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To: Chief of Naval Research
Office of Naval Research
Navy Department
Washington 25, D. C.

Via Paul H. Kratz re: Final Report,
c/o University of Pa. Contract NB onr 64200
3320 Walnut St. Welded Continuous Frames
Philadelphia 4, Pa. and Their Components

Attention: Mr. J. M. Crowley, Code 438

Dear Sir:

Enclosed are 8 copies of the Final Report on
this contract for the period ending October 1, 1950.
This report, designated as Progress Report J, is
forwarded in compliance with the terms of the
contract.

Sincerely yours,

Lynn S. Beedle
Assistant to the Director

cc: T. R. Higgins
B. G. Johnston
Armed Forces Special
Weapons Project
E. F. Cox
L. Grover
P. Kratz
W. Spraragen
ONR Scientific Section
(N. Y.)

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(NOT FOR PUBLICATION)

Welded Continuous Frames and Their Components

PROGRESS REPORT J

Final Report to Office of Naval Research
on Contract N8onr--64200 for the period
July 1, 1949 to September 30, 1950

October 31, 1950

This report is submitted to the Office of Naval Research in compliance with the contract noted above with Lehigh University. The material reported here is in addition to the contents of a similar report¹ prepared for the previous year's work.

At the special request of the Bureau of Ships, a letter covering similar material was prepared as of March 25, 1950, copies of which were submitted to ONR. Much of that material has been duplicated herein.

I PERSONNEL

Bruce G. Johnston, former director of the Laboratory, has been in general supervision of the work. Since September 2 he has been at the University of Michigan as professor of structural engineering. He continues to be associated with the project in the capacity of consultant.

William J. Eney, Head of the Department of Civil Engineering and Mechanics is contributing advice on the project as Director of the Laboratory.

Lynn S. Beedle, Assistant to the Director, has been in direct charge of the project.

Chien-huan Yang, Research Assistant, has carried out the program of analysis and tests on continuous beams and simulated frames tested as beams.

(1) Progress Report F, General Report on First Year's Work, June 1, 1949.

October 31, 1950

Jan M. Ruzek, Research Assistant, has carried out part of the column test program and, toward the end of the period, started the detail work on the frames.

A. Anthony Topractsoglou, Research Assistant, completed one phase of the continuous frame connection program.

E. Russell Johnston, Jr., assistant professor, joined the group in June, 1950, devoting his attention to the connection and frame phases of the program.

Cyril D. Jensen, professor of civil engineering, is contributing his services, and directing his attention to general aspects of the program.

Robert L. Ketter, was appointed Research Assistant in July, 1950. His principal effort is on the column program for The Office Naval Research. He has worked on the continuous beam and connection programs.

II REPORTS ISSUED

Quarterly Status Reports were issued as required by Welding Research Council and Office of Naval Research under dates of October 12, 1949, January 18, 1950, April 17, 1950, and July 19, 1950. These are regularly published in the WELDING RESEARCH COUNCIL REPORTS of PROGRESS.

Reports for Publication (1)

Progress Report No. 2, "Tests of Columns Under Combined Moment and Thrust"; Proceedings, Society for Experimental Stress Analysis, Volume VIII, Number 1. (This was noted in Progress Report F and has now been published).

Dissertation, "Connections for Welded Rigid Portal Frames" was completed by A. A. Topractsoglou and is available on loan from the Lehigh University Library. A report covering its contents is being prepared for publication in the Welding Journal.

Reports to Lehigh Project Subcommittee (1) Not for publication

Progress Report F, general progress report, June 1, 1949.

(1) In addition to those listed in Progress Report F

October 31, 1950

Progress Report G, "Structural Research at Cambridge University", by Lynn S. Beedle, January 30, 1950. This is a report of a three-month visit to the Engineering Laboratory, Cambridge University, England.

Progress Report H, "Flexure of I-Sections Above the Elastic Range". Discussion by C. H. Yang and Lynn S. Beedle of a report by W. H. Weiskopf.

Progress Report I, "Special Semi-Annual Report", March 8, 1950.

Progress Report J, Final Report to Office of Naval Research, October 31, 1950.

Proposals Issued

- (d) September 1, 1949, to Lehigh Project Subcommittee. Revised proposal for connection tests.
- (e) December 6, 1949, to Office of Naval Research. Renewal and extension were requested of the contract with the Navy for continuous beam, connection, and frame research.
- (f) April 27, 1950, to Office of Naval Research. Request for increase and extension of ONR support.
- (g) April 21, 1950, general proposal to A. O. Smith Corporation.
- (h) August 25, 1950, to Lehigh Project Subcommittee. This describes portal frame tests now being conducted.
- (i) May 9, 1950, to Office of Naval Research. This covers the 1950-1951 ONR program of research.

III TRIPS, MEETINGS ATTENDED & PAPERS DELIVERED

- (1) At the invitation of Professor J. F. Baker, arrangements were made for Lynn S. Beedle to visit Cambridge University, England, and to work with the group there. Progress Report G covers the details. A brief description of the Lehigh Project was presented at the meeting of the Institution of Structural Engineers and was published in *The Structural Engineer*, Vol. XXVIII, No. 7, July, 1950.

October 31, 1950

- (2) Third Symposium on Plasticity, Brown University, September 8-9, 1950. "Plastic Behavior of Continuous Beams of Wide-Flange Section" by Chien-huan Yang, Lynn S. Beedle, Bruce G. Johnston.

IV OBJECTIVES

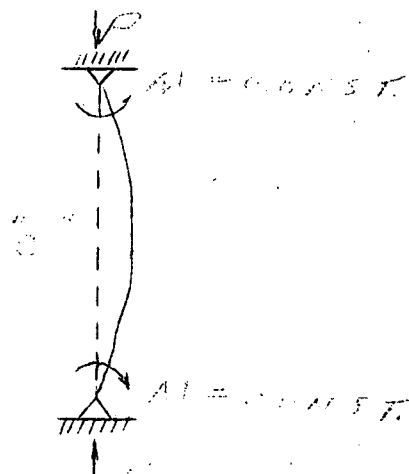
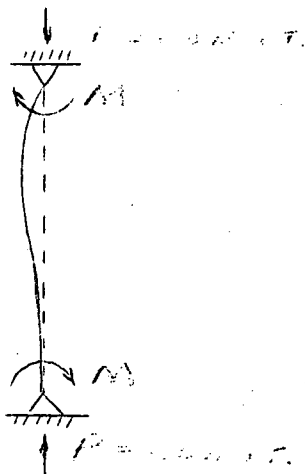
At its meeting in New York on March 24, 1950, the Lehigh Project Subcommittee of the Structural Steel Committee, Welding Research Council, approved the following statement of objectives.

1. To determine the behavior of steel beams, columns, and continuous welded connections with emphasis on plastic behavior, and to develop theories to predict such behavior.
2. To determine how to proportion various types of welded continuous frames to develop the most balanced resistance in the plastic range so that the greatest possible collapse load will be reached.
3. To determine procedures of analysis that will enable one to calculate the collapse loads of welded continuous frames and to verify the analysis by suitable tests.
4. To determine procedures of analysis that will enable one to calculate the elastic and permanent deformations in welded continuous frames in the range intermediate between elastic limit and collapse load.
5. To explore limitations in the application of plastic range design over and above deformation limitations, namely, fatigue, local buckling, lateral buckling, etc.
6. To develop practical design procedures for the utilization of reserve plastic strength in the design of continuous welded frames.

V TESTS COMPLETEDColumns

Test Number	Section	Length*	Test** Conditions	Constant Loading	
				P/Pcr	M/My
6	4WFL3	16'	b	0.26	-
7	4WFL3	16'	b	0.26	-
8	8WFL3	16'	c	-	0.13
9	4WFL3	16'	b	0.10	-
10	4WFL3	16'	b	0.49	-

* Add 11 1/2" to obtain exact distance between knife edges.



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Continuous Beams (single span with "overhanging ends", force at end of cantilever sections regulated to keep beam level over support points.)

Test No.	Section Used	Loading	Distance Between Supports
B4	8WF40	1/3 point	14'
B5	8WF40	1/3 point	14'
B7	14WF30	1/3 point	14'

Connections

Model	Type*	Initial Moment Arm	
A	2 (S)**	25.1"	
B	2B (H)	38.1	
C	15 (H)	30.9	
D	4 (H)	25.1	} Length and form of stiffeners varied
E	4 (H)	25.1	
F	4 (H)	25.1	
G	5A (C)	43.6	} Radius and thickness of inner flange varied
H	5A (C)	30.9	
I	5A (C)	23.9	} Number, position, and length of stiffeners varied
J	5A (C)	25.0	
K	8B (S)	25.1	} Length and form of stiffeners varied
L	8B (S)	25.1	
M	8B (S)	25.1	
N	16 (H)	33.8	

* See Table 1.

** Designators are S: square knee, H: haunched knee, and C: curved knee.

VI SUMMARY OF RESULTS

The detailed results are being presented in separate reports. For the purposes of this FINAL REPORT, a resumé has been prepared covering some of the important observations.

General

1. The simple plastic theory gives promise of considerable application in the analysis and design of steel structures. If sections were rectangular and if bending moments were applied about the "weak" axis, plastic methods could have wider application. Since engineering structures employ rolled wide-flange or I-shaped sections bent primarily about their strong axes, a study of such details as local buckling and shear is essential.

The study of behavior will make possible the analysis of many existing structures with a view towards increasing allowable loads when this becomes necessary. It appears that modifications to design procedures may be made which will enable the designer to use a large percentage of the potential increase in load-carrying capacity beyond the elastic limit.

2. Tests have indicated that certain types of loading will cause structural members to fail in a mode other than that predicted by the usual plastic theory. Thus, in addition to bending deformation, the following must be considered:

a. Plastic or inelastic instability

- 1) Local buckling
- 2) Lateral buckling
- 3) Web buckling and crippling
- 4) General bending instability

b. Shear yielding

Beams

The following tentative conclusions are drawn from the final report of the beam program which is being prepared for publication.

1. The assumption of linear plastic strain for sections loaded into the plastic range is not as accurate as supposed.

2. The assumption of linear plastic strain is more accurate for annealed beams than for "as delivered" beams.

3. Stress-relief annealing causes a lowering of the static bending strength.

4. Because of strain hardening, the ultimate loading of continuous beams as predicted by the simple plastic theory is exceeded (provided local or lateral buckling does not occur).

5. For simple beams under third-point loading the collapse moment is slightly below that predicted by the simple plastic theory.

6. In many instances the deflection rather than carrying capacity will determine the ultimate loading condition.

7. There is no evidence of increased upper yield point or increased bending strength due to the non-uniform stress distribution in bending.

8. The influence of type of welded detail at the support points of continuous beams appears to be minor. It is tentatively concluded that stress concentrations at supports, heat-affected zones and residual stresses inherent in welding do not significantly reduce the load-carrying capacity in the plastic range. These factors do cause plastic deformations at loads lower than predicted. This statement is limited to the type of structure tested in which the members were free to shift under the action of welding shrinkage forces.

9. Members which deform by plastic shear develop large deflections before plastic hinges are obtained. Thus, if deflection is to be kept low, a section must be chosen which will not yield in shear. Local "shear" yielding which occurs due to combination of high bending stress and shear stress does not reduce carrying capacity seriously.

Columns

1. Provided local or lateral buckling does not occur, the load-moment interaction curve provides a means of accurately predicting the plastic strength of columns.

2. For the SWF31 columns tested with a slenderness ratio of about 50, good agreement with the interaction curve predicted by the simple plastic theory was obtained for medium and low range of P/P_y . In these tests the column bases were kept fixed and moment was applied at the top; the axial

load was maintained constant. When the constant axial load became high, the development of a modified plastic hinge was prevented by inelastic lateral buckling. As the slenderness ratio was increased the load at which this instability failure occurred became relatively lower.

3. Failure to develop the moment predicted by the plastic theory may be due to general bending instability, lateral buckling or local buckling.

4. For the three 4WF13 columns tested, the influence of prior plastic deformation on load-carrying capacity is minor.

Connections (See Table 1)


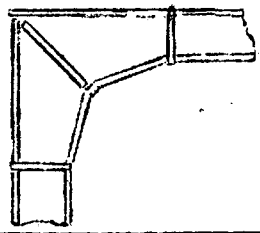
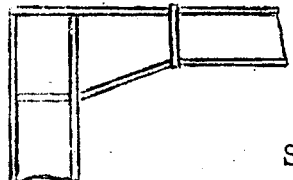
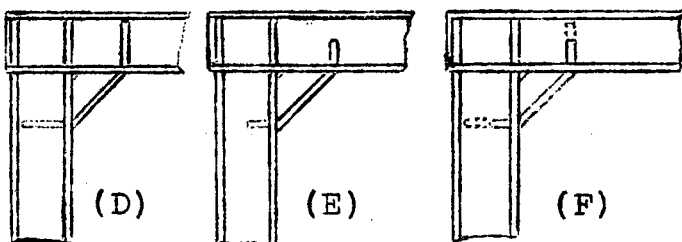
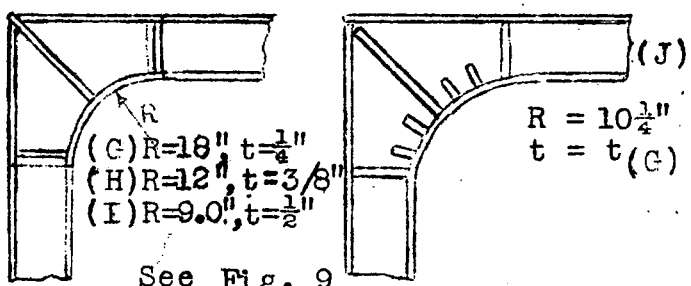
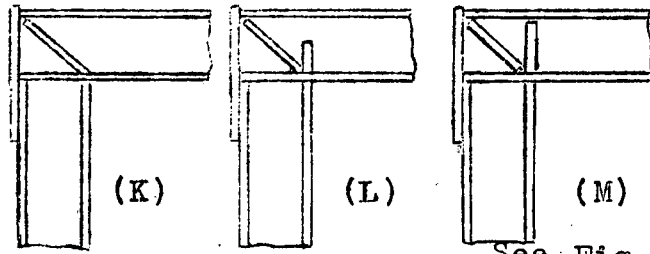
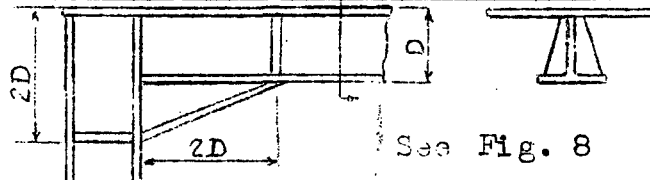
1. It is possible to design and fabricate with economy simple connections which will carry the full plastic moment. Most of these connections are as rigid or more rigid than an equivalent length of beam and those of the square type will maintain the plastic hinge through relatively large rotations when supported laterally.

2. Tests on knees thus far indicate a plastic instability type of failure. The load-deformation curves rise to a maximum and fall off more or less rapidly. The adequacy of the connection will partially be indicated by the amount of rotation necessary to develop full plastic strength at other places in the structure. Lateral support is essential in all connections.

3. In portal frame knees, moment are transmitted around the connection from beam to column primarily by shear. Unless special shear stiffening is provided, by means of diagonal brackets, extra thickness of web material or by the insertion of a haunch, many typical rolled sections will yield in shear before the yield moment is reached. If the plastic hinge is subsequently attained, it is accompanied by large rotations.

4. The importance of adequate lateral support is not to be minimized. Whenever support can be provided at points of maximum strain, the lateral buckling which results from local instability may be prevented.

TABLE II
Corner Connection Tests

Test Model	Type of Conn.	Number of Specimens	Sketch
A	2	1	 <p style="text-align: right;">See Fig. 3.</p>
B	2B	1	 <p style="text-align: right;">See Fig. 4.</p>
C	15	1	 <p style="text-align: right;">See Fig. 7.</p>
D E F	4	3	 <p style="text-align: center;">See Fig. 5</p>
G H I J	5A	4	 <p style="text-align: center;">See Fig. 9</p>
K L M	8B	3	 <p style="text-align: center;">See Fig. 6</p>
N	16	1	 <p style="text-align: right;">See Fig. 8</p>