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July 19, 1949

File No. 205

Dr. R. M. Robertson
Office of Naval Research
U. S. Navy Department
Washington 25, D. C.

Report on contract N8onr64200
Lehigh University

Dear Dr. Robertson:

Enclosed are six copies of our Progress Report "F" submitted in accordance with requirements established by the Office of Naval Research. We believe it serves as the "final report" upon receipt of which the fourth quarter payment may be made to Lehigh University.

This report does not constitute the final report for the project, since it is a continuing investigation. As you know, the contract was extended recently.

In the event you wish us to make further distribution of this report we will be glad to do so.

Sincerely yours,

Lynn S. Beedle
Research Engineer

Bruce G. Johnston
Director

LSB:BGJ:fs

CC: P. H. Kratz
J. M. Crowley
J. F. Baker
William Spraragen
LaMotte Grover
T. R. Higgins

Enclosure

(NOT FOR PUBLICATION)

Ultimate Strength of Welded Continuous Frames and Their Components

Progress Report F

General Report on the first year's work
July 1, 1948 to June 30, 1949

July 15, 1949

It is intended that this report give a general summarizing description of the work of the group at Fritz Engineering Laboratory, Lehigh University, up to the present time.*

PERSONNEL

Dr. Bruce G. Johnston, Director of the laboratory, has been in general supervision of the work.

Lynn S. Beedle, Research Engineer, has been in direct charge of coordinating the work of the entire project.

C. H. Yang, Research Assistant since April, 1948, has done the work on testing and analysing continuous beams, simply-supported control beams, and simulated frames tested as beams. He is responsible for design of continuous beam test apparatus.

Jan M. Ruzek, Research Assistant, has been with the group since May, 1948, conducting one of the column tests, but working primarily on the connection and rigid frame phase of the investigation. He designed the connection test apparatus and the single-span frame test equipment. He has developed the designs for the various types of rigid frame connections.

C. H. Chen, Research Assistant, came to the group on July 1, 1948. He has done the research work on the column test program since that time, and has designed several modifications to the test apparatus.

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*The contract with the Office of Naval Research (June 15, 1948, to June 14, 1949) covered the investigation of continuous beams, connections and frames. For completeness, however, the work on columns is also described.

A. A. Topractsoglou, Instructor in Civil Engineering, has worked with Mr. Ruzek on the connection test program. He has given his time voluntarily since March of this year. Together with Mr. Ruzek, he conducted the first test and has spent considerable time in analysis of results of that test.

REPORTS ISSUED

Quarterly progress reports were issued as required by the Welding Research Council and the Office of Naval Research. These were dated October 13, 1948, January 18, 1949, April 8, 1949, and July 11, 1949. They are regularly published in WRC "Reports of Progress".

Reports for Publication:

Progress Report No. 1, "Plastic Behavior of Wide Flange Beams" by William W. Luxion and Bruce G. Johnston, September 8, 1948. This has appeared since then in Welding Journal, November, 1948. This report describes the results and analysis of 6 tests on simply-supported beams of 8 WF section, loaded to ultimate failure.

Progress Report No. 2, "Tests of Columns Under Combined Moment and Thrust", by Lynn S. Beedle, Joseph A. Ready, and Bruce G. Johnston, May 20, 1949. This report is scheduled for publication in the Proceedings of the Society for Experimental Stress Analysis. It described the method of testing columns and includes a discussion of the behavior of restrained columns.

Reports to the Lehigh Project Subcommittee:

Progress Report A, general progress report, November 26, 1948.

Progress Report B, "Plastic Behavior of Continuous Beams", by C. H. Yang, May 26, 1949. This is a report on results of three tests: two continuous beams and one simply supported control beam.

Progress Report C, "Strength of Columns under Combined Bending and Compression", by C. H. Chen, May 27, 1949. This report describes results of tests on three 8 WF 31 columns.

Progress Report D, "Test of a Rigid Frame Knee", by A. A. Topractsoglou and Jan M. Ruzek. This is a description of test results of connection type 7.

Progress Report E, "Design of Three Connection Types and Proposal for an Additional Test". This presents the working drawings for connections 2, 4, and 5A, and proposes test of connection 8A.

Proposals issued:

(a) May 12, 1948, to Welding Research Council. This was later reprinted in the WRC "Reports of Progress", Vol. III, No. 7, July, 1948, p. 1. It describes the whole program.

(b) May 7, 1948, to Office of Naval Research. It describes initial plans for tests of continuous beams, connections, and frames.

(c) March 25, 1949, to Office of Naval Research. Ronowal was requested of the contract with the Navy for continuous beam, connection, and frame tests for the year 1949-1950.

MEETINGS ATTENDED AND PAPERS DELIVERED

1. Bruce Johnston: to annual meeting of the American Welding Society, October, 1948, Progress Report No. 1.

2. Bruce Johnston: to Second Symposium on Plasticity* Brown

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* This meeting was attended by all the personnel of the group.

University, "Tensile Stress-Strain Characteristics of Structural Steel".

3. Lynn Beedle: to Plasticity Symposium (above), discussion of Professor J. F. Baker's presentation "The Application of the Theory of Plasticity to the Design of Building Structures".

4. Lynn Beedle: to Spring meeting, SESA, May, 1949, Progress Report No. 2.

In addition, two informative and interesting meetings were held with Professor J. F. Baker during his recent visit to the United States.

PROBLEM STATEMENTS

In order to keep attention focused on the specific problems involved in plastic behavior and plastic design, Appendix I is presented. These problems have either grown out of the investigation or have been called to our attention. Some of these are amplified in Appendix II. Problems have been grouped as follows:

a. Specific problems relating to particular structural members.

1. Ultimate strength of columns -- combined loading
2. Continuous beams
3. Rigidity, strength and economy of connections
4. Correlation of the above components in study of frames

b. Additional problems of a more general nature.

The mere listing does not mean that the problem is unsolved.

TESTS COMPLETED

Columns

Test Number	Section	Length*	Test Conditions†	P/Pcr (approximate)	Purpose
Pilot	4WF13	16'	e, d-b	.5 (d and b)	Pilot investigation
1	8WF31	6'	d	0.13	Simulate a frame
2	8WF40	6'	d,b	.1, .14, .15	Simulate a frame
3	8WF31	16'	b	.5	General program
4	8WF31	16'	b	.125	General program
5	8WF31	16'	b	.8	General program

Flexure axis on all tests: x - x

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

† "e": both ends pinned; "d": opposite end pinned; "b": opposite end fixed.

Beams

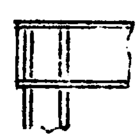
Test No.	Type of Test	Size of Member	Distance between Supports	Load
B_1	Simple beam control	8WF40	14'	1/3 point
B_2	Continuous beam with central span fully restrained(1)	8WF40	14'	1/3 point
B_3	Continuous beam simulating rigid frame.(2)	8WF40	14'	1/3 point

(1) Force at end of cantilever sections regulated to keep beam level over support point.

(2) Cantilever load regulated to keep end in same horizontal plane as support points.

Connections

1 14 WF 30)
8 WF 31) type 7 corner test (7'arms)



Frames

None

SUMMARY OF RESULTS

Columns

The behavior of restrained columns bent in single curvature has been described (2)*. Under restraint it has been shown that beams framing into such columns must be able to carry greater than simple beam bending moment. (2) Although such tests are possible with the apparatus described, an experimental study of the behavior of elastically restrained columns under axial load alone is not planned. Such an investigation is being sponsored by Column Research Council and the Public Roads Administration at Cornell University. In certain of the tests in the Lehigh program, however, attempts will be made to determine "negative" stiffness factors.

In all column tests conducted up to the present time, axial load has been maintained constant, moment being applied at one end with the opposite end either fixed or pinned. Duplicate experiments are planned of several of the tests recently completed to investigate the influence of method of loading. In this case, moment will be held constant while axial load is applied up to collapse.

The interaction curves for initial yield and ultimate strength have been studied. (2)(C) Good agreement between test results and calculated values have been observed for low and medium range P/Pcr. At high ratio of P/Pcr, the agreement was not good. (C) For the one test at this high ratio the development of a hinge at the top was inhibited by lateral buckling. Additional such tests, together with some under axial load alone, should be made. (C)

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*Numbers or letters in parenthesis refer to lettered or numbered progress reports to which reference may be made for further information.

Failure to develop full plastic hinge moment in a column may be due to:(C)

(1) general instability due to inelastic buckling

(2) lateral buckling

(3) local buckling

In tests where local buckling occurred it did not impair the development of Mp. It did, however, prevent the section from continuing to carry this moment and stopped further increase of moment at the opposite end of the member.(C) In the future, more readings will be taken on tests after the buckling load is passed.

Good agreement in carry-over factor in the elastic range was observed for tests at low and medium ratio of P/Pcr, except for irregularities at low loads.(2) (C) Carry-over factors increase in the plastic range.

Beams

The important conclusions from the simply supported beam tests are:(1)

1. The M-Ø curves for structural steel beams, laterally supported, can be predicted satisfactorily from the stress-strain tensile test curves and the usual theory of plastic bending based on the assumptions of uniform distribution of yield and strains proportionate to the distance from the neutral axis.
2. Agreement between experimental and theoretical M-Ø curves, as calculated from the test coupon strength, was better for annealed beams than for as-welded beams.
3. Stress relief annealing causes a lowering of overall static bending strength.

4. The tests give no evidence of increased upper yield point or increased bending strength due to the non-uniform stress distribution in bending.

For the simple beam control test, (B) the ultimate strength was observed to be about 9% below the calculated value.

The continuous beams tested thus far (B) are, to a large degree, control tests for the investigation in which various connection details will be inserted at supports. The only modification to the members was to install stiffener plates at load points and to weld load carriers at the third-points and at the ends. No annealing was attempted. The possible effect of welded splice plates and other welding details will be observed in the coming tests.

Interest of the Bureau of Yards and Docks* in the effect of redistribution of moment after initial yielding due to residual stress and stress-concentrations prompted a study of such behavior. In the two tests completed only 1/4" fillet welds were applied to stiffener plates over the supports, and in both tests it seems that "slip" due to plastic flow and subsequent redistribution of moment is small. (B)

With regard to ultimate strength, good agreement was obtained with the control test. (B) Strain hardening at the supports caused these effective end moments to increase above Mp, thus raising the maximum observed overall load on the structure about 12% over that predicted in the "fixed-ended" beam test and to 2% less than predicted in the case of the simulated frame test. In the latter case yielding commenced at the supports and at the center simultaneously. (B)

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*"Future Developments in Welded Steel Buildings", by A. Amirikian. Welding Journal, Aug., 1948, p. 593.

Lateral buckling was observed in both continuous beam tests. The lateral support frame, however, prevented the beams from collapsing due to this deformation. Thus the limiting bending resisting moment was approached.(B)

One repeated load test was conducted as a pilot investigation. A decreasing increment of deflection was observed between a very low load and a load between initial yield and collapse. Due to insufficient number of cycles it cannot be established that the "set" deflection at the low load was approaching a limit.(B)

Connections

One test of design type 7 has been completed. The initial yield strength of the weaker member (column) was exceeded, but failure occurred prior to the development of full plastic moment of this member.(D)

Large deformations due to shear failure in the web of the knee commenced when the load reached 50% of the calculated full plastic moment of the column. This observed load at shear failure agreed well with the computed value. Continuous increase in load was observed, however, up to final failure.

There were numerous separate modes of failure observed at the end of test :(D)

(a) local buckling of beam and column flanges,

(b) crack of the web plate material in the beam at its end due to stress concentration,

(c) deformation of the rigid box formed by beam flanges and stiffeners, and,

(d) complete shear yielding in the web.

It is believed that results obtained could not be significantly improved by duplicate tests.

Designs of three additional approved connections were completed (E), and the committee was asked to criticize them. These were approved in general at the November, 1948, meeting. As a result of the recent June 2 meeting, further proposals are to be prepared.

A fourth additional type (8A) has been designed (E) following a suggestion by Mr. Jonathan Jones and was presented to the committee for consideration.

Frames

As has been mentioned, no frames have been tested. It was previously recommended (A) that tests of frames be deferred until the four connection types were investigated. Two frame tests are planned to show the influence of the bracketed corner as against one without additional support. Exact details are yet to be decided. In addition there remains the program of frame tests contained in our original proposal.* It is felt that the frame program should be commenced at an early date but should still await the completion of additional connection tests.

As was previously noted, connection type 7 commenced to fail in shear at a load about 50% of the calculated column hinge value. This same behavior would be expected in a frame constructed with the same details. The redistribution of moment would occur, as mentioned in discussing continuous beam tests, and the central span would receive an additional increment of moment. From an "ultimate strength" point of view, it thus seems essential to develop a connection which is stronger in shear than 7 and 8. Types 1 (not approved) and 2 (approved) (A) should accomplish this.

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* proposal (a), page 8.

Further, this shear yielding at low load cannot be simulated on a continuous beam, and this deficiency has not previously been recognized. It is concluded that connection details used in the continuous beam tests simulating rigid frames can be observed only to evaluate the effect of stress concentration and residual stresses (rolling and welding).

Frame test apparatus has been designed and its construction is substantially complete.

SPONSORS

Financial support for the work of the first year was received through the Welding Research Council and the Office of Naval Research from:

American Institute of Steel Construction
American Iron and Steel Institute
Bureau of Yards and Docks
Bureau of Ships

Column Research Council of Engineering Foundation also supported the work in an advisory capacity. The assistance of these organizations is sincerely appreciated.

APPENDIX I

Problems Relating to Specific Structural Members

a. Ultimate strength of columns under combined axial load and moment.

1. Relationship between moment and load between initial yielding and collapse.

2. True collapse interaction curve including effect of deflection in plastic range.

3. Investigation of lateral buckling (elastic and plastic) including the effect of true torsional buckling.
4. End effects in columns -- displacements of ends, variation in I, semi-rigid connections.

5. Strength of a column as part of single-bent frame with no side-sway. Variables are: l/r, flexure axis, P/Pcr, End condition, size of specimen.

6. Modification of (5) to include side forces at the ends.

7. Determination of negative stiffness factors and strength of columns under such loading.

8. Effect of splice on column behavior

9. Effect of reversing the sense of the applied moment.

10. Flexure about axes other than x-x or y-y.

b. Load-carrying capacity of continuous beams

1. Influence of various welded connection details at support points. Effect of residual stress on redistribution of moment.

2. Influence of shape of member.

3. The degree to which a frame may be simulated.

4. Effect of redistribution of loading.

5. The influence of local and lateral buckling.

c. The rigidity, strength and economy of various rigid-frame connections, including interior connections and built-up sections.

d. Correlation of the above in tests of rigid frame structures.

Additional Problems of General Application

1. Plastic flow in the inelastic range of stress
2. Age-hardening
3. Influence of shear yielding
4. Basic load-deformation diagrams
5. Design requirements insofar as deflection is concerned
6. Fatigue in structures loaded in the inelastic range
7. Repeated variable distribution of loads of limited number of cycles in inelastic range (shake down)
8. Strain-hardening
9. Influence of plastic yielding on redistribution of stress
10. Plastic design procedures (including factor of safety)
11. Local buckling and width-thickness specifications
12. Lateral buckling
13. Influence of residual stress on plastic strength
14. Moment distribution procedures for inelastic structures.
15. Live loads for use in design
16. Theoretical deflection of plastically deformed members
17. Effect of moving loads

APPENDIX II

Ultimate Strength of Welded Continuous Frames

PROBLEM STATEMENTS

1. Plastic Flow in the Inelastic Range of Stress

For structural steel members loaded in the elastic region, there is no elongation with time at a constant load so long as the temperature is that encountered in normal operation...say at room temperature. However, once the elastic limit is passed, then time-effects are observed. For constant load, there is gradual elongation. It is a phenomenon that, in its effect, is similar to "creep".

The problem becomes significant when an effort is being made to determine the ultimate load carrying capacity of a structural member. During testing in the plastic region, it is necessary to know how long to allow the member to deform under constant load before a set of readings are taken. This reduces to determining the effect of testing technique (specifically, testing speed) on observed strength of the member.

A certain amount of critical review of literature will be necessary, as well as an analysis of the work of other investigators. This will be followed by tests on standard tensile coupon specimens, after which check-tests could be made on simply-supported beams.

2. Age-hardening

Age-hardening may influence the behavior and apparent strength of structural steel members tested in the plastic region, particularly if long times of testing are involved because of a rate of loading requirement.

An investigation into this problem is desirable. It would be analytical in its initial stages, with confirming tests.

3. <u>Influence of Shear Yieldng on the Bending Moment Carrying Capacity and the Deflections of Structural Steel Members</u>

The subject of shear yielding and the moment to shear ratio has been the subject of considerable speculation. Some structural sections are so proportioned that shear yielding is quite possible under certain loadings.

A considerable amount of test data have been obtained, but there has never been an opportunity to study these "shear data" and make a complete analysis of results. A report of some British work on the subject should be received shortly. This and other related publications will be studied. If more tests are needed they will be proposed.

The problem has two slightly different aspects:

(a) shear in the web of beams

(b) shear in the knee of a beam column connection.

4. <u>Basic Load-deformation Diagrams for use in Specifying the Strength of Structural Steel Members.</u>

The stress-strain diagram is reasonably constant in the region below the elastic limit. However, above that point many different variations may occur. This has been reported on recently by Dr. Johnston at the Symposium on Plasticity at Brown University.

In elastic structures, strength and rigidity are based on an assumed yield point and on a modulus of elasticity.

No such standards exist on a rational basis for a structure loaded in the plastic range.

Either a minimum stress-strain diagram or an average stress-strain diagram for use as a basis in determining the real strength of structural steel members in the plastic range is needed.

The project should include a study of the sort of test specimen that should be used as a standard ... whether this should be the customary tensile specimen or the bending specimen; also, what modifications should be made to include effect of variation in yield point between web and flange material. In this investigation the methods of statistical analysis should be applied to the interpretation of the data.