IDFSM found a W200x100 section to be satisfactory.

Point	Bending Moment (kN-m)	Elastic Torque (kN-m)	Limit State Exceeded
1	0.00	9.00	S.L.S
2	1.79	8.92	S.L.S
3	3.57	8.84	S.L.S
4	5.35	8.76	S.L.S
5	7.07	8.68	S.L.S
6	8.80	8.60	S.L.S
7	10.51	8.52	S.L.S
8	12.21	8.44	S.L.S
9	13.89	8.36	S.L.S
10	15.55	8.28	S.L.S
11	17.20	8.20	S.L.S
12	18.87	8.12	S.L.S
13	20.45	8.04	S.L.S
14	22.05	7.96	S.L.S
15	23.63	7.88	S.L.S
16	25.20	7.80	S.L.S
17	26.75	7.72	S.L.S
18	28.29	7.64	S.L.S
19	29.81	7.56	S.L.S
20	31.31	7.48	S.L.S
21	32.80	7.40	S.L.S
22	34.27	7.32	S.L.S
23	35.7	7.24	S.L.S
24	37.17	7.16	S.L.S
25	38.64	7.08	S.L.S
26	40.00	7.00	S.L.S
27	41.35	6.92	S.L.S

3

OF/DE

3

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

28	42.77	6.84	---
29	44.13	6.76	---
30	45.47	6.68	---
31	46.80	6.60	---
32	48.11	6.52	---
33	49.41	6.44	---
34	50.69	6.36	---
35	51.95	6.28	---
36	53.20	6.20	---
37	54.43	6.12	---
38	55.65	6.04	---
39	56.85	5.96	---
40	58.03	5.88	---
41	59.20	5.80	---
42	60.35	5.72	---
43	61.49	5.64	---
44	62.61	5.56	---
45	63.71	5.48	---
46	64.80	5.40	---
47	65.87	5.32	---
48	66.93	5.24	---
49	67.97	5.16	---
50	68.99	5.08	---
51	70.00	5.00	---
52	68.99	5.08	---
53	67.97	5.16	---
54	66.93	5.24	---
55	65.87	5.32	---
56	64.80	5.40	---
57	63.71	5.48	---
58	62.61	5.56	---
59	61.49	5.64	---
60	60.35	5.72	---
61	59.20	5.80	---
62	58.03	5.88	---
63	56.85	5.96	---
64	55.65	6.04	---
65	54.43	6.12	---
66	53.20	6.20	---
67	51.95	6.28	---
68	50.69	6.36	---
69	49.41	6.44	---
70	48.11	6.52	---
71	46.80	6.60	---
72	45.47	6.68	---
73	44.13	6.76	---
74	42.77	6.84	---
75	41.39	6.92	---
76	40.00	7.00	---
77	38.59	7.08	---
78	37.17	7.16	---
79	35.73	7.24	---
80	34.27	7.32	---
81	32.80	7.40	---
82	31.31	7.48	S L S

83	29.81	7.56	S L S
84	28.29	7.64	S L S
85	26.75	7.72	S L S
86	25.20	7.80	S L S
87	23.63	7.88	S L S
88	22.05	7.96	S L S
89	20.45	8.04	S L S
90	18.83	8.12	S L S
91	17.20	8.20	S L S
92	15.55	8.28	S L S
93	13.89	8.36	S L S
94	12.21	8.44	S L S
95	10.51	8.52	S L S
96	8.80	8.60	S L S
97	7.07	8.68	S L S
98	5.33	8.76	S L S
99	3.57	8.84	S L S
100	1.79	8.92	S L S
101	0.00	9.00	S L S

7.10 Combined Bending and Torsional Loading within a Laterally Unsupported Segment

Structure Type: Simply supported beam (three laterally unsupported segments)

Problem Definition: Automatic design of a beam with discrete lateral supports (same geometry and in-plane loads as the example given in section 7.3) and with a torsional loads of 10.0 kNm applied within one of the laterally unsupported segments as shown in Figure 7.40. The steel grade was specified as G40.21-M87 Grade 300W steel.

Solution: The torque diagram and the corresponding design results are shown in Figures 7.41 and 7.42, respectively.

Figure 7.40: Loads and geometry: Combined bending and torsion on a laterally unsupported segments

Figure 7.41: Torque diagram

Figure 7.42: Design result: Combined bending and torsion on a laterally unsupported segment

Discussion:

The program IDFSM assumes that the reaction to the applied torque is taken out by the flexural capacity of the lateral supports. This is illustrated in Figure 7.41 by the zero torque values in the segments adjacent to the torsionally loaded segment. The maximum moment for the moment torque interaction diagram is defined by the interactive buckling capacity of the beam. All other applicable limit states design checks are made and are given in the engineering reports.

Chapter 8

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

8.1 Conclusions

The program IDFSM — “Interactive Design of Flexural Steel Members for Bending and Torsion”, provides engineers with a comprehensive and practical tool for designing and evaluating the capacity of beams subjected to bending and/or torsion. It provides for comprehensive descriptions of the structural system and loads without labourious cryptic input. The graphics-oriented user interface has been designed for the analysis/design process and does not require a manual for use. Positive visual responses are given for any action.

As an engineering design software which handles a large variety of problems ranging from the trivial to complex, IDFSM makes extensive use of current and ongoing

research for problems that are not handled by CAN/CSA-S16.1-M89 directly, but a reference to as rational methods of analysis and design.

8.2 Recommendations and Future Work

The modular format and separation of program code for the engineering analysis/design and user interface modules make the adaptation, expansion, revision and integration of IDFSM relatively easy. Generally, the following recommendations refer to expansion of the capabilities of the program, some of which are in progress.

- Extend the program to include shapes other than W and WWF shapes, like Angles, Channels, Tee's, S-shapes and Z-shapes. The primary reasons why these singly symmetric and non-symmetric shapes have not been included are:
 1. The lateral-torsional buckling behaviour is not well understood and,
 2. There is not a limit states design approach for combined bending and torsion. This could be addressed using the same approach as described in AISC (1983), where the combined maximum stresses due to bending and torsion is limited to the yield stresses. These routines already exist for Channels and Z-shapes in TORSTEEL.
- Add continuous beams (i.e. crane girders) as another flexural system. The additional work would involve some modifications to the user interface and minor changes with respect to the organization of design routines to evaluate multispans.
- Add modules for the analysis/design of decks, composite decks and beams, stub girder systems, plate girders and OWSJ's. With each flexural member

type additional specialized user interface and design modules would have to be developed.

- Implement the Albert & Kennedy (1991) finite element module for evaluation of the lateral-torsional buckling capacity of beams. This method is considered to give the best possible solutions to beam stability problems and has already been incorporated into the user interface portion of IDFSM.
- Porting the program IDFSM to PC applications.
- Integration of IDFSM with other member and connection design modules for the integrated design program for steel buildings. The complete integrated program will evolve over a period of time as more modules are developed. Currently, the program would be integrated with an existing module SCADD, "Steel Connection, Analysis, Design and Detailing", to design the connection from the beam to the supporting members. This would eliminate the need to define the coping dimensions as they are determined within SCADD and end reactions as they are determined with IDFSM. The integration of these two modules would be relatively simple as both programs have similar data structures.

The next evolutionary step in the integration process would be the integration of IDFSM with a good 3D frame analysis program such as CU-STAND, Cornell University (1989). This would allow for the development of file structures and user interfaces for the design of a large number of beams. Additional algorithm would be developed to determine the optimum number of beam sections selected and their sizes for a building.

Chapter 9

REFERENCES

- AISC 1983. Torsional Analysis of Steel Members. Chicago, IL, U.S.A. American Institute of Steel Construction.
- Albert C., Essa H.S. and Kennedy D.J.L. 1991. Stability of Steel Beams in Cantilever-Suspended Span Construction. Department of Civil Engineering, University of Alberta, Edmonton, Alberta.
- Albert C. and Kennedy D.J.L. 1991. Inelastic Distortional Buckling of Beams, Finite Element Program. Department of Civil Engineering, University of Alberta, Edmonton, Alberta.
- Anumba, C.J. and A.S. Watson A.S. 1992. An innovative approach towards designer-oriented CAD systems. *The Structural Engineer*, 70(9): 165-168.
- Brohn D.M. 1992. A new paradigm for structural engineering. *The Structural Engineer*, 70(13): 239-240.
- Cheng, J.J.R. 1992. Design of Steel beams With End Copes. Department of Civil Engineering, University of Alberta, Edmonton, Alberta.

- Cheng, J.J.R., Yura, J.A., and Johnson, C.P. 1984. Design and Behaviour of Coped Beams. Department of Civil Engineering, The University of Texas at Austin, PMFSEL Report No. 84-1.
- Chu, K., and Johnson, R.B. 1974. Torsion in beams with open sections. ASCE Journal of the Structural Division, **100**(ST7): 1397-1419.
- CISC. 1989. Roof framing with cantilever (Gerber) girders & open web steel joists. Canadian Institute of Steel Construction, Willowdale, Ont.
- CISC. 1991. Handbook of Steel Construction (5th ed.). Canadian Institute of Steel Construction, Willowdale, Ont.
- Cornell University, 1989. Programmer's manual for CU-PREPF, CU-STAND, and CU-QUAND. Cornell University, Ithaca, New York, U.S.A.
- CSA. 1989. Steel Structures for Buildings (Limit States Design), National Standard of Canada, CAN/CSA-S16.1-M89. Canadian Standards Association, Rexdale, Ont.
- CSA. 1987. Structural Quality Steels. National Standard of Canada, CAS/CAN G40.21-M87. Canadian Standards Association, Rexdale, Ont.
- Driver, R.J., and Kennedy, D.J.L. 1987. Combined flexure and torsion of I-shaped steel beams. Structural Engineering Report 144, Department of Civil Engineering, University of Alberta, Edmonton, Alberta.
- Driver, R.J., and Kennedy, D.J.L. 1989. Combined flexure and torsion of I-shaped steel beams. Canadian Journal of Civil Engineering, **16**(2): 124-139.
- Duchesne D.P.J. and Thomson S. 1992. State of the art in Civil Engineering program integration. Proceedings of the Second Canadian Conference on

Computing in Civil Engineering.

- **Duchesne, D.P.J. and Humar, J.L. 1991. Engineering Software - A Structural Consultant's Perspective. Canadian Journal of Civil Engineering. 18: 303-311.**
- **ECOM Associates, 1991. SD4C Steel Beam/Column Design. ECOM Associates, Milwaukee, Wisconsin, U.S.A.**
- **Essa H.S. and Kennedy, D.J.L. 1992. Design of cantilever beams against lateral-torsional buckling. Department of Civil Engineering, University of Alberta, Edmonton, Alberta.**
- **Galambos, T.V. 1988. Guide to Stability Design Criteria for Metal Structures (4th ed.). Structural Stability Research Council, John Wiley & Sons, Inc., New York, NY.**
- **CISC 1992. Gravity Frame Design 3, User's Guide and Technical Reference Manual. Canadian Institute of Steel Construction, Willowdale, Ontario.**
- **Johnston, B.F. 1976. Guide to Stability Design Criteria for Metal Structures (3rd ed.). Structural Stability Research Council, John Wiley & Sons, Inc., New York, NY.**
- **Kollbrunner, C.F., and Basler, K. 1969. Torsion in Structures (2nd ed.). Springer-Verlag, Berlin.**
- **Kollbrunner, C.F., Hajdin, N., and Obradović, P. 1979. Elastic-plastic fixed ended beam of I-section subjected to bending and warping torsion. Institut für Bauwissenschaftliche Forschung Publikations, No. 46, May, p. 1-40.**
- **Kulak, G.L., Adams, P.F., and Gilmor, M. I. 1990. Limit States Design in Structural Steel. Canadian Institute of Steel Construction, Willowdale, Ont.**

- McGuire W. 1992. Computers and Steel Design. Modern Steel Construction. July, 1992. p.39-42.
- Murray D.W. 1988. Program for Plane Frame Analysis. University of Alberta.
- NRC, 1988. National Building Code of Canada. National Research Council of Canada, Ottawa, Ontario.
- Nethercot D.A., and Trahair, N.S. 1983. Design of laterally unsupported beams. Chapter 3, Ed. Narayanan, R. Beams and Beam-Columns—Stability and Strength. Applied Science Publishers, Barking, Essex, England,
- Nethercot, D.A. 1983. Elastic lateral buckling of beams. Chapter 1, Ed. Narayanan, R. Beams and Beam-Columns—Stability and Strength. Applied Science Publishers, Barking, Essex, England,
- Nethercot, D.A. 1979. Design for Structural Stability. Constrado Nomographs, Granada Publishing, London.
- Nethercot, D.A. 1973. The Effective Lengths of Cantilevers as Governed by Lateral Buckling. The Structural Engineer. 515:161-168.
- Ojalvo, M. 1975. Warping and Distortion at I-Section Joints Discussion. ASCE Journal of Structural Division. 103(ST1).
- Pastor, T.P., and DeWolf, J.T. 1979. Beams with torsional and flexural loads. RSCE Journal of the Structural Division. 105(ST3): 527-538.
- Razzaq, Z., and Galambos, T.V. 1979. Biaxial bending tests with or without torsion. ASCE Journal of the Structural Division, 105(ST11): 2163-2185.
- Rahimian, A. 1992. Engineering Software Company's Advanced Integrated Beam Design Program. Modern Steel Construction. May, 1992. p. 12-13.

- Schmitke C.D. and Kennedy, D.J.L. 1985. Effective lengths of laterally continuous, laterally unsupported steel beams. *Canadian Journal of Civil Engineering*, **12**:603-616.
- W.E.S.1992. *Structural Optimization Design & Analysis (SODA), User Manual (Release 3.1)*. Waterloo Engineering Software, Waterloo, Ontario.
- Sourochnikoff, B. 1951. Strength of I-beams in combined bending and torsion. *ASCE Transactions*, **116**: 1319-1342.
- Sun. 1991(a). *Sun C++ Programmers Guide*. Sun. Microsystems, Inc.
- Sun. 1991(b). *Sun FORTRAN User's Guide*. 1991. Sun. Microsystems, Inc.
- Timoshenko S.P., and Gere, J.M. 1961. *Theory of elastic Stability*. McGraw-Hill, New York.
- Trahair, N.S. 1983. Inelastic lateral buckling of beams. Chapter 3, Ed. Narayanan R. *Beams and Beam-Columns—Stability and Strength*. Applied Science Publishers, Barking, Essex, England.
- Yong, L.P., and Trahair, N.S. 1992. Prebuckling deflection and lateral buckling I, theory. *Journal of Structural Engineering*, **118**(11):124-139.

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