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The Collapse Strength of Steel Columns

Interim Report No. 1

CLASSIFICATION OF COLUMN PROBLEMS

By

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Fritz Laboratory Report No. 226.2
Classification of Column Problems

I. INTRODUCTION

As indicated in the proposal for this investigation (1), the first step in the study of the collapse strength of steel columns was to make a classification of the problems and influencing factors in order to provide a system for arranging existing data on the subject. A tentative classification was suggested in the proposal.

The purpose of this interim report is to present an agreed-upon chart with a description of the type of material to be considered under each heading. This has resulted from conferences between the writer and Dr. Bruce Johnston. Those who are interested in this program may wish to make suggestions regarding arrangement or emphasis, remembering that the objective of the project is:

(a) to evaluate what is now known regarding the ultimate strength of steel columns, including summary of tests, and on that basis,
(b) to develop methods of predicting the collapse strength of columns.

The study is to emphasize columns of the type used in industrial and tier buildings. The behavior of columns beyond the elastic limit is of primary importance.

Other classifications of the column problem have been presented by Salmon, Bleich, Jakkula & Stephenson, and in several Column Research Council reports. These are referred to where appropriate.

The next step to follow the development of the chart is the ticketing of references in such a manner that all the reports and abstracts concerning columns collected in the primary survey by Dr. Johnston may be arranged under the appropriate headings of the chart. Consideration has been given to a "key sorting" system. There may be insufficient abstract cards to justify this system.

Abstract cards are to be furnished by Dr. Bruce Johnston.
II. CHART

(I) MODE OF FAILURE (elastic and inelastic buckling)

1. Bending
2. Bending and Torsion
3. Bending and Local Buckling**
4. Bending, Torsion, and Local Buckling

(II) INFLUENCING FACTORS

A. Type of Member

1. Cross-sectional form (prismatic members)
2. Slenderness ratio
3. Longitudinal variation in cross-section
4. Initial eccentricities and initial curvature
5. Action of splices
6. Size of cross-section

B. Type of Structure (columns in trusses and rigid frames)

C. Boundary Conditions (load and restraint)

1. Type and location of loads
   a. End forces and moments (3 coordinate axes)
   b. Intermediate loads: lateral and longitudinal
2. End Restraints (3 coordinate axes) and supports
3. Lateral Support
4. Encasement
5. Action of End Connections
6. Column Footings

D. Mechanical Properties of Material

1. Type of Material (steel)
2. Variation in Material Properties throughout Member
3. Effect of Fabrication Processes on Material Properties
4. Residual Stress Due to Fabrication Process

E. Time Effects

1. Impact
   a. Blast loading

* Description of each item is contained in Section III.

** Chapter 8 of the Monograph is to include a treatment of local instability.
There are certain limitations in this classification. Fatigue, brittle fracture modes of failure and failure due to repeated loading in the plastic range are not considered.

Although a classification of the failure of columns was not a primary purpose of the Jakkula-Stephenson survey (2) their "Table of Data" contained in the section, "Selected Column Tests Summary" lists modes of failure as follows:

1. Local-Flange
2. General
3. Local
4. Local Buckling of Flange (Tee-shape)
5. Torsional and Local Buckling

The Bleich survey (3), also contains a classification of column problems and the original outline headings are summarized in Appendix A.

The first Column Research Council questionnaire survey (4) also classified column problems, again on a slightly different basis and this is contained in Appendix B. The same scheme has been used in the second survey (5).


III. SCOPE OF ITEMS IN THE CHART

The following is a brief description for each item presented in Section II.

(I) MODES OF FAILURE (buckling)

1. **Bending** - (Integral Collapse) Columns that fail by bending deflection ... pin-ended columns (elastic and inelastic) ... bending failure due to applied moments about the weak axis ... beam columns ... for a limited range only, collapse due to bending about the strong axis ... instability due to the formation of plastic zones or hinges. Pin-ended columns are not ordinarily found in buildings but will be considered here because of their importance in the later analysis. Typical problems are shown in Fig. 1.

![Fig. 1: Typical Bending Problems](image)

- **Indication of restraint provided by adjoining members.**
- **"weak" axis**
- **Limited L/r and axial load range**
- **"strong" axis**

2. **Bending and Torsion** - Torsional Buckling of Columns ... columns that fail due to combined bending and twist ... columns with bending moments or restraints in the "strong"
direction ... the influence of non-symmetrical cross-sections ... open cross-sections. Fig. 2.

Fig. 2

3. **Bending and Local Buckling** - Columns that collapse due to local buckling of flange elements ... influence of cross-sectional shape ... local wrinkling of lacing bars. For WF-shaped members that are deformed by bending in the plastic range, and providing that the column is relatively short, the carrying capacity is limited by local buckling of the flange elements as shown in Fig. 3. Local buckling may also be a limitation when bending occurs about the weak axis. It is understood that a treatment of local buckling is to be emphasized in Chapter 8 of the monograph.
4. **Bending, Torsion, and Local Buckling** - This is a combination of bending, torsion and local buckling that occurs, for example, when WF columns of relatively short length are loaded in such a way that the maximum moment is not at the column end. Bending and twisting action occur, followed in the later stages by local buckling of the flange.

**(II) INFLUENCING FACTORS**

A. **Type of Member**

1. **Cross-sectional Form** - The Jakkula-Stephenson survey\(^2\) lists 25 column types for buildings and bridges. These are shown in Fig. 4.

![Fig. 4](image-url)
It will be recognized that a large number of these are more common for compression members in bridges. In this project, Types 1 and 2 will receive predominant attention. The shape may either be WF or American Standard I, and although only about 2% of U.S. tonnage is of I-shape, this section is so common in Europe that it will require study. The solid T should be added to the types shown in Fig. 4 as well as the channel and built-up I-shape with unequal flange widths.

2. **Slenderness Ratio** - This is a basic variable in all column problems, the ratio of length L to radius of gyration, r. Each treatment will be concerned with this influencing factor.

3. **Longitudinal Variation in Cross-Section** - Non-uniformity along the member ... variable cross-sections ... columns with cover plates .... longitudinal lines of welds or rivets ... latticed columns ... batten plates ... perforated cover plates ... non-prismatic columns ... columns with off-sets ... referring to Fig. 4, all column types except 1, 10, 11a.

4. **Initial Eccentricities and Initial Curvature** - Built-in and accidental eccentricities and curvature ... review of tolerances ... one end twisted with respect to opposite end ... ends out of square.
5. **Action of Splices** - Influence of riveted or welded splices on column strength.

6. **Size of Cross-Section** - Primarily a study of the size or scale effect ... comparison of tests whose conditions are identical with the exception of size of cross-section. This will also involve the cross-sectional form and residual stress.

B. **Type of Structures** (Columns in trusses and rigid frames)

This study is primarily that of the behavior of the isolated column as influenced by type of member, boundary conditions, mechanical properties of the material, and the rate of loading. Sections 9-14 of the monograph being prepared by Dr. Johnston at the University of Michigan will each deal with the complete frame of which the column is a part. As indicated in the proposal(1), progress "notes" will be prepared as appropriate for inclusion with other sections of the monograph and will treat the behavior of the column as part of particular structural types. In this section would be presented information relating particularly to framed columns.

C. **Boundary Conditions** (Load and Restraint)

1a. **Type and Location of Loads**: End Forces and Moments - Axial load ... eccentric loads ... lateral loads ....
bending moment plus axial force. Fig. 5(6) shows three coordinate axes about which moments may be applied or in reference to which axial thrusts or lateral forces may be applied.

Fig. 5

Typical loading conditions which are combinations of axial load and moment are shown in Fig. 6, taken from an earlier Lehigh University report of a project currently underway(7).

Fig. 6

(6) Johnston, Bruce G., "Columns". Section 7 of monograph on the Collapse Strength of Steel Structures, University of Michigan, November, 1951.

lb. **Type and Location of Loads: Intermediate Loads**

(lateral and longitudinal) ... Loads parallel to column axis but offset from it ... thrusts inclined to column axis ... lateral forces applied between the ends ... forces applied through crane brackets.

2. **End Restraints or Supports** - Knife-edge supports ... pin ends ... flat ends ... rollers ... spherical ends ... restraining action due to adjoining members. Since in each case there is an almost infinite variety of possibilities, only the important practical cases will be treated (See also Fig. 5). In Fig. 7 from Ref. 7 is shown a simple example of the development of restraint in a frame. With constant loads \( P \) the column loads shown as \( F \) are increased until the frame collapses. The column end moments decrease from (a) to (b) and finally reverse for loading (c).

![Fig. 7](image-url)
The Jakkula-Stephenson survey\(^{(2)}\) classified support or "loading conditions" as shown in Fig. 8.

<table>
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<th>SYMBOL</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
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<td>END CONDITION</td>
<td>FLAT</td>
<td>ROLLER, PIN, OR KNIFE EDGE</td>
<td>SPHERICAL</td>
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<td>LOAD CONDITION</td>
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--- Dashed line represents axis of roller, pin or knife edge support.
. Dot represents location of spherical bearing block.

![Diagram of loading conditions](image)

Fig. 8

The Preliminary report\(^{(6)}\) of section 7 of the monograph also classifies various restraint conditions for columns.

3. **Lateral Support** - Influence on column capacity of lateral support along the length ... restraining action of intermediate lateral connections ... influence of deformation of lateral support.

4. **Encasement** - The restraining action (both local and lateral) of casing material ... its efficiency when cracked.

5. **Action of End Connections** - Slip in riveted connections ... deformation in corner connections of rigid frames ... column base plate connections.
6. **Column Footings** - Degree of rigidity provided by foundations in preventing rotation of column base. This will be of more importance in the case of foreign structures, a greater percentage of which are designed for a "fixed" condition at column bases. Fig. 9.

![Diagram of column footing](image)

**Fig. 9**

**D. Mechanical Properties of Material**

1. **Type of Material** - Emphasis on structural steel ... foreign structural steels ... alloy steel ... effect of changes in stress-strain diagram on column performance ... simplifications for predicting column behavior.

2. **Variation in Material Properties Throughout Member** - Variations across cross-section ... variations along the member.

3. **Effect of Fabrication Processes on Material Properties** - Summary of section 2 of monograph pertaining to this topic ... considerations necessary for predicting column strength ...
riveting ... welding ... punching ... cold rolling ... forming ... strain hardening and aging ... Bauschinger effect.

4. Residual Stresses due to Fabrication Processes
   Residuals due to cooling after rolling and due to welding, local heating, cold bending ... influence of shape and size of cross-section on magnitude of residual stress.

E. Time Effects
   1. Impact: Blast Loading - Dynamic response of columns ... elastic and inelastic behavior.

IV. ACKNOWLEDGMENTS

The chart presented in Section II is the result of a gradual development. The original suggestion to prepare a chart to cover a much broader field was made by Mr. Jonathan Jones. Others who have participated in the arrangement are Dr. Bruce Johnston, Dr. Knud E. Knudsen, Dr. C. H. Yang, and Mr. Robert L. Ketter.

A considerable amount of material has also been drawn from references 3, 4 and 6 which could not be acknowledged conveniently in the text.
Appendix A

Tentative Outline of Chapter Headings

Bleich: "The Buckling Strength of Metal Structures"

A book of the above title is scheduled to be published as an Engineering Societies Monograph in January, 1952. The following topics were originally proposed in a letter dated June 23, 1947. Revisions have naturally been made since that time. Compression members other than columns for bridges and buildings are also treated in the work.

1. The Fundamental Features of the Buckling Problem
2. The Mathematical Treatment of Stability Problems in Structural Analysis
3. Buckling of Axially Loaded Columns. The Elastic and Inelastic Range of Buckling
4. Built-Up Columns
5. Built-Up Columns Having Variable Moments of Inertia
6. Eccentrically and Laterally Loaded Columns
7. Bending and Twisting of Thin-Walled Members
8. Buckling of Compression Members Having \( \overline{\overline{T}} \, \overline{\overline{L}} \) Cross Section; Torsional Buckling
9. Lateral Buckling of I-Shaped Beams Subject to Loading in the Plane of the Web
10. Elastic Stability of Frameworks Having Stiff Joints
11. Compressive Strength of Tapered Struts
12. Buckling Strength of Members Considered as Part of a Truss
13. Compression Members in Rigid Frames
14. Buckling Strength of Axially Loaded Columns Elastically Supported at Intermediate Points
15. The Three-Dimensional Column Problem
16. Buckling of Rectangular Plates Acted Upon by Compressive Stresses in Their Planes Along Two Opposite Edges
17. Compressed Plates Having Longitudinal Stiffeners
18. Compressed Rectangular Plates Transversely Loaded
19. Elastic Stability of Web Plates in Girders
Appendix B
Lundquist Survey(4)

SUBJECT CLASSIFICATION

I. Bending Deflection - This group contains problems relating to columns that fail by bending deflection. Typical for the group are the following problems:

- Axial force with end moment
- Eccentricities
- Axial force and end moments with transverse loads;
  - Beam-Columns
- Design of columns with perforated cover plates
- Buckling load for arches

II. Combined Bending and Twist - Typical subjects of the group are:

- Angle & tee struts
- Buckling of compression flange of beams

III. Local Buckling - This group includes those types of members that fail by local buckling of the cross-section. Examples are:

- Local instability failures of columns
- Plates and shells - with or without stiffeners;
  - cylinders

IV. Bracing Members - Typical subjects of this group are:

- Design of column bracing; evaluation of bracing effect on strength
- Bracing for compression flange of beam

V. Plate Girder - Typical subjects of this group are:

- Design of intermediate stiffeners of a plate girder
- Buckling of girder web

VI. Through Bridge Design Problems

VII. Miscellaneous

- Material properties of various alloys
- Testing methods
- Specifications, handbooks, books
- Time and impact effects

VIII. Non-Metallic Columns

IX. Research Facilities and Suggestions for Research

Response to questionnaires