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J. W. Fisher

L. S. Beedle

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BIBLIOGRAPHY ON BOLTED AND RIVETED JOINTS

by

John W. Fisher, M.ASCE, Associate  
Professor of Civil Engineering, Lehigh University

and

Lynn S. Beedle, F.ASCE, Professor of  
Civil Engineering and Director Fritz Engineering  
Laboratory, Lehigh University

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Sponsored by

Research Council on Riveted and Bolted Structural Joints  
in cooperation with

ASCE Structural Division Task Committee on Structural Connections

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\* To be supplied to ASCE with final manuscript. It is included in reports 302.1, 302.2

\*\* The abstracts are to be inserted into this listing and will form section 5. Item 7 will not be included in the Manual.

1. ABSTRACT

In this bibliography are presented abstracts of most of the work that has been performed during the past two decades on bolted and riveted joints. The last major bibliography on this topic was prepared by De Jonge and covered material published before 1944. This study covers literature on the subject up to September 1966. The abstracts are preceded by some historical notes which show the development of fasteners, related materials, research and specifications.

Instructions are provided to aid in the use of this bibliography. Each abstract follows in principle the format recommended by the Engineers Joint Council. A series of graphical summaries are also presented for many abstracts, and this provides a rapid summary of the types of connections and of the variables studied in the individual references.

In addition to the abstracts, several lists are included for the user. These include subject and author indexes and a list of Research Council work.

## 2. ACKNOWLEDGMENTS

The investigation which led to the preparation of this bibliography was conducted at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania. The Research Council on Riveted and Bolted Structural Joints sponsored the project.

The work has been guided by the Council's Committee on Bibliography (Mr. R. B. Belford, Chairman and Messrs. J. E. Burke, E. L. Erickson, T. R. Higgins, J. I. Parcel (deceased) and E. J. Ruble, members). The authors acknowledge their advice and are appreciative of the support of the Research Council in this work.

Sincere appreciation is due Messrs. R. N. Allan, A. Gopal, R. Kormanik, J. H. Nieckoski and N. Parikh who prepared many of the abstracts. Special thanks are due to T. Tsuiji who prepared several tables for Section 7, which provides a graphical summary of many of the abstracts, and to K. H. Gaedke who assisted in the preparation of many of the German language articles.

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The authors also wish to thank the members of the ASCE Task Committee on Structural Connections through which much of the work of

the Council finds an avenue to the Structural Division membership.

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### 3. INTRODUCTION

Much valuable research has been performed in recent years on bolted and riveted structural connections, much of which was initiated by the Research Council on Riveted and Bolted Structural Joints, formed in 1947. A list of published Council reports was presented in Ref. 61-16.\* The last major bibliography on this topic was prepared by De Jonge,<sup>1</sup> covering material published before 1944.

A project was started at Lehigh University in September of 1963, sponsored by the Research Council on Riveted and Bolted Structural Joints (hereafter referred to as "the Council") to prepare a bibliography on the subject. It was considered that such a bibliography would fill a number of functions. It would be useful to structural engineers and others who need ready access to the material published since 1944, especially to those concerned with the high-strength bolts which have come into use in the past seventeen years. It would provide researchers with summaries of past work to guide them in formulating new projects. Furthermore, it would help eliminate unnecessary duplication of literature searches in this field.

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\* Numbers refer to abstracts and list of references. The designation "61-16" denotes the year 1961, the 16th entry.

(1) De Jonge, A. E. R., "Riveted Joints: A Critical Review of the Literature Covering Their Development", ASME, New York, 1945.

The main emphasis in this manual is on Council-sponsored work. Important articles and reports published by others also have been abstracted if abstracts were not otherwise available. Because bolted joints have been investigated more extensively than riveted joints in the past two decades, most of the material selected for this bibliography deals with high strength bolts and joints fastened with these devices. The coverage extends in time from 1897, taking into account articles not included by De Jonge, and continuing from 1944, the terminal date of De Jonge's survey. Most of the articles were reported in the English language literature. However, the bibliography also includes articles appearing in German, Dutch, Austrian, Japanese, French, Belgium, Swiss and Italian periodicals.

Initially, it had not been anticipated that it would be possible in this survey to go beyond the collection of a list of references and abstracts. However a first step has been taken towards an eventual evaluation of the results of the research by preparing a fairly complete chronology of developments in the field. In the following section some historical notes are presented which show the development of fasteners, of research on bolted connections and of specifications. In the future it is planned that more work will be done on this aspect of the project.

Following the section concerned with "historical notes" is a section on procedures for use in the bibliography. There follow the references and abstracts and the tables which provide a graphical summary

of papers (types of tests and variables studied). These are followed by a list of Council reports and appendixes which contain Council objectives, membership, and a discussion of the development of the Council's specifications. Author and subject indexes follow.

4. HISTORY OF BOLTED AND  
RIVETED JOINTS

Prior to 1945

The possibility of using high-preload bolts in steel-framed construction was first demonstrated by Batho and Bateman in their report included in the publication of the second report of the Steel Structures Research Committee in 1934.<sup>2</sup> Extensive laboratory tests were conducted and reported. It was concluded that bolts with a minimum yield strength of 54 ksi could be tightened sufficiently to give an adequate margin of safety against slip of the connected parts. It was recommended that the bolts be installed with a torque wrench in order to insure the attainment of the preload.

Subsequent tests on high-strength bolts performed at the University of Illinois by W. M. Wilson were reported in 1938.<sup>3</sup> It was concluded from the test results that "the fatigue strength of high-strength bolts appreciable smaller than the holes in the plates, was as great as that of well-driven rivets if the nuts were screwed up to give a high tension in the bolts".

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<sup>2</sup> Batho, C., and Bateman, E. H., "Investigations on Bolts and Bolted Joints," Second Report of the Steel Structures Research Committee H. M. Stationary Office, London, 1934.

<sup>3</sup> Wilson, W. M. and Thomas, F. P. "Fatigue Tests on Riveted Joints", Bulletin No. 302, University of Illinois Engrg. Experiment Station, 1938.

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Note: Refs. 2 and 3 are discussed in De Jonge's work.

1945

In 1945 Maney (45-3) reported on studies of single bolts and how to predict the bolt preload. At about the same time he began a research project directly related to bolted connections (46-5). With a few preliminary tests it was shown that bolts torqued into the inelastic region provided a suitable clamping force (50-16).

1947

The Research Council on Riveted and Bolted Structural Joints, formed in 1947, provided the impetus for the rapid development of the high-strength bolt in the United States. The Council sponsored studies of high-strength bolts and of their use in structural connections. Also contributing to the development of the high-strength bolt at this early stage was the American Railway Engineering Association.

1948

Under AREA sponsorship, Wyly and Carter in 1948 studied the problem of fatigue failures of floor beam hangers of railway bridges (49-11). The hypothesis was advanced that these failures were due to high stress and strain induced by rivet bearing, and a high-clamping force bolt was proposed as a means of minimizing the effect of bearing. This hypothesis was verified and later reported in Ref. 55-19.

The AREA initiated studies on the possibility of using high-strength bolts in bridge maintenance, and the Association of American Railroads began a program of field installations and feasibility studies.

302.3

The earliest installation was in 1948 in a bridge of the Pennsylvania Dock Company at Ashtabula, Ohio. This program confirmed the adequacy of the behavior of bolted connections under load. (50-3, 50-5).

1949

The American Society of Testing Materials in conjunction with the Research Council prepared a tentative specification for the materials for high-strength bolts, a specification which was approved in 1949 and revised in 1951 under ASTM designation A325.

1950

A symposium on high-strength bolts was presented at the Engineering Conference of the American Institute of Steel Construction in 1950. The results of the studies reported in Refs. 50-4 to 50-6 were summarized. Also discussed was some of the work being sponsored by the Research Council.

1951

Using the results of its research (50-13) and other information, the Research Council prepared and issued its first specification in January 1951. This specification permitted the rivet to be replaced by the bolt on a one-to-one basis.

1952

By 1952 a number of laboratory and field investigations had been completed and the results were presented at a symposium on high-

strength bolts at the Centennial Convention of ASCE at Chicago (55-13 to 55-20). Stewart (55-13) summarized the Research Council's activities and presented a brief resume of the development of high-strength bolts in the United States. Munse, Wright and Newmark (55-16) summarized the results of static and fatigue tests on small bolted structural joints. These tests confirmed earlier studies which indicated the superiority of high-strength bolts over rivets. Additional tests comparing the static and fatigue strengths of bolted and riveted joints were reported by Baron and Larson (55-17).

An extensive series of tests were described by Hechtman, Young, Chin and Savikko regarding the slip characteristics of bolted joints under static loads (55-18). Carter, Lenzen and Wyly (55-19) presented test results to support a hypothesis for the cause of and remedy for fatigue failures in structural joints. It was shown that the fatigue strength of bolted joints exceed the fatigue strength of riveted joints. Higgins and Ruble (55-20) reviewed the behavior of mechanically fastened joints; described the development of high strength bolts; and discussed tightening procedures, costs and recent developments.

A number of studies of "joint efficiency" were reported in 1952. Wilson, Munse and Cayci (52-10) summarized results of completed tests and reported on a program of tests on flat plate joints. This

was followed by extensive tests of small joints and the formulation of empirical rules by Schutz (52-12). This study indicated that closer correlation was obtained with the proposed "relative gage" method than with any previous method.

Additional studies to determine the strength of hot-driven rivets subjected to combined shear and tension were summarized, and an empirical interaction curve was given by Higgins and Munse in 1952 (52-16). Previous investigations had not covered the full range of shear-tension ratios.

#### 1953

An extensive investigation which included many tests of riveted double-shear aluminum joints was reported by Francis (53-4). Theoretical solutions were presented for the elastic and inelastic ranges. Although it was concerned specifically with aluminum joints this study contributed significantly to the knowledge of the behavior of all double-shear splices.

#### 1954

Minor revisions based on the Research Council's continuing research program (50-13, 53-7) were incorporated into the revised specification issued in February 1954. In December 1955 an appendix was issued to answer questions concerning the application of the specification.

The first German research work was reported in 1954 by Steinhardt and Mohler (54-11). Sufficient experience and knowledge had been gained through laboratory work, field studies and reports of American practice to enable the German Committee for Structural Steelwork to issue subsequently a preliminary Code of Practice (56-22).

Tests at the University of Illinois in 1954 demonstrated that high-strength bolts tightened well past their yield strength and then subjected to tension were not adversely affected (54-5, 56-11).

#### 1955

Pre-tension control was the subject of several investigations. The use of pneumatic impact wrenches was found to reduce field labor costs. The development of wrench calibrators led to the use of calibrated wrenches to provide bolt tension. In 1953 and 1955 Drew (53-8, 55-7) reported on studies of several methods of tightening high-strength bolts and the development of a one-turn tightening method. This resulted in a one-full-turn-of-the-nut-from-the-finger-tight pretensioning procedure being approved by the Research Council and included in the Appendix distributed in 1955. Additional studies reported by Pauw and Howard (55-5, 55-8) supported this procedure.

Considerable interest in the slip behavior and ultimate strength of large bolted connections led to several preliminary tests of A7 steel bolted butt splices (55-1, 55-2, 55-17). These tests all indicated that

the strength of the fasteners in shear far exceeded the strength of the net section.

#### 1956

The results of studies on the effect of bearing ratio on riveted joints subjected to static loads were summarized by Jones in 1956 (56-23). This paper showed that joint strength will not be reduced if bearing stresses are increased. Additional test results supporting this conclusion were later published by Munse (59-32).

#### 1957

In 1957 a test was performed on an A242 steel joint connected by A325 bolts (57-23). Results of these tests also reflected a fastener strength in excess of net section strength.

An extensive research program was begun at Lehigh University in 1957 "to study the behavior under static tension loads of large plate joints connected with high-strength bolts to determine if fewer bolts may be used than required by current specification". The results of the first phase, reported by Foreman and Rumpf (58-13), indicated that the 1954 design specification was unduly conservative when slip into bearing could be permitted.

A symposium was organized by the West German Steel Construction Industry and held in Essen in 1957 (58-22 to 58-26). The existing knowledge on high-strength bolted connections was summarized and the "Preliminary Directions" for friction-type joints were reviewed.

1958

In 1958 a second symposium was sponsored by the Research Council during the Annual meeting of ASCE in Chicago. A summary of Council-sponsored investigations and a list of Published Council reports was given by Ruble (59-57). Munse, Peterson and Chesson presented results of tests to determine the behavior of connections in which the rivets and bolts carried loads in tension (59-56). Douty discussed these tests (61-18) and presented an approximate analysis (57-14). Tests to determine the moment-rotation characteristics of standard web angle connections were described by Munse, Bell and Chesson (59-55). The specimens were similar to the riveted connections tested by Hechtman and Johnston (47-8). Hanson presented the results of numerous fatigue tests of joints of high-strength steels (59-58); joints connected with high-strength bolts had higher fatigue strengths than those connected by rivets. The type of connected steel had little influence on fatigue strength. The effects of punched holes, misalignment, painted faying surfaces, bolt tightening method, and faying surface conditions on the slip and ultimate strength, were reported by Vasarhelyi et al (59-59). Ball and Higgins reported on studies and tests made to develop a modified turn-of-nut procedure (59-60) and the procedures developed for the bolt installation of the Mackinac Bridge were reported by Kinney (59-61).

1959

In the United Kingdom, the general practice was quite similar to American practice and specifications. In 1959 a symposium on high-

strength bolts was organized by the Institution of Structural Engineers. The results of laboratory and field experience were presented. (59-9 to 59-28) The British Standards Institute formed a committee to prepare a directive on design procedure and field practice. The Institute issued British Standard 3139 (59-54). Dealing only with bolt material, it is almost identical to ASTM A325. In 1960 British Standard 3294 (60-37) was issued to establish design procedure and field practice.

Several papers concerned with moment connections using high-strength bolts were published (59-13, 59-17). Different schemes for bolting interior beam-to-column connections were tested. It was shown that bolted connections could be designed to develop the plastic moment of the connected material. There were no premature failures except those which could have been predicted and prevented.

Chesson and Munse reported on additional studies of large riveted and bolted truss-type connections (59-30) similar to the riveted connections reported on in 1957 (58-12). The results of tests of a riveted plate girder with a thin web were reported by Vasarhelyi, Taylor, Vasishth and Yann (60-9).

Several studies of the behavior of single bolts during tightening and calibration were reported. Bendigo and Rumpf reported on extensive calibration studies of single bolts (59-37). Load-rotation and load deformation characteristics were discussed. A preliminary report on relaxation tests of high-strength bolts by Lewitt,

Chesson and Munse, (59-38) indicated that losses due to relaxation are small.

1960

Additional tests reported by Lewitt, Chesson and Munse in 1960 showed that a hardened washer is not needed to prevent minor bolt relaxation resulting from the high stress concentration under the head or nut of the heavy-head A325 bolt (60-4). Also, studies of the heavy structural bolt installed without hardened washers indicated that its performance under static and fatigue conditions is equal to that of the regular semi-finished bolt then in use with hardened washers. As a result, the new (1960) Specification permitted the elimination of the washer at the bolt head or nut, whichever was not turned in tightening.

For the first time since the introduction of the high-strength bolt, it was officially recognized that bolts have strength properties superior to those of rivets. Up to this time, design for rivets with bolts substituted for rivets on a one-for-one basis. New design rules for bearing-type connections based on research at Lehigh University (60-2, 61-15), established increased bolt shear stresses. The tests indicated that shear must be through the body and not through the threads to realize the full strength of the bolt. Also, because of the desirability of high preload the required minimum tension was increased to be equal to the bolt proof load (60-11). Allowable stresses in tension were increased substantially, for tests demonstrated that bolt fatigue strength under this loading condition was not adversely affected (61-17). The

installation procedure for the turn-of-nut method was modified after extensive development by Bethlehem Steel Corporation (58-3, 61-24).

Rumpf (60-21) adapted the methods described by Francis (53-4) to bolted bearing-type joint of A7 steel. Excellent correlation was obtained between the theoretical values and the experimental data.

Considerable attention was given high-strength bolting at the 6th Congress of IABSE, at Stockholm. Most of the papers dealt with developments in Europe (60-25 to 60-28, 60-32 to 60-38). Sattler considered the application of high-strength bolts to composite concrete and steel girder structures (60-25). Steinhardt reviewed research undertaken at Karlsruhe since the early 50's (60-26, 60-28). Wright and Lewis reviewed the developments in the U.S. and Great Britain (60-32), and Thurlimann summarized work undertaken at Lehigh University (60-34).

#### 1961

In 1961 Hansen used Rumpf's analytical method in determining the effect of pitch in ten hypothetical joints (61-9). Also, Hansen and Rumpf reported several tests of large bolted connections (61-14) which extended the work reported earlier (58-13).

Additional studies at Cambridge University of bolted beam-to-column connections were reported by Sherbourne (61-10) and extended the work reported earlier by Johnson, Cannon and Spooner (59-17). A major

investigation of high-strength bolted connections in plastic design was initiated at Cornell University in 1961. Part of this work was reported by Douty and McGuire in 1963 (63-7).

#### 1962

Tests conducted at the University of Illinois to determine the effect of the elimination of both washers on the static and fatigue strength were reported by Knoell, Chesson and Munse (62-3). This study showed no significant reduction in strength as a result of omitting washers. Additional bolt calibration studies of heavy-head bolts were reported in Ref. 62-2.

Because of the results of its continuing research program, the Council specification was updated in 1962. Washers were no longer required (62-13). Tightening procedures were modified as a result of the additional calibration studies (62-2, 64-17).

A symposium on high-strength bolts was organized in East Germany in 1962. Tests undertaken in East and West Germany as well as Austria were reviewed and discussed (62-15 to 62-22).

#### 1963

The results of tests on bolted lap joints and large riveted joints were first reported in 1962 (62-8, 62-12). These tests showed that in longer joints the end bolts sheared before the full joint

strength was developed. A few calibration and relaxation tests of A354 bolts were reported by Chesson and Munse (64-17). Calibration tests were begun at Lehigh University on A354 bolts having dimensions similar to the heavy-head A325 bolts. Preliminary results of these tests were presented by Christopher and Fisher in 1963 (63-2).

The results of a number of investigations conducted at the University of Illinois were published by ASCE in 1963. Lewitt, Chesson and Munse described the fatigue behavior of bolted connections (63-16). Consideration was given to joints assembled with bolts subjected to shear-type loadings and to direct tensile loading. Chesson and Munse reported on extensive tests of truss-type tensile connections (63-17). Several analyses of joint efficiencies were described and compared with test data. A subsequent report by Munse and Chesson (63-18) further discussed the factors which affect the behavior of connections and presented an empirical method for computing joint efficiency.

Bendigo, Hansen and Rumpf published the results of tests of long bolted A7 steel joints and riveted joints (63-20). It was shown that in longer connections, bolts sheared before all bolts could develop their full shearing strength. The results of tests of A440 steel joints connected by A325 bolts were reported in the same year by Fisher, Ramseier and Beedle (63-12). Particular attention was given to the slip behavior and ultimate joint strength. Also, the calibration studies reported in Refs. 59-37 and 62-2 were published by Rumpf and Fisher (63-19).

A criterion for designing bearing-type connections was proposed by Fisher and Beedle, (63-1); allowable stresses to be based on the shear strength of the fastener rather than on the old "balanced design" concept. The latter was shown to be without a rational basis.

Chang and Vasarhelyi (63-8) reported on tests involving misaligned holes in bolted joints. It was concluded that misalignment has little or no effect on joint strength.

Because additional research had been performed and the behavior of structures in the field had been evaluated, the preliminary Code of Practice issued by the German Committee for Structural Steelwork in 1956 was revised and issued as a Code of Practice (63-26). This code only permits the use of "friction-type" connections.

Miscellaneous studies of A325 and A354 bolts summarized by Chesson and Munse (64-17) included relaxation tests, determining the effect of sloping surfaces on turn-of-nut installation, and fatigue studies of bolted connections without washers.

Several suggestions were made for use of galvanizing on the faying surfaces of bolted joints (63-9, 63-13).

A report of progress of the Cornell University work on the plastic design of bolted connections was presented by Douty and McGuire (63-7). The essential feature in the results of the beam-to-column con-

nection tests was that the connections were able to carry the plastic moment and rotate inelastically through a very large angle. Tests of beam splices showed similar results. In fact, the actual buckling failure occurred outside the connection in the member itself. A report by Beedle and Christopher (64-21) summarized tests of bolted moment connections reported in abstracts 59-48, 59-17, 61-10 and 63-7.

#### 1964

Chiang and Vasarhelyi, (64-4) reported on tests of small joints to determine the coefficient of friction. A36, A440 and A514 steel were studied. A basic friction test was also discussed and compared with the results of the bolted connection tests.

Fisher (64-3) developed mathematical models which established the relationship between deformation and load throughout the elastic and inelastic regions for the component parts of bolted butt splices. A digital computer program was developed for the solution of bolted plate problems in order to make practicable what otherwise would be too tedious. The solution was used to study the effect of joint length, pitch, variation in fastener diameter, and variations in the relative proportions of the bolt shear area.

The results of tests of single high-strength bolts under combined tension and shear were reported by Chesson, Faustino, and Munse (64-6). Most of the tests were conducted on A325 bolts, but a few tests

of A354BD bolts were included. The interaction ellipse presented was similar to that described earlier for rivets (52-16).

The results of calibration tests of A490 bolts are reported in Refs. 64-5 and 64-7. These tests at Lehigh and the University of Illinois were made on bolts taken from the same lot. The tests conducted to determine whether testing procedures constitute a variable, were in close agreement.

As a result of the preliminary studies conducted on A354 and A490 bolts, (63-2, 64-5, 64-6, 64-7, 64-17, 64-55) the Council revised its specification again in 1964 to include both A325 and A490 bolts.

The results of studies of a full size bolted railway bridge during erection and service was reported by Chesson (64-51). This showed clearly that the bolted joints did not slip under working loads.

Considerable attention was devoted to high-strength bolts and connections at the 7th Congress, IABSE, in Rio de Janeiro. Experimental work and applications were discussed (64-26 to 64-32). Particular attention was given to bolts subjected to tension and to the differences in design criteria used in various countries.

#### 1965

Sterling and Fisher (65-1) reported on the results of tests designed to evaluate the earlier developed solution (64-54) for ultimate joint strength. Good agreement was obtained in this study.

Chesson (65-3) reported on exploratory fatigue tests of A490 bolts subjected to tension with prying. This study indicated that A490 bolts had about the same fatigue strength as A325 bolts. Chen and Vasarhelyi (65-8) reported tests of joints with main plates of different thicknesses and without fills. Only a small effect was noted. Douty and McGuire (64-14) reported the work on bolted moment connections and recommended design formula. Several research studies mentioned earlier were published by ASCE (65-15 to 65-21). These included Chesson's report on bolted bridge behavior (65-15), Wallaert and Fisher's study of shear strength of single bolts (65-16), Vasarhelyi and Chang's study of misaligned holes (65-17), the criteria for designing bearing-type connections suggested by Fisher and Beedle (65-18); Chesson, Faustino and Munse's report on single bolts subjected to tension and shear (65-19), Fisher and Rumpf's solution of ultimate joint strength (65-20), and the calibration study undertaken jointly by Lehigh and the University of Illinois (65-21). This latter series of controlled tests showed that substantially identical results were obtained in the two laboratories.

The final report of the 7th Congress, IABSE, was published in November 1965 and contained several discussions and thoughts on high-strength bolted joints (65-31 to 65-25). It was again noted that a wide difference existed in the slip coefficients and factors of safety used in various countries. Also, additional discussion was directed at the topic of bolts in tension particularly when subjected to repeated loading.

1966

Early in 1966, Macadam (66-2) reported on failures of bolts in the Wolf Creek structural plate pipe culvert.

P. J. Gill (66-3) analyzed the tightening of high-strength bolts statistically and showed that when the minimum preload was set at 80% of the minimum tensile strength, twist off failures may result or the bolts may be under-tightened.

Chesson (66-5) reported the results of preliminary tests of joints assembled with bolts and adhesives. The results indicated that epoxies increased the resistance to slip and reduced the magnitude of slip. Brookhart, Siddiqui and Vasarhelyi (66-6) reported on preliminary studies of galvanized bolts and bolted joints. The turn-of-nut method was found more reliable than the torque control method. Also, the coefficient of slip decreased with the thickness of galvanizing. Divine, Chesson and Munse (66-8) also reported on galvanized bolts and joints. The galvanized bolts had substantial reduction in torqued tension strength when not properly lubricated. Bee's wax was found to be the best lubricant. Also studied were the relaxation characteristics and static and fatigue strength. Relaxation losses were greatest with the heaviest galvanized coating on the plate and with galvanized bolts. The loss was twice the loss for plain bolts and plate. The average slip coefficient was about half the normal value for clean mill scale. Fatigue strength was about the same as for ungalvanized joints.

Lewitt, Chesson and Munse (66-7) reported on studies of standard bolted web angle connections. Factors which affect the moment-rotation characteristics were studied. Recommendations were made for the utilization of the restraint characteristics of flexible connections in design.

Christopher, Kulak and Fisher (66-9) reported on the calibration of alloy steel bolts. This study showed that high strength bolts have ultimate load capacities in torqued tension which vary from 80 to 90% of the direct tensile strength. Hence, if minimum strength bolts were supplied and experienced the maximum reduction due to torquing, it would not be possible to tighten these bolts to proof load by any known technique.

As a result of the studies reported in Refs. 66-3 and 66-9, the Council revised its specification in 1966 and set the required installed tension in both A325 and A490 bolts to 70% of the specified minimum tensile strength. Corresponding changes were made in the allowable working stresses for applied tension and shear in friction-type connections for A490 bolts. Also added to Specification was a table of washer dimension tolerances.

Sterling and Fisher (66-12) reported on theoretical and experimental studies of A440 steel joints fastened by A490 bolts. Good agreement was obtained between theory and test results. The currently

used design values were shown to be conservative. Bannister (66-13) reported on the moment-rotation characteristics of bolted moment connections. Graves (66-15) pointed out that the use of large A490 bolts resulted in substantial economies as compared with A325 bolted joints. A theoretical study by Kormanik and Fisher (66-17) showed that the behavior of hybrid joints of A36, A440 and A514 steel was similar to that of homogeneous joints. The average shear strength was equal to or greater than the strength of homogeneous joints.

This completes a brief historical survey of developments in the field of high-strength bolts up to the present (September 1966). In a remarkably short time the high-strength bolt has found wide spread application in practice, and new developments have been rapidly incorporated as a result of the Council's research work and its Specification which is continually being revised to reflect the new knowledge obtained.

5. REFERENCES AND ABSTRACTS

The references and abstracts in this section appear in chronological order. Complete bibliography information is included with each abstract. Reports which were first distributed as laboratory or project reports and later published are included. Reports which appeared more than once (as in the ASCE Proceedings and Transactions prior to 1963) are listed in the order in which they appeared, but the abstract included for only one of the references.

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Note: In the published version of this Bibliography there will follow the 619 articles referenced and abstracted in this survey. For illustrations of the format (in which the type will of course be very much smaller), three pages are included.

## SAMPLE OF SECTION 5

- 49-1 Pickel, W. F.  
TIGHTENING CHARACTERISTICS OF NUT AND STUD ASSEMBLIES,  
Product Engineering, January, 1949

The consistent tightening of bolts and nuts is dependent upon thread surface, lubricant, material of the rubbing surfaces, and conditions of the nut face. Tests are described that measure the effect of the above parameters on the tightening characteristics of nut and bolt assemblies. A series of good torque application practices are presented and equations for computing the total stress involved are derived. Among the torque application practices suggested are: (1) bolts may be tightened in tension to 75% of the yield strength, (2) nuts should apply a tension load to the bolt equal or greater than the external load to be supported in service, (3) minimum thickness of thread plating provides best results, (4) minimum clearance between bolt and hole gives best results.

- 49-2 Kovac, J. J.  
PRELOADING INTERNAL WRENCHING BOLTS, Fasteners, Vol. 6,  
No. 2; 1949, pp. 10-12

Experimental tests were conducted on NAS bolts to determine the relationship between bolt preload and torque. Bolts of the following sizes were tested: 3/8-in., 7/16-in., 1/2-in., 9/16-in., 5/8-in., and 3/4-in. Twelve bolts, two of each size were tested with lubricated threads, while twelve more bolts, two of each size were tested without lubricant. Eighteen bolts, three of each size were tested with an ANC-147 anti-seize compound under the bolt head as well as on the threads. The completely lubricated bolt showed a considerable increase in efficiency for all six sizes. It was found that the loss in efficiency from friction at the bearing surface under the bolt head was more severe than from friction developed in the threads.

- 49-3 Ros, M., and Ceradine, G.  
STATIC AND FATIGUE TESTS WITH DIFFERENT TYPES OF COVER  
STRAPS WELDED ON AND MACHINED FROM THE SOLID STEEL MATERIAL  
AND ALSO WITH LAP JOINTS, Bericht Nr. 168, EMPA, Zurich,  
1949

Reported are 3 groups of tests to determine the fatigue strength of the specimens and to support mathematical evaluation of the fatigue strength. The group of interest is the third group, Lap Joints, of which 9 were tested in static tension and fatigue in riveted, welded,

and combined riveted and welded conditions. The lateral deflections are reported for the different joints, and a comparison is made between the measurements and the calculations.

49-4 Hechtman, R. A.

CONDITIONS AFFECTING THE SLIP OF STRUCTURAL STEEL BOLTED JOINTS, The Trend in Engineering, University of Washington, Vol. 1, No. 4, October 1949, pp. 12-18

The slip in several types of bolted joints under load and the conditions which affect this slip are investigated and reported. The specimens consisted of double lap bolted joints made from plain-carbon structural steel plate. The bolts were rough forged from high strength structural steel. In one series of tests the bolt hole clearance was increased while the bolt tension was kept constant. The test results indicate that a reduction of the clearance in bolt holes is much more effective in decreasing the amount of slip than an increase in the bolt tension.

49-5 Cayci, M. A.

FATIGUE STRENGTH OF RIVETED JOINTS, M. S. Thesis, University of Illinois, 1949

This report reviews German literature on the fatigue strength of riveted joints and compares the results of the German tests with the results of similar tests conducted at the University of Illinois. The test variables compared and their effect on the fatigue strength are as follows: kind of steel, influence of friction between plates, unit rivet bearings, unit rivet shear, relation of minimum to maximum stress in stress cycle, and transverse distance between rivets. A summary of the results of all tests and the effect of the variables is given.

49-6 Wilson, W. M., and Munse, W. H.

THE FATIGUE STRENGTH OF VARIOUS DETAILS USED FOR THE REPAIR OF BRIDGE MEMBERS, Bulletin No. 382, University of Illinois Engineering Experiment Station, 1949

Experiments were conducted to determine the relative fatigue strength of various devices proposed or actually used to strengthen or repair old bridge members to discover and eliminate those methods that involve details with low fatigue strength, and to determine quantitatively the fatigue strength of the members thus strengthened or repaired. The methods included the shortening of eyebars of reinforced

bridge members for which an increased area has become necessary due to an increase in load and other expedients used to splice members in service.

- 49-7 Lenzen, K. H.  
BOLTED JOINTS UNDER FATIGUE LOADING, Fasteners, Vol. 6,  
No. 1, 1949, pp. 6-9 (See Abstract 50-16)
- 49-8 Pickel, W. F.  
TIGHTENING CHARACTERISTICS OF NUT AND STUD ASSEMBLIES,  
Fasteners, Vol. 6, No. 1, 1949, pp. 10-13 (See Abstract 49-1)
- 49-9 Lenzen K. H.  
THE EFFECT OF VARIOUS FASTENER ON THE FATIGUE STRENGTH  
OF A STRUCTURAL JOINT, Bulletin 480, AREA, June-July,  
1949 (See Abstract 50-16)
- 49-10 RCRBSJ  
PROGRESS REPORT OF RESEARCH COUNCIL ON RIVETED AND BOLTED  
STRUCTURAL JOINTS, Bulletin 482, AREA, September-October,  
1949 (See Abstract 50-13)
- 49-11 Wily, L. T., Scott, M. B., McCammon, L. B., and Lindner, C. W.  
A STUDY OF THE BEHAVIOR OF FLOOR BEAM HANGARS, Bulletin  
482, AREA, September-October, 1949 (See Abstract 50-15)

9. APPENDIXES1. OBJECTIVES OF RESEARCH COUNCIL ON RIVETED AND BOLTED STRUCTURAL JOINTS

Because it is generally recognized that current practices in the design of riveted and bolted connections have been developed empirically and that many of these practices and the joint capacities predicted therewith are not supported by scientific data, the Research Council on Riveted and Bolted Structural Joints has been organized to carry on investigations to determine the suitability and capacity of various types of joints used in fabricated structural frames. It is expected that the Council's work will result in the promulgation of more economical and efficient practices.<sup>a</sup>

2. CHAIRMEN OF THE RESEARCH COUNCIL

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W. C. Stewart	1950-1954
E. J. Ruble	1954-1958
E. L. Erickson	1958-1961
R. B. Belford	1961-1965
J. L. Rumpf	1965-

3. CURRENT AND PAST MEMBERS OF THE RESEARCH COUNCIL

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 R. B. Banks, Northwestern University  
 F. Baron, University of California  
 D. C. Beam, Canadian Institute of Steel Construction  
 J. L. Beckle, New York Central Railroad.

<sup>a</sup> Based on statement appearing in Abstract 50-13

\* Deceased

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R. A. Hechtman,	Consultant
T. R. Higgins,	American Institute of Steel Construction
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L. G. Holleran,	Clark, Rapuana and Holleran
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B. L. Wood,	Consulting Engineer
G. B. Woodruff,	Consulting Engineer
L. T. Wyly,	Northwestern University (Ret.)
J. A. Zecca,	The Engineering Foundation

#### 4. SOME NOTES ON THE RESEARCH COUNCIL SPECIFICATIONS

##### 1951

The Research Council formed in 1947, approved its first specification on January 31, 1951 after examining the results of the research it planned and sponsored on high-strength bolts. The reliability of structural joints fastened by high-strength bolts had been demonstrated in field tests performed by the Association of American Railroads under actual operating conditions and in laboratory investigations. This initial specification allowed the replacement of A141 steel rivets with A325 bolts of the same nominal diameter. Additional details are given in Ref. 51-7 and 51-11.

##### 1954

Because the first specification was prepared while research was still in progress, it was necessarily conservative. On February 27, 1954, the Research Council approved a revised specification based on further laboratory and field experience. Among the changes was permission to use flat washers on wide-flange beams with a 1:20 sloping flange. Painting of the faying surface was approved for joints in which slip into bearing was permissible. The installation procedure with impact wrenches was modified. In recommending that bolt tension be set 15% above the minimum tension the Council recognized that torque measurement is not a dependable means of determining bolt tension. Also, the inspection procedures were relaxed because of the dependability of the high-strength bolt.

1955

As a result of questions by users of the specification, the Research Council provided authoritative guidance in an Appendix on December 15, 1955. Also, as a result of studies of installation methods (53-8,55-6,55-7) the Council endorsed the one-turn-of-nut-from-finger-tight method as a satisfactory method of tension control.

1960

In March 1960 a new edition of the specification was issued which recognized the greater strength of joints connected by high-strength bolts. Up to 1960 the accepted design practice was direct substitution of bolts for rivets of equal size. However, the Council had accumulated sufficient data to permit establishment of an adequate design procedure for bolted joints. Two different designs were allowed, "friction-type" connections and "bearing-type" connections. Designers could take full advantage of the higher-strength bolts, and allowable bolt stresses were increased 45% for the latter type of connection. A newly designed heavy-hexagon structural bolt with a larger head and shorter thread length was approved. Tightening procedures were clarified and the minimum bolt tension was increased to equal the bolt proof load. Installation by the turn-of-nut method was modified and because of uncertainties in torque-tension relationships in the field, all torque information was eliminated. The required size of hardened washers was reduced and the omission of the washer under the bolt head or nut (whichever was not being turned in tightening) was permitted. A

commentary similar to the 1955 Appendix was added to interpret many of the requirements and furnish the user with reference data. Comments related to this specification are given in Refs. 60-11, 60-13 and 60-14.

#### 1962

In March 1962, a revised specification was adopted which clarified and modified the 1960 edition. Bolts installed by the turn-of-nut method were no longer required to have washers under either bolt or nut. Also, research had indicated that  $\frac{1}{2}$ -turn-of-nut after proper snugging was sufficient to load the bolt beyond the minimum tension regardless of size or length. An additional quarter turn was required for each bevel surface (1:20) when bevel washers were not used. The heavy-hex structural bolt was adopted as standard, while the regular semi-finished bolts were accepted as substitutes. In addition, special type fasteners were sanctioned provided certain criteria were satisfied. Additional discussion of the 1962 Specification is given in Ref. 62-13.

#### 1964

A further revision was adopted in March 1964. It incorporated the results of additional research and was applicable to both A325 and A490 bolts. Most of the research since 1962 was conducted to develop a higher strength bolt for use with high-strength steels. In making the specification applicable to both A325 and A490 bolts it was necessary to modify existing practice for uniformity. The required size of hardened

washers was further reduced because their primary function is to provide a non-galling surface. Washers were required under both the nut and bolt head when the A490 bolt is used with A7 or A36 steel and under the turned element in higher strength steels. Installation by the turn-of-nut method was again modified because tests (63-2,64-5,64-7) had shown that long A490 bolts require a greater nut rotation to produce the required minimum tension. Although the A325 bolt did not need the additional rotation, the same provision was applied in the interest of uniformity in field practice. A new section included in the specification defined the inspection procedure recommended by the Research Council.

1966

In September 1966, a revised specification was adopted by the Council which modified the suggested design stresses for A490 bolts. When first introduced in 1964, it was required that they be tightened to their specified proof load because this was the requirement for the A325 bolt. However, calibration studies reported in Ref. 66-9 had shown that high strength bolts have ultimate load capacities in torqued tension which usually varied from 80% to 90% of the direct tensile strength. Since the ratio of proof load to specified minimum tensile strength was 0.8 for A490 bolts, bolts supplied with minimum strength properties and which experienced the maximum reduction due to torquing could not be tightened to proof load by any method of installation. Also, studies by Gill (66-3) indicated that tightening to the 0.8 ratio with calibrated

wrenches might result in some bolts twisting off during installation or in some cases lead to undertightening. As a result of newer calibration studies in which it was shown that some bolts might be twisted off during installation or that some might be undertightened (66-3, 66-9), the required installed tension for A490 bolts was reduced to 70% of the specified minimum tensile strength.

The required minimum tension for A325 bolts was also set at 0.7 of their specified minimum tensile strength for consistency. This required only slight changes as the ratio of proof load to specified minimum tensile strength was already in the vicinity of 0.7.

Since resistance to slip is dependent on the bolt clamping force, the allowable stresses for A490 bolts in friction-type connections was reduced to reflect the decreased required clamping force.

Also, the tolerance on nut rotation was decreased to  $30^{\circ}$  over or under in recognition of the lesser rotational capacity of the A490 bolt.

A table of washer dimension tolerances was added to provide guidance to users on the variations in thickness that might be expected.