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Lynn S. Beedle

Bruce Johnston

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LEHIGH UNIVERSITY  
FRITZ ENGINEERING LABORATORY  
DEPARTMENT OF CIVIL ENGINEERING AND MECHANICS  
BETHLEHEM, PENNA.

P R O P O S A L

The Influence of Residual Stress on Column Strength

and

The Mechanical Properties of Rolled Shapes and Plates

By

Lynn S. Beedle, Lehigh University  
and  
Bruce G. Johnston, University of Michigan

I. I N T R O D U C T I O N

In 1946 Committee D of Column Research Council recommended as follows:

"Rolled sections, sections built up by welding, and sections fabricated by bolting or riveting generally have material residual stresses both compression and tension, in the member. In addition, the member may have residual moments and shears incident to relative deformations in the fabrication of the structure of which the member is a part. The effect of these residual stresses on the strength of compression members is subject to question. Some experimental results indicate little or no effect; however, for certain conditions the effects may not be negligible. This investigation is primarily experimental."

Some of the work done since that time has been summarized in a previous report-proposal (1). Some very recent test results carried out at Lehigh during 1950 and 1951 show that:

- (1) The strength of a concentrically loaded steel column cannot be predicted on the basis of applying the tangent modulus concept to the results of small

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(1) Fritz Engineering Laboratory Report No. 220A.3, October 22, 1951, "The Influence of Residual Stress on Column Strength - A Proposed Pilot Program", by Lynn S. Beedle.

coupon tests;

- (2) The percent reductions below "coupon test" values are shown in the following table:

<u>L/r</u>	<u>%Reduction</u>
(a) <u>Theoretical - based on assumed residual stress pattern</u>	
85	35%
40	10
0	0
(b) <u>Observed reductions in column tests</u>	
56	10%
(c) <u>Theoretical-analytical reductions observed in cross-section test</u>	
85	30%
0	7*

The general results of the Lehigh test on a full-cross-section have been presented in an unpublished report(2).

## II. STATEMENT OF THE PROBLEM

In view of the above discrepancies between theory and experiment, the following main questions must be answered:\*\*

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\* A portion of this reduction is due to inelastic instability, which is a function of cross-sectional shape.

\*\* Phrasing suggested by Mr. Jonathan Jones in a letter dated October 22, 1951.

(2) "Summary Report", Fritz Laboratory report No. 205.13, pp 16-20, September 17, 1951. (This material is also included in Ref. 1).

A. DO PRESENT FORMULAS OR DESIGN RULES FOR STEEL COLUMNS REQUIRE MODIFICATION?

The Column Research Council has gone on record to adopt the tangent modulus formula; applied to coupon test results this formula will not properly predict the strength of as-delivered steel columns<sup>(1)</sup>. It is thus necessary to explore further a means of accounting for residual stress in the tangent modulus concept ... or else to modify the statement. For rational design modification is necessary.

The reductions in column strength mentioned in Section I have been attributed in the past to other causes (eccentricity, curvature, etc). As a result (and this should always be kept in mind) buildings have been and are being built that are entirely safe. In some cases the factor of safety may have been selected on the basis of reductions actually due to residual stress but assumed to be due to other causes<sup>(3)</sup>.

B. BY HOW MUCH HAS THE STRENGTH OF COLUMNS BEEN OVER-ESTIMATED ASSUMING 33000 PSI YIELD POINT BASED ON MILL TESTS?

For some slenderness ratios the over-estimation has been very little or none at all. For others, the evidence indicates a considerable error.

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(3) Yang, Beedle, and Johnston, "Residual Stress and the Yield Strength of Steel Beams" Fritz Laboratory Report No. 205B.8, Section VII, September 10, 1951.

The problem of properties of the material cannot be separated from the general objectives. Committee A has outlined the problem<sup>(4)</sup>.

C. WHAT SPECIFIC CHANGES SHOULD BE MADE IN COLUMN DESIGN PROCEDURES TO TAKE INTO ACCOUNT RESIDUAL STRESS?

It is hoped that the results of the research proposed below will provide an answer to this question.

An outline of the variables in the residual stress problem is included in Appendix I of Ref. 1, p. 20.

D. WHAT ARE THE MATERIAL PROPERTIES OF PLATES THAT MAKE UP COMPOSITE STRUCTURES?

Committee A has prepared a statement<sup>(4)</sup> outlining the need for collecting compressive (and corresponding tensile) stress-strain data for plates and shapes.

E. WHAT IS THE BENDING STRENGTH OF VARIOUS ROLLED SHAPES?

To an extent this is beyond the scope of the title. On the other hand, if the material properties are going to be determined on the basis of coupon tests, it would be highly advantageous to explore for a large number of rolled shapes the relation between coupon tests and bending strength.

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(4) Research Committee A, "Recommendation for Research" (for the purpose of determining the Tangent Modulus), January 5, 1951.

### III. PROPOSAL

In order to provide a basis for answering the above questions, an experimental and analytical project is proposed. The immediate question is the following:

WHAT IS THE BEHAVIOR OF A COLUMN CONTAINING RESIDUAL STRESS AND HOW CAN THIS BEHAVIOR BE PREDICTED WITH SATISFACTORY ENGINEERING ACCURACY?

Three conditions of residual stress are involved:

- (a) Residual stress due to cooling - symmetrical pattern
- (b) Residual stress due to cooling - non-symmetrical pattern
- (c) Residual stress due to cold-straightening - usually non symmetrical.

Each of these three conditions may have a different influence and each will require study. It will be attempted as early in the program as possible to ascertain the most critical condition for the largest number of columns and concentrate attention on this phase.

A number of approaches to correlate column strength with residual stress are possible:

- (a) Apply the Tangent-Modulus concept to the test of a specimen containing residual stress.
- (b) From a measured residual stress pattern develop an analytical expression for buckling strength
- (c) Carry out a large program of column tests
- (d) Develop "new" methods for establishing the desired correlation.

Both (a) and (b) above would require tests of some columns of various slenderness ratios but not in the same magnitude as involved in (c). Approach (d) will be necessary for a solution of the influence of non-symmetrical patterns.

Attention will first be given to WF shapes, followed by angles, channels, and possible I-shapes.

The work on plates would consist of a collection of such data as requested by Committee A<sup>(4)</sup>.

With regard to Question E on bending properties, a tentative scheme for testing short lengths under bending moment would be developed. A few pilot tests would then be appropriate.

#### IV. L I M I T A T I O N S

The following limitations are suggested for this particular proposal (for the purpose both of time and from a consideration of the budget):

- (1) Primary attention will be given to steel for bridges and buildings (ASTM A-7) for the column tests.
- (2) The main emphasis will be on columns (WF and Angles).
- (3) Secondary attention will be given to
  - a. plates of alloy or low alloy
  - b. shapes of alloy or low alloy; channel and I-sections (A-7)
  - c. bending tests
- (4) Only concentrically loaded columns are considered.  
The problem of the influence of residual stress on columns in frames and columns under combined axial

load and bending is an important one but is not included under the proposed budget. Work is underway separately at Lehigh<sup>(5)</sup>.

- (5) The testing machine at the Fritz Engineering Laboratory has a capacity of 800,000 pounds. For an average yield-point stress of 40,000 psi twenty square inches of cross-sectional area constitutes the top limit. The following table gives the maximum size that can be tested within each of the main categories:

<u>Wide-Flange</u>	<u>I-Section</u>	<u>Angles</u>	<u>Tees</u>
8WF67	20 I 65.4	(all)	
10WF66		8x8x1-1/8	12 T 65
12WF72			13 1/2 T 72.5
14WF68	<u>Channels</u>		15 T 62
16WF71			16 1/2 T 65
18WF70	18 L 58		
21WF68	(all)		

Committee A or Lehigh University could call for proposals (beyond the scope of the budget below) for the larger tests that will be desirable (5,000,000-lb machine is at Philadelphia Navy Yard and possibly arrangements can be made with ONR to carry out tests there which would involve both the cross-sections and one column for some cross-sections). Residual stresses could still be measured at Lehigh.

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(5) CRC Project O.<sup>2</sup>/<sub>3</sub>.D at Lehigh University; See CRC Quarterly PROGRESS REPORTS.

## V. PROCEDURE (General)

### 1. Cross-Section Study

The procedure for cross-section tests is as follows:

- (1) Select a member in the as-delivered condition
- (2) Cut a full cross-section length such that only a small percentage of the residual stress is relieved by the cutting.
- (3) Test in the flat-end condition, measuring the average shortening for each load increment.
- (4) Plot the resulting average stress-average strain curve and determine the tangent modulus at various stress values.
- (5) Plot the column curve with the data of (4) above by solving the equation, 
$$L/r = \pi \sqrt{E_t / \sigma}$$
- (6) Conduct column tests using same shape at several  $L/r$ .

The pilot program has been set up on this basis, only one shape of cross-section being involved. It is tied in with tests completed in 1950-1951. If the correlation is confirmed by the additional tests outlined, then the next step appears to be a similar program for a limited number of critical shapes, followed by a broader study of a large number of cross-section tests.

The pilot investigation calls for a determination of residual stress level and the determination of stress-strain diagrams from individual coupon tests. This is necessary in order to answer questions "A" and "B", and the main question of this proposal (p. 5).

No real answer to the question can be given without knowing the material properties of the section and the residual stress level present in the columns tested.

It may be unnecessary to measure the residual stress in these later tests. It may be possible to determine the distribution from the cross-section test by assuming a shape and solving for the necessary constants. Another measure of the residual stress level may also be obtained by observing the load at which the first yield line is formed.

## 2. Analytical Expressions from Measured Residual Stress Patterns

For symmetrical patterns, as mentioned earlier, work has already been done<sup>(3)</sup>. Correlation remains to be established with column tests. See the figure contained in Encl. II of Ref. (1).

## 3. Column Tests

Whatever column tests are conducted the following are the slenderness ratios that could well be used:

$$L/r = 60, 80, 90$$

The reductions over the values predicted by tangent modulus applied to coupons are most severe in this range.

Attention must be given to the amount of cold-straightening that has been done on the column.

## 4. Cold-Bending Study

One approach would be to cold-bend a column a known amount, anneal it, then cold-straighten it again. The cooling patterns would be eliminated, but there would be present a (known) cold-straightening pattern.

*Hx*  
*Says*  
*too little*

## 5. Separation of Variables

It would be of value to over-all knowledge of column behavior to give attention to the separate effects of eccentricity of load and initial curvature. This will be done as time permits.

## 6. Specific Test Procedures

This has been covered in Ref. 1.

## VI. DISCUSSION

From work that has been done up to the present time test of cross-sections has seemed the most likely approach for a symmetrical pattern of cooling residual stress. Good correlation has been established between a limited number of column tests and the column curve obtained from the average stress-strain diagram for the cross-section tested<sup>(1,2)</sup>. This approach has further appeal since it is consistent with the tangent modulus concept.

From a cost point of view the cross-section tests are in a favorable position as well. Columns are expensive to test. Based on the cost of a cross-section test, a set of tension specimens and a set of compression specimens are each about 50% more expensive. Residual stress measurements cost about the same as a cross-section test for small shapes. The cost of a column test is greater by a factor of about 4 or 5.

The short cross-section test takes into account two additional variables:

- (a) local buckling of the flange elements
- (b) the yielding process.

Concerning (a), local buckling (inelastic) commences at some time

following yielding due to residual stress. Regarding (b), the yielding process is not the same as assumed in the theory; however, the short cross-section test would inherently include the effect of any variation.

The variation in yield point between web and flange material (commonly observed) will cause a curvature in the average stress-average strain diagram over and above the curvature due to the effect of residual stress.

#### VII. CONCLUDING REMARKS

The reduction in column strength due to residual stress, already ~~been~~ demonstrated by test, means that less emphasis need be placed on the curved portion of the stress-strain diagram for small coupons. Attention must be given to the larger variations in average behavior of the material.

This proposal is written for the purpose of continuing studies aimed at developing a method for predicting the behavior of columns containing residual stress (symmetrical and non-symmetrical and due to cooling and cold-straightening). Ultimately it is hoped that a recommendation can be made as to specific changes in design procedures to take into account residual stress.

Since the problem is so closely related, the basic material properties are also to be determined in this program for certain shapes and plates of structural grade steel.

#### VIII. BUDGET AND PERSONNEL