1963

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NOTES ON THE HISTORY OF RESEARCH IN STEEL STRUCTURES

by Lynn S. Beedle

1. INTRODUCTION

Since its founding in 1909 the Fritz Engineering Laboratory of the Civil Engineering Department at Lehigh University has served industry through its research programs and its industrial test facilities. With the cooperation of Bethlehem Steel Company, the Laboratory was modernized in 1954-55 and this enabled the University to continue to provide fine facilities for research in a number of fields of Civil Engineering. This modernization was carried out under the leadership of Prof. Wm. J. Eney, head of the Civil Engineering Department, and of the Fritz Laboratory.

The Fritz Laboratory got its start just two years after the grey mill was built at Bethlehem, and some of the "new WF shapes" were used by John Fritz in building the Laboratory. Initially, it was used for the undergraduate instruction laboratories and for special tests. In 1928 it was reorganized, and under Professor Willis Slater's leadership as director, graduate instruction and research began.

Except for interruption during World War II continuous metals research programs have been underway since about 1928, predominantly in structural steel. The sponsors of this research have included the following:

American Institute of Steel Construction
American Iron and Steel Institute
American Railway Engineering Association
Association of Iron and Steel Engineers
Bethlehem Steel Company
Column Research Council
Department of Commerce: Bureau of Public Roads
Fort Pitt Bridge Works
Fellowships of the American Welding Society began in 1933, and similar support has continued almost uninterrupted since then. Most recently these appointments have taken the form of "research assistantships".

Prior to the time that the American Institute of Steel Construction began to support research (1946), much of the work in structural steel was financed by private companies. Some of the projects were limited to special tests; others were full-fledged research investigations. At Fritz Laboratory in the early days it was the Bethlehem Steel Company and the McKinley-Marshall Company that sponsored much of the work.

2. HISTORY OF STEEL

The history of steel structures and their development is outlined in Table 1. The table shows the remarkable advance of steel construction over a relatively short period. Intensive research into the maximum strength of steel structures began in this country relatively recently (1946), and yet the results of much of that work find application in even the most routine of designs today.

A good review of the most recent developments in steel research would be afforded by a study of the work of the various research councils, most of which are organized under Engineering Foundation. Those councils of particular interest
from the standpoint of steel structures are the Column Research Council, the Research Council on Riveted and Bolted Structural Joints and the Welding Research Council.

The American Institute of Steel Construction has long been a leader in steel research and the far-sighted vision of its Research Committee and of its director of engineering and research, Mr. T. R. Higgins, is responsible for much of the advance made in recent years. In the past few years or so the American Iron and Steel Institute has taken a more prominent role than it had previously in supporting research in steel structures.

Stimulated by the desire to learn more about steel, to make more effective use of our resources, and to provide more economical structures consistent with safety, engineers and educators have been working to extend the frontiers of knowledge. Among the many topics of steel research on which a brief historical would be of interest, the following will be reviewed: Plastic Design, Crane Girders, Residual Stresses, Columns, and the Column Research Council, High-Strength Bolts, Plate Girders, Welded Connections, Fatigue of Wires, Torsion of Beams, Steel Floors.

3. PLASTIC DESIGN

Engineers and research workers have been stimulated to study the plastic strength of steel structures and its application to design for three principal reasons: (a) it has a more logical design basis, (b) it is more economical in the use of steel, and (c) it represents a substantial saving of time in the design office. Quoting from Ref. 5:

"The methods of designing nearly all steel structures in the past were based upon an allowable stress which incorporated a factor of safety against the elastic limit. Plastic design, on the other hand, represents the utilization of the reserve strength manifested during deformation beyond the elastic limit."
"The first application of plastic design could almost be called "unconscious". There are at least a dozen ways in which the ductility of steel has been counted upon in (so-called) elastic design—knowingly or not. In the first place, certain factors are neglected because of the compensating effect of ductility; in the second place, working stresses have frequently been revised because the "normal" value was too conservative.

"The first 'conscious' application of plastic design was in Hungary in 1914. (It was used in the design of apartment buildings). A period of research followed. Then in 1939 plastic design saw considerable practical application in the design of shelters for protecting families against bomb blast. One million, two-hundred thousand shelters were built, and documented evidence shows that they performed as predicted, deforming plastically to absorb impact but remaining intact to afford the necessary protection.

'The British Standards Specification 449, as issued in 1948, contained a clause permitting the use of plastic design. Four years later (1952) the first building in England was erected according to the plastic method. From that time on, the progress was very rapid and by 1958 more than 600 structures had been designed by the plastic method. Although they were mostly industrial buildings, they also included several four- and five-story structures.

"In this country, the introduction of a 20 per cent increase in allowable stress at points of interior support was a partial recognition of reserve plastic strength. This was adopted by the AISC in 1946.

"The first building to be designed by the plastic method on this continent was in Canada about 10 years later. It was a two-story frame with beams continuous over six spans. A few months later in 1957 a warehouse was erected in Sioux Falls, South Dakota.

"The AISC Specification for plastic design was adopted in December 1958 but by this time at least a score of plastically-designed structures had been built in spite of the out-dated codes.
Research on this subject commenced at Lehigh University in 1946, following a suggestion made in 1945 by the Welding Research Council concerning the nature of the research which it wished to resume (at Lehigh University). In addition to WRC, the program was supported by the Navy Department, the American Iron and Steel Institute, and the American Institute of Steel Construction. At about the same time, work was starting at Brown University under sponsorship of the Navy Department on a critical survey of the mathematical theory of plasticity. This work, in part, was an outgrowth of problems faced by the Bureau of Ships in designing the underwater protection systems in naval vessels to absorb underwater explosions through plastic deformation. Both of these investigations, of course, took cognizance of the valuable work of Prof. J. F. Baker and his staff at Cambridge University (England).

In 1940 Professor Haddrell presented his paper on limit design to ASCE(11), and since that time both that society and the American Welding Society, the SESA, the AISC, AISI, and ASCE as well as others have scheduled technical sessions where research results and evaluations of plastic design have been presented.

In 1955 a "summer course" at Lehigh University presented a plastic design conference in a form suitable for engineering educators. The AISC National Engineering conference at Lehigh University in 1956 was devoted entirely to plastic design, the material being presented primarily for the engineer(12). AISC-sponsored "Regional Conferences" followed in the years 1956-58. An AISC lecture series, designed for practicing engineers, was then begun; the material being presented in over 40 major cities throughout the country.

In 1956 the ASCE Committee on Plasticity Related to Design took action to join with an existing Welding Research Council Committee for the purpose of preparing a "Commentary" on Plastic Design. This Commentary demonstrates the applicability of plastic analysis to design of structural steel beams and frames.(13)

In addition to the AISC Specification (and based upon it), the four major national building codes of the United States have now adopted plastic design. These are the Building Officials Conference of America, the International Building Officials Conference, the Southern Building Congress, and the National Board of Fire Underwriters. Most local codes have adopted plastic design"
With the completion of the first phase of research, work commenced in earnest on plastic design of multi-story building frames in 1958. Work is now reaching the point that another special "summer course" is being scheduled at Lehigh in 1965 to present the findings. More recently, stimulated first by Bethlehem Steel Company, began on the application of plastic design to steels with a yield point higher than that of structural carbon steel.

4. CRANE GIRDERS

An outstanding example of rapid application of the results of research into design use—and at a crucial time—as the research on crane girders in 1940 and 1941. This work was published in 1941(14) and made possible a complete revision of the AISE crane specifications in 1942(15), in time to be useful just before the great expansion of the steel mills in 1942, and with a resulting saving of many tons of steel.

It was also the first work that touched on the idea of residual stresses as a factor in buckling problems, and the period following World War II was to see further studies of the influence of residual stresses on column strength at Lehigh.

5. RESIDUAL STRESSES, STABILITY PROBLEMS, AND THE COLUMN RESEARCH COUNCIL

The study of stability problems in bridges and buildings was one of the major structural research efforts of the past decade. It is not accident that one of the first entries on Table 1 refers to "L. Euler". It shows how many years man has been struggling with the stability problem.
In recent years progress has been rapid and systematic, and part of the reason for this is the stimulus given by the Column Research Council. For a number of years prior to 1941, the Committee on Design of Structural Members of the ASCE had been working on metal column problems. In order to broaden support of these studies and to stimulate direct financial aid to research projects, the Column Research Council was formed in 1944. Membership consisted of representatives of interested institutes, societies, companies, government bureaus, and other research councils (16).

The chairman of the earlier ASCE Committee was Dr. Bruce G. Johnston, who became director of Frits Laboratory in 1943. He was one of the prime movers in the formation of Column Research Council and served as its chairman from 1958 (to 1962).

The Column Research Council has continued active work. In addition to supporting research, it conducts an annual Technical Session at which investigators interested in stability problems exchange their most recent findings. In 1960 it published a "Guide" which incorporated the results of research that had progressed to the point that the structural engineer could put them to use. (17) It is the basis for many specification changes. Currently this Guide is being revised to incorporate findings from the most recent research.

Lehigh University was able to make major contributions to column research both prior to and following the formation of the Column Research Council. These contributions include extensive studies of the material properties of steels (18), of eccentrically loaded columns (19, 20), and research on steel columns under combined bending moment and axial thrust (21, 22). This latter work lead to some
breakthroughs in plastic design, and it also made possible the modification of current building specifications\(^{(23)}\). Similarly, earlier studies at Lehigh on the nature of yielding of structural steel made possible development of new rules with respect to permitted width-thickness ratios for projecting elements\(^{(24)}\).

Another most significant contribution to knowledge that was gained from research at Lehigh University has been the influence of residual stresses. These are stresses which are found to a greater or lesser degree in all steel shapes—either rolled, flame cut or welded. Residual stresses were found to be a major factor in the strength of centrally loaded steel columns. This finding was really a contribution of the "Committee on Research" of the Column Research Council, out of discussion of similar residual stress effects mentioned above in the local buckling of crane girders, and the initial measurement of residual stresses in steel shapes as part of a project on the plastic bending strength of steel beams in 1958. The basic initial concept was developed at Lehigh in the early 1950's, and the research has continued in Fritz Laboratory ever since\(^{(27)}\). As a necessary part of these studies, and also under the guidance of the CRC, a comprehensive survey of the compressive strength of structural carbon steel has been completed. Presently the studies are focused on welded shapes, and this work should lead to recommendations for the most effective proportioning of such columns\(^{(28,29)}\).

6. HIGH STRENGTH BOLTS

Within the past 15 years the high strength bolt has become a major fastener of structural steel parts. Despite the high strength of these bolts as compared with rivets, the first bolted connections were designed according to
specifications in which one rivet was replaced by one bolt. This application was made possible as a result of the work of the Research Council on Riveted and Bolted Structural Joints\(^3\), the research being conducted mainly at the University of Illinois, at Northwestern University, and at Purdue University. Stiffening of the bottom chord of the Golden Gate Bridge was one of the first major applications of high strength bolts, and this work was done in 1953-54.

In 1957 research commenced at Lehigh University that was aimed at capitalizing on the greater strength of the bolt in comparison with the rivet. It was found that fewer bolts than formerly required could be used to transmit forces from plate to plate, and the first results were published in 1960\(^{30}\). This permitted another major change in the specifications of the Research Council on Riveted and Bolted Structural Joints which has guided the work\(^{31}\).

With the information gained thus far, it is now possible to move on to studies of bolted joints fabricated with higher strength steels and stronger bolts. These studies should lead to even more economical steel construction.

7. **PLATE GIRDERS**

Early work on the buckling of the webs of girders was done in cooperation with the Bethlehem Steel Company and its fabrication division, the McClintic-Marshall Corp. in 1933-34. This work provided a rather complete experimental solution to the web buckling problem\(^{32}\). Work was started at Lehigh University in 1957 to determine whether or not the buckling load was the proper basis for the design of a plate girder. After a number of years it was demonstrated both experimentally and theoretically that girders do not fail by sudden buckling as indicated in the earlier theory, but instead the load-carrying capacity was considerably higher than that determined by the theory then in use.
These results were published by the Welding Research Council\(^{(33)}\) and American Society of Civil Engineers,\(^{(34)}\) followed by appropriate revisions to the AISC Specification and to parts of the AASHO Specification, thus permitting the use of more efficient and economical girders.

In view of the change in design, it was then necessary to commence an exploration of the fatigue behavior of these girders and this work is now being done at Lehigh and elsewhere\(^{(35)}\). Alternate forms of stiffening the web are also being studied at Lehigh, and girders with higher strength steels are also being tested.

3. **WELDED CONNECTIONS**

When Prof. Willis Slater came to the Fritz Laboratory in 1928 as its first director, welding was coming to the forefront as a means of connecting structural elements. As Prof. Slater wrote in a report to Sigma Xi,\(^{(36)}\)

"Welding of structural steel has recently been taking the place of riveting in certain important building projects, and on my arrival at Lehigh University, almost before I had gotten my chair warmed up, Professor Jensen (Cyril D.) was at work outlining a research program on the welding of steel beams to steel columns. Professor Uhler soon fell into line, and after nearly two years of hard work they wrote a paper for the American Welding Society, which has been reprinted as a Bulletin of Lehigh University. This was nearly the first research work of its kind, and it does credit to Lehigh University."

And so it went. Almost continuous research followed that beginning effort, and as a result the use of welded structures is commonplace. The study of welded connections was another essential phase of research that lead to the application of plastic design.
9. FATIGUE OF WIRES

The Bethlehem Steel Company has always taken a major interest in wires for suspension bridges. Quoting again from Ref. 36:

"In the spring of 1929 the engineering profession was startled by information that the wires in the suspension cables of two important suspension bridges, then under construction, were snapping under a loadless than the weight of the structure. Specimens of the wire were brought to Lehigh University and tests were started simultaneously at Fritz Laboratory and in the Department of Metallurgical Engineering to ascertain the conditions. However, even before preliminary results could be secured, the McClintic-Marshall Company, engineers and contractors for the bridges, took positive action, dismantling completely the cables that had been erected and replacing the wires with a wire which had stood the tests of years in previous structures. As our test results were secured, they justified the action of the McClintic-Marshall Company, for wires which showed high strength have failed rapidly to failure, broke after a few days of carrying an extremely low load. We then carried out an extensive series of tests on the wire which was used for replacement. This wire made a good showing, and a paper based upon our report, was written by Leon S. Hoisieff, Consulting Engineer, called in by the McClintic-Marshall Company, and published in the PROCEEDINGS of the American Society for Testing Materials.

"Mr. Hoisieff, who is an eminent authority on suspension bridges, has long been trying to bring about a thorough laboratory investigation of suspension bridge wire, and it required this near-disaster to bring the manufacturers and fabricators to the point of recognizing its importance."

Research studies have continued, periodically, since then. Bethlehem Steel Company investigators have recently been studying at Fritz Laboratory the fatigue characteristics of full-size strands cut from the hangers of the George Washington Bridge to determine their behavior after ( ) years of service.
10. TOSSION OF BEAMS

Quoting from the report of Dr. Ing. Lyse, the second director of Fritz Lab(32):

"Probably the most unknown problem of structural steel design is the one on torsional resistance. At the suggestion of and with the support of the McClintic-Marshall Corp., a thorough investigation was started in the fall of 1932. This investigation has included a great number of torsion tests of full-sized structural-steel beams, supplemented with a successful application of the soap-film analogy for tests on effect of slope of flanges and thickness of fillets. The forthcoming report will for the first time give a complete experimentally verified solution of the torsional problem in structural-steel sections."

The results were useful to the practicing engineer, manifested by the fact that the 1934 "Bethlehem Manual of Steel Construction" contained the design formulas recommended in the research report(39) and listed the torsional constants for all rolled shapes in common use at the time.

11. STEEL FLOORS

In 1935 experiments were begun on thin steel plate floors(40). The work was sponsored by the American Institute of Steel Construction and the McClintic-Marshall Corporation. Following this work which was published in 1937 (41), not a great deal further was done in this country. It remained for European engineers to study further the behavior of stiffened steel plate floor systems. They also gave the system a name: orthotropic plate. The term is a contraction of "orthogonal" and "anisotropic" and thus conveys the concept of different properties in the longitudinal and transverse directions. As a result of the European studies, and examination by American engineers, several recent applications of this technique have found their way into practice in the United States(42).
12. **SUMMARY**

Among the topics not mentioned in these notes but on which significant research has been carried out at Fritz Laboratory are the following:

- Riveted Connections of Beams to Columns
- Web Buckling in Steel Beams
- Welded Structural Brackets
- Steel Transmission Towers
- Rigid Frames in Steel
- Semi-Rigid Beam-to-Column Connections
- Flexible Welded Angle Connections
- Stiffened Plates in Compression
- Hot Metal Ladles
- Photoelastic Investigation of Stresses in Cranes
- Ladle Hooks
- Pressure Vessel Research
- Shell Roof Construction
- Non-Uniform Torsion in Built-Up Girders
- Columns with Perforated Cover Plates
- Preflexed Beams

Also not incorporated in this summary are the major contributions to knowledge that have been made possible through work in the Metallurgy Department at Lehigh University. Of special interest in this connection would be those related to weldability and to the studies that have led to the recommendations for the control of brittle fracture in steel plates for cold temperature applications.

Compared with progress made in the past, we are living in a time of "revolution" in structural concepts and thought. Those engaged in research have been privileged in recent years to be able to see their contributions to the advancement of knowledge taken up and applied in the engineering profession. In this respect acknowledgment is due the steel industry for the forward-looking attitude in supporting much of the research and in facilitating its application to design.
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Table 1.2. Historical Outline of Developments in Steel Structures

<table>
<thead>
<tr>
<th>Year</th>
<th>Event/Invention/Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1676</td>
<td>Hooke's law developed</td>
</tr>
<tr>
<td>1744</td>
<td>Euler's buckling of bars</td>
</tr>
<tr>
<td>1780</td>
<td>Tests by Paine of cast-iron arch bridge models</td>
</tr>
<tr>
<td>1820</td>
<td>Cast-iron columns used in Philadelphia building</td>
</tr>
<tr>
<td>1823</td>
<td>Navier formulated differential equation for buckled plate</td>
</tr>
<tr>
<td>1828</td>
<td>puddle steel bridge in Vienna, Austria</td>
</tr>
<tr>
<td>1840</td>
<td>First iron truss in U.S. (Baltimore and Ohio Railroad)</td>
</tr>
<tr>
<td>1843</td>
<td>Wrought iron lighthouse built on Block Island</td>
</tr>
<tr>
<td>1847</td>
<td>Squire Whipple presented stress analysis of truss systems</td>
</tr>
<tr>
<td>1853-58</td>
<td>First building with wrought iron frame (Cooper Union six-story frame)</td>
</tr>
<tr>
<td>1856</td>
<td>Steel first made in U.S.</td>
</tr>
<tr>
<td>1862</td>
<td>Bessemer steel bridge, Holland</td>
</tr>
<tr>
<td>1873-74</td>
<td>Cast-iron double-deck railroad bridge, St. Louis</td>
</tr>
<tr>
<td>1873</td>
<td>First tabulated values of properties of rolled shapes</td>
</tr>
<tr>
<td>1876</td>
<td>Eiffel Tower</td>
</tr>
<tr>
<td>1877</td>
<td>First specifications in U.S. (individual consulting engineers and railroad companies)</td>
</tr>
<tr>
<td>1879</td>
<td>First all-steel (Bessemer) railroad bridge, Glasgow, Missouri</td>
</tr>
<tr>
<td>1881</td>
<td>Electric arc welding introduced</td>
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<tr>
<td>1884</td>
<td>First building with steel frame (Home Insurance Co. Building, Chicago, designed by W. Jenney)</td>
</tr>
<tr>
<td>1888</td>
<td>Riveted connections used in Tacoma Building in Chicago</td>
</tr>
<tr>
<td>1893</td>
<td>Formation of Office of Road Inquiry, Dept. of Agriculture (forerunner of Bureau of Public Roads)</td>
</tr>
<tr>
<td>1900</td>
<td>Grey mill installed at Bethlehem, Pa.; first WF shapes rolled in 1908</td>
</tr>
<tr>
<td>1909</td>
<td>First building erected with WF shape (American Optical Co., Worcester, Mass.)</td>
</tr>
<tr>
<td>1913</td>
<td>First tests to demonstrate &quot;plastic hinges&quot; conducted by Kazinczy</td>
</tr>
<tr>
<td>1914</td>
<td>AASHO first organized</td>
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<tr>
<td>1921</td>
<td>AISC first organized</td>
</tr>
<tr>
<td>1923</td>
<td>First AISC specification for buildings issued (written by five practicing engineers; chairman, Prof. G. Swain of Harvard)</td>
</tr>
<tr>
<td>1926</td>
<td>First AASHO specification issued</td>
</tr>
<tr>
<td>1936</td>
<td>Studies of plastic design initiated at Bristol University by J. F. Baker, later (1944) at Cambridge University</td>
</tr>
<tr>
<td>1936</td>
<td>First revision in AISC specification (minimum required yield stress for ASTM A3 steel raised from 30 to 33 ksi)</td>
</tr>
<tr>
<td>1945</td>
<td>Provision made in AISC specification for welded connections, refinements for rivets and bolts, lateral buckling formula, &quot;20% increase&quot; provision</td>
</tr>
<tr>
<td>1946</td>
<td>Research on ultimate strength of structures and components, commenced at Lehigh University. Mathematical theories of plastic behavior of materials studied at Brown University</td>
</tr>
<tr>
<td>1946</td>
<td>First AISI specification</td>
</tr>
<tr>
<td>1949</td>
<td>First specification for high-strength bolts</td>
</tr>
<tr>
<td>1957</td>
<td>First plastic design in North America (D. T. Wright)</td>
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<tr>
<td>1957</td>
<td>First plastic design in U.S. (W. A. Milek)</td>
</tr>
<tr>
<td>1961</td>
<td>Complete revision to AISC specification</td>
</tr>
<tr>
<td>1963</td>
<td>Revision to AISC, AREA, AWS specifications</td>
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