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Design Recommendations for Multi-Story Frames

PLASTIC DESIGN COMMENTARY - SPECIFICATION - RECENT PROGRESS

SUMMARY REPORT

by

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TABLE OF CONTENTS

1. INTRODUCTION

This report briefly summarizes the work that has been done during the fiscal year of 1967-1968. It consists of the following three phases of activities:

A. Revision of ASCE Manual 41 "Commentary on Plastic Design in Steel"

B. Revision of AISC Specifications

C. Recent progress in Plastic Design

Much of the activities has been completed, written up, and distributed to the members of the appropriate committee or subcommittee of the ASCE for review. Table 1 is a list of the distributed reports.

2. REVISION OF PLASTIC DESIGN COMMENTARY

The Ad Hoc Committee consisting of thirty-four members was formed in July 1967 to revise the 1961 edition of the ASCE Manual No. 41 "Commentary on Plastic Design in Steel". The list of the Ad Hoc Committee Members is given in the Appendix which is a reprint of the draft of "Foreword to the Second Edition". This second edition is prepared under the auspices of the WRC Subcommittee and the ASCE Structural and Mechanics Divisions. The entire membership of these three major committees is given in Table 2.

At its Ad Hoc Committee Meeting on July 21, 1967 in New York City, it was agreed that the following scope of revisions be adopted to provide the necessary guidance to the certain members of the Ad Hoc Committee who would prepare the initial drafts:

1. The revision is to be a modest one.
2. Basic approach is still simple plastic theory but with modifications where necessary to extend its applicability.
3. The Commentary is expanded to include braced multi-story frames.
4. Steels with a well-defined yield plateau are considered. The upper limit of the yield stress is 65 ksi.
5. The scope is limited to planar structures only.
6. Primarily static loading is considered, however, some attention is given to repeated loading effects.

Having established this scope, the committee went forward with the revisions and had, within one year, completed revisions of the first eight chapters. The remaining two chapters are now in draft form.

The second edition will have a new chapter on Multi-story Frames (see Table 3). In addition, three new articles have been added to the Commentary in view of their increasingly important role in the plastic method of design of steel structures. These articles are: (1) the role of strain hardening, (2) moment balancing method, and (3) column deflection curves.

Table 4 outlines the major changes in the Commentary. As pointed out earlier, Arts. 2.3 and 3.4 are added because of their increased importance, particularly as applied to the plastic design of multi-story frames. In Chapter 4 the article on material is expanded to include A36, A441, and A572 steels. Formulas are given for computing the plastic moment of composite concrete and steel beams. Load factors are reduced in accordance with the new AISC Specification.

The inclusion of the recent results on the behavior of high-strength (A441 and A572) members and frames can be found in Chapter 5.

Chapter 6 is substantially revised in view of the recent development in the effect of shear force on the load-carrying capacity of steel members, the phenomena of local and lateral buckling of beams and the recent results on the behavior of steel beam-to-column connections subjected to repeated inelastic strains.

Article 7.4 "Rotation Capacity" has been replaced by the new article "Column Deflection Curves" because of the latter's importance in the design of beam-columns in multi-story frames. The column deflection curve concept provides not only the means to determine the ultimate strength of columns but also their rotation capacity. It is now possible to provide the structural designers with a formula for checking the possible occurrence of lateral-torsional buckling for laterally unbraced beam-columns. Article 7.6 "Frame Stability" has been moved to Chapter 10.

Article 8.6 "Details with Regard to Welding" has been revised substantially. It will now have a new recommended design value for fillet welds. Article 8.8 "Details with regard to bolting" has been expanded and formula for computing the prying force in a fastener is also given.

Design guides to limit deflection have been added to Chapter 9. "Multi-Story Frames" is a new chapter. It will contain a detailed description of the technique recommended for designing braced multi-story frames and some discussions on unbraced multi-story frames under gravity and combined loads.

3. REVISION OF AISC SPECIFICATION

The revision of AISC Specification Part 2 is near completion. The major changes are summarized in Table 5. Briefly the scope is expanded to permit the use of plastic method for designing braced multi-story frames. Load factors of 1.85 and 1.40 have been reduced to 1.70 and 1.30 respectively and steels of yield stress levels in the range of 36 to 65 ksi are permitted for use in plastic design in the new specification. A new section on vertical bracing systems has been added. Columns can now be designed with a simple formula of

$$\frac{P}{P_{cr}} + \frac{C_m M}{M_m(1 - \frac{P}{P_e})} \leq 1.0.$$

The section on web crippling is moved to Part 1 of the Specification. The maximum b/t ratio of 8.5 has been revised so that the new specification will have a list of maximum permissible b/t ratios for the different grade steels. The depth-to-width ratio of beam and girder webs has also been revised. The new specification will have $\frac{d}{w}$ ratio for the case of $\frac{P}{P_y} \leq 0.27$ and that of $\frac{P}{P_y} > 0.27$. Finally the revised specification will have new lateral bracing rules for beams under moment gradient and uniform moment.

4. RECENT PROGRESS IN PLASTIC DESIGN

A survey of the application of plastic design was first made in 1960.* Up to that time plastic design had its greatest application in low buildings in the United Kingdom and the United States. Today plastic design has gained wider acceptance and already thousands of low buildings that were designed plastically have been built in many parts of the world. A few countries like United States, Canada, and the United Kingdom also have multi-story buildings which were designed by the plastic method. Table 6 summarizes the extent of the applicability of the plastic method of design in the various countries cited in this report. Not less than ten countries (Tables 6 and 7) have or will have building specifications that formally approve the use of plastic technique for designing steel structures. The recommended load factors vary considerably in all countries as can be seen in Table 7. This is unavoidable partly because of the different climatic conditions and partly because of the different state of art that has been reached. Nevertheless it is gratifying to know that a European Task Group on Plastic Design has been formed recently in an attempt to work out a common specification for the European countries.

*Beedle, L. S. "On the Application of Plastic Design" Fritz Engineering Laboratory Report No. 205.70, Lehigh University

APPENDIX

Foreword to the Second Edition

Since publication of the First Edition, there have been notable developments in plastic design of steel structures. A substantial amount of literature has been published as a result of the research work completed since the first publication. Formal recognition has been given to plastic design in building specifications; it is now "Part 2" of the AISC Specifications for buildings and bridges, and many of the provisions of Part 1 (Allowable-Stress Design) were affected by the research on the plastic behavior of structures. There has been significant application of the method, not only to low buildings, but also to a number of multi-story frames. The substantial amount of research on multi-story frames and on higher strength steels resulted in a summer conference at Lehigh University in 1965 which brought into focus a number of the new problems and many of their solutions.

The ASCE Structural Division Committee on Plastic Design therefore took steps to prepare a revision to this Manual. The contents are extended, as are its recommendations, to reflect the developments since the beginning of this decade.

The object of the committee was to prepare a modest revision. The basic approach is still the simple plastic theory but with modifications where necessary to extend its applicability. In addition to covering low unbraced frames, the Commentary is expanded to include braced multi-story frames. Unbraced multi-story frames are not covered. Steels with a well-defined yield plateau are considered, the upper limit of the yield stress being 65 ksi. The scope is also limited to planar structures. The loading is considered to be primarily static; however, some attention is given to repeated loading effects that are characteristic of those associated with earthquakes.

The Ad Hoc Committee for the preparation of this Second Edition is made up of the members of the original two committees of WRC and ASCE, of designated members of the present Committee on Plasticity of the Engineering Mechanics Division, of the ASCE Structural Division Committee on Plastic Design, and of Lehigh University investigators.

This Commentary results from a series of drafts prepared by certain members of the Ad Hoc Committee, and subsequently reviewed by the entire membership of the three major committees listed earlier. Authors of the original drafts were Messrs. S. C. Batterman, W. F. Chen, G. C. Driscoll, Jr., J. W. Fisher, T. V. Galambos, W. C. Hansell, M. G. Lay, L. C. Lim, L. W. Lu, B. M. McNamee, A. Ostapenko, and E. P. Popov. In addition the committee had the help and advice of overseas representatives from

The committee recommends this Manual for study by all structural engineers.

Ad Hoc Committee

H. Allison	J. Heyman
J. F. Baker	T. R. Higgins
S. C. Batterman	M. R. Horne
E. R. Bryan	B. G. Johnston
W. F. Chen	M. G. Lay
G. C. Driscoll, Jr.	S. L. Lee
D. C. Drucker	L. C. Lim
T. C. Fan	L. W. Lu
M. Fialkow	C. Massonnet
J. W. Fisher	B. M. McNamee
G. F. Fox	W. H. Munse
Y. Fujita	A. Ostapenko
T. V. Galambos	E. P. Popov
K. Gerstle	D. Sfintesco
J. A. Gilligan	B. Thurlimann
W. J. Hall, Jr.	M. Wakabayashi
W. C. Hansell	L. S. Beedle, Chairman

TABLES

TABLE 1 - REPORTS

Report No.	Title	Author	Date of Issue
345.1	Plastic Design Commentary: Foreword to the Second Edition	L. S. Beedle	12-18-67
	Chapter 1, Introduction	L. W. Lu	12-18-67
	Chapter 2, Basic Principles	S. C. Batterman T. V. Galambos	12-18-67
	Chapter 3, Analysis and Design	A. Ostapenko	2-5-68
	Chapter 4, General Provisions	L. C. Lim	2-5-68
	Chapter 5, Verification of Plastic Theory	L. C. Lim	2-27-68
	Chapter 6, Additional Design Considerations	W. F. Chen T. V. Galambos E. P. Popov	3-7-68 3-7-68
	Chapter 7, Compression Members	T. V. Galambos	6-25-68
	Chapter 8, Connections	J. W. Fisher	
	Chapter 9, Deflections	G. C. Driscoll, Jr.	
	Chapter 10, Multi-Story Frames	W. C. Hansell G. C. Driscoll, Jr. J. H. Daniels B. McNamee	
345.4	Mechanical Properties of A36 and A441 Steels	L. C. Lim L. W. Lu L. S. Beedle	(Draft)
345.7	Summary Report	L. S. Beedle L. W. Lu L. C. Lim	
345.8	Recent Developments in Plastic Design Practice	L. S. Beedle	

OTHER RELATED REPORTS

237.34A	Ductility as a Basis of Steel Design	L. S. Beedle	April 1968
	Part 2 - AISC Specifications (1968)		(Draft)

345.7

TABLE 2 JOINT COMMITTEE (SECOND EDITION)

Structural Steel Committee	Engineering Mechanics Div.	Structural Division
Lehigh Project Subcommittee	Committee on Plasticity Related to Design	Committee on Plastic Design
J. A. Adams	Alfredo H. S. Ang	P. F. Adams
A. Amirikian	R. E. Ball	Lynn S. Beedle
Lynn S. Beedle	Steven C. Ball	W. E. Blessey
C. F. Diefenderfer	Steven C. Batterman	G. F. Fox
G. F. Fox	Anthony M. Di Goia, Jr.	J. A. Gilligan
T. V. Galambos	Daniel C. Drucker	W. C. Hansell
J. A. Gilligan	T. V. Fan	T. R. Higgins
Ira Hooper	Morris N. Fialkow	W. H. Munse
B. G. Johnston	Theodore V. Galambos	D. L. Tarlton
R. L. Ketter	William J. Hall	L. W. Lu, Chairman
K. H. Koopman	Kerry S. Havner	
C. F. Larson	R. M. Haythornthwaite	
W. A. Milek	D. R. Jenkins	
N. M. Newmark	Seng-Lip Lee	
N. Perrone	T.H. Lin	
E. Pisetzner	N. C. Lind	
John Vasta	Egor P. Popov	
T. R. Higgins, Chairman	Herbert A. Sawyer, Jr.	
	Paul S. Symonds	
	Theodore G. Toridis	
	George Winter	
	Ching-Yi Yang	
	Kurt H. Gerstle, Chairman	

TABLE 3 CONTENTS

TABLE 3 (Continued)

TABLE 4 MAJOR CHANGES IN COMMENTARY

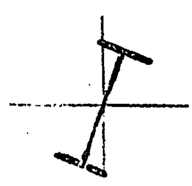
Article	First Edition (1961)	Second Edition (1968)
2.3 Role of Strain Hardening	Not included	New Article added (Increased importance of its role)
3.4 Moment Balancing Method	Not included	New Article added (Importance for multi-story frames)
4.3 Material	Only A7 steel(33 ksi)	A36, A441, A572 (36 ksi to 65 ksi)
4.6 Plastic Moment	For steel sections only	Expanded to cover composite beams
4.8 Load Factors	Gravity 1.85 Gravity + Wind 1.40	Gravity 1.70 Gravity + Wind 1.30
Ch.5 Verification of Plastic Theory		Added Structures tested since first edition
6.1 Shear Force		No change (corrected inconsistency in the derivation of interaction equations)
6.2 Local Buckling	Theory was based on orthotropic plate model (Haaijer)	New theory (Lay) uses a strain-hardening modulus based on discontinuous σ - ε relationship. Also consider moment gradient (See also AISC Spec. Table)
6.3 Lateral Buckling	 (White)	 (Lay) Moment gradient case: Uniform moment case: Method for computing Rotation Capacity Lateral Bracing Requirements
6.4 Variable Repeated Loading	Brief description	Added Part B - Repeating Inelastic Strain (Importance for building frame subjected to earthquake vibration)

TABLE 4 MAJOR CHANGES IN COMMENTARY (continued)

7.4 ~~Rotation Capacity~~ Column Deflection Curves	CDC's not treated	New article replaced the old article. (Importance for the design of beam-columns in multi-story frames)
7.5 Influence of Lateral-Torsional Buckling		Recommendation given: $\frac{P}{(P_{cr})_y} + \frac{M_{eq}}{M_{cr}(1 - \frac{P}{P_e})} = 1$
10.5 Frame Stability ~~7.6~~	$2 \frac{P}{P_y} + \frac{L}{70r} \leq 1.0$	General treatment presented
8.7 Details with regard to Welding	Fillet : $\tau_f = \frac{\sigma_y}{\sigma_w}$ x allowable stress	Fillet: $\tau_f = 0.5\ \sigma_u$
8.8 Details with regard to bolting	Brief description	Gave formulas for details with regards to the plying force Q
9.7 Deflection		Added design guides to limit deflection: $\frac{L}{d} = \frac{882}{\sigma_y}$ Discussed computer application
Ch. 10 Multi-Story Frame		New chapter added. (Applicability of plastic method of design to multi-story frames now available)
Glossary	Ultimate load Ultimate Load	Plastic Limit Load (Analysis) Design Ultimate Load (Design)

TABLE 5 - AISC REVISIONS PART 2

Section	1963	1968
2.1 Scope	Continuous beams in multi-story frames	Plastic design in braced multi-story frames
Load Factor	D.L. + L.L. 1.85	1.70
	D.L. + L.L. + Wind or Earthquake 1.40	1.30
2.2 Structural Steel	A7, A373, A36	A36, A242, A441, A529, A572, A588
2.3 Vertical Bracing System	(not included)	New section added
~~2.3~~ 2.4 Columns	Column strength in terms of B, G, H. J, etc.	$\frac{P}{P_{cr}} + \frac{C_m M}{M_m(1 - \frac{P}{P_e})} \leq 1.0$
Frame stability	$\frac{P}{2P_y} + \frac{L}{70r} \leq 1.0$	Use K factor to the above formula
~~2.4~~ 2.5 Shear		No major changes
~~2.5~~ 2.6 Web Crippling		Moved to Part 1
~~2.6~~ 2.7 Minimum Thickness	$\frac{b}{t} = 8.5$ (A36)	Grade — b/t: 36 — 17.0 42 — 16.0 45 — 15.0 50 — 14.0 55 — 13.0 60 — 12.5 65 — 12.0
	$\frac{d}{w} < 70 - \frac{P}{P_y}$	$\frac{d}{w} = \frac{410}{\sqrt{F_y}} (1-1.4 \frac{P}{P_y})$ when $\frac{P}{P_y} \leq 0.17$ $\frac{d}{w} = \frac{255}{\sqrt{F_y}}$ when $\frac{P}{P_y} > 0.27$

TABLE 5 - AISC REVISIONS PART 2 (continued)

~~2.7~~ 2.8 Connections		No major changes
~~2.8~~ 2.9 Lateral Bracing	$\ell_{cr} = (60 - 40 \frac{M}{M_p})\, r_y$ $\not< 35\, r_y$	$\ell_{cr} = \frac{1375}{F_y}\, r_y$ when $\frac{M}{M_p} \geq 0.5$ $\ell_{cr} = \frac{1375}{F_y}\, r_y + 25 r_y$ when $\frac{M}{M_p} < 0.$[illegible]

TABLE 6 - PLASTIC DESIGN: STATUS

Country	Low Building Design	Multi-story Frames	Plastic Design Specification
U. S. A.	Extensive application	A few	AISC - Part 2
Australia	Used for portal frames	Aware of none	A.S. CA1 SAA, 1968
Belgium	Little Application	Aware of none	Addendum to NBN1
Canada	Extensive Application	A few	CISC, 1967
Czechoslovakia	A few	Aware of none	
France	None	None	Not yet
Germany	Aware of none	Aware of none	Not yet
Hungary	Under current consideration (mostly reinforced concrete buildings)		Hungarian Design Code (draft form)
India	A few	Aware of none	I.S. 800
Japan	Not yet	Aware of none	Recommendations in draft form
Switzerland	L.F.=1.80 (check for composite beam only)	Aware of none	Not yet
United Kingdom	Nearly every portal frame	A few multi-story frames on the basis of "open" specifications, "up to the designer"	BSS 449
Yugoslavia	Some	Aware of none	Under study
Europe	Task Group on Plastic Design is working on a common specification		

TABLE 7 LOAD FACTORS IN VARIOUS COUNTRIES

Country	Shape Factor (f)	LOAD FACTOR: Dead Load + Live Load	LOAD FACTOR: Dead Load + Wind or Earthquake Forces	Types of Load Factors
U.S.A.	1.12	1.70	1.30	2
Australia	1.15	1.75	1.40	2
Belgium	1.12	1.68	1.49 (1.12 for extreme wind)	3
Canada	1.12	1.70	1.30	2
Czechoslovakia		1.10 - 1.30	1.30 - 1.40	17
Hungary	1.05	-	Method I: 1.2 - 1.5 Method II: Complicated	3 4
India	1.15	1.85	1.40	2
Japan		1.2D + 2.1L and 1.4(D+L) (normal condition) 1.2(D+L) + 1.5S₁ (under snowfall) (D+L) + 1.5K; (D+L+S₂)+1.5K (under earthquake) (D+L) + 1.5W₁ (under typhoon) (D+L+S₂) + 1.5W₂ (under whirlwind)		6
United Kingdom	1.15	1.75	1.40	2
Yugoslavia		D = 1.33, L = 1.50 + Additional Combinations		

D Dead Load

L Live Load

K Earthwuake Force

S_1 Maximum Snow Load

S_2 Mean Snow Load

W_1 Wind Force (Under Typhoon)

W_2 Wind Force (Under Whirlwind)

SOME MULTI-STORY FRAMES DESIGNED BY PLASTIC THEORY

Year	Identification	Tons Struct. Steel	psf	Cost/sf	Stories	Bays	Spans	Design Basis
1957	Tower Building, Little Rock, Arkansas							1956 AISC Proceedings 1963 Spec. Part Two
1967	Stevenson Apts. Maryland	369	6.3	$1.17	11	15	3	196[illegible] Lu Notes
1968	Phillips Building	340	8.6	$1.42	11			
1967	Hungerford Plaza, Maryland	168 60 (O.W.J.)	6.9	$1.21	4 (Office Building) 1 (Shopping Complex)			" "