Development of Design Rules for Composite Construction

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Historical development of the requirements for the design of composite structures made up of steel elements and concrete, as practiced in the United States, is reviewed. Included are buildings and highway bridges. After a brief description of the origins of composite construction in America, an emphasis is placed on early design rules issued by the American Institute of Steel Construction (AISC), American Association of State Highway Transportation Officials (AASHTO), the Joint Committee on Concrete and Reinforced Concrete, and the American Concrete Institute (ACI). The discussion is divided into two parts. The first, dealing with composite beams, traces the development of the AISC and AASHTO requirements; it also includes remarks on the strength of stud shear connectors placed in the trough of a steel deck. AISC, Joint Committee and ACI provisions for composite columns are the subject of the second part of the discussion.

ROLLED SECTIONS COMBINED WITH CONCRETE

The first well documented structural use in America of rolled wrought iron beams embedded in concrete was in the Ward House, a private residence completed in Port Chester, NY, in 1877. It took more than another decade before the new combination of the two structural materials began finding wider applications. By that time steel rather than wrought iron was used for civil engineering structures. In buildings, reinforced concrete started replacing wood and masonry in floor construction during the late 1880s and the 1890s. Concrete embedment of steel beams for fireproofing became common practice by the end of the 19th century.

In bridges, steel beams embedded in concrete were introduced with the issuance of a U.S. patent to the Austrian engineer Josef Melan in 1894. Melan bridges consisted of several parallel rolled beams that were bent to the curvature of a flat arch and completely embedded in a solid concrete slab. They were built in the East and the Midwest on both highway and railway networks. By the early days of the twentieth century straight rather then curved beams became common.

The Druecker warehouses, built in Chicago in 1898, were among the first with steel columns encased in concrete. This scheme was reversed in 1901 when pipe columns were filled with concrete to increase the capacity of a crane bay in the new Government Printing Office in Washington, DC.

For building applications, design rules for composite construction in structural steel and concrete were developed over the years primarily by the American Institute of Steel Construction and the American Concrete Institute. The American Association of State Highway and Transportation Officials, and its predecessor the American Association of State Highway Officials (AASHO), developed and issued similar rules for highway bridges. Another organization that included design rules for composite construction in its specifications was the American Railway Engineering and Maintenance-of-Way Association (AREMA). Their requirements for composite beams for railway bridges generally followed the AASHTO lead. Requirements for the design and construction of composite slabs were issued by the American Society of Civil Engineers (ASCE) and those for welding stud shear connectors by the American Welding Society (AWS).

The paper is based mostly on recollections and on documents cited in the bibliography. It is limited to elements composed of structural steel sections or pipe combined with reinforced or plain concrete. The concrete interacting with the steel section may be present in the form of a slab or an encasement or both, or as fill for the pipe. Many portions of the text originated in the source documents listed in the bibliography. Longer verbatim transfers are clearly identified and presented in quotation marks. The material contained in this paper was first presented at the J.W. Fisher Symposium held at Lehigh University in August 2002.

To refresh his memory, the author checked some items with his mentor Chester P. Siess of the University of Illinois and with a few other friends and colleagues involved at various stages of the development of design rules for composite construction. Their contributions are hereby acknowledged with thanks.

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COMPOSITE BEAMS

AISC Requirements

Composite beams are designed according to the provisions of two AISC specifications: *Load and Resistance Factor Design Specification for Structural Steel Buildings* adopted on December 27, 1999 and the *Specification for Structural Steel Buildings—Allowable Stress Design and Plastic Design* adopted on June 1, 1989 and updated by a supplement issued in December 2001.

Allowable Stress Design

The story of design codes for steel construction started with mill handbooks. Perhaps the first of them, the *Pocket Companion*, was published in 1876 by Carnegie Brothers & Co., Limited, proprietors of Union Iron Mills in Pittsburgh. The full name of this publication was *Pocket Companion of Useful Information and Tables, Appertaining to the Use of Wrought Iron*. It included cross-sections, design tables and properties of 3-in. to 15-in. deep I-beams as well as of other rolled shapes and riveted girders, and the ultimate strength of columns and struts. Areas of “flat rolled iron,” weights and areas of square and round bars, unit weight of substances and coefficients of their linear expansion by heat, mathematical tables and miscellaneous other information useful in structural design were also listed.

The *Pocket Companion* was limited to Carnegie products. This earliest predecessor covered most of the items that were found in the AISC allowable stress design (ASD) manuals even though the content of individual items was considerably less extensive. Subsequent editions of the *Pocket Companion* added steel products at first and, later, omitted the wrought iron altogether. Other design manuals appeared over the next few decades as, for example, those of Pottsville Iron and Steel Company, A. & P. Roberts & Company, Cambria Iron Company, Lackawana Steel Company, Bethlehem Steel Company and Republic Iron and Steel Company.

AISC undertook the promotion of uniform practice in the industry shortly after its founding in 1921. It selected a committee from among the leading talent in the academic, engineering and architectural professions to prepare a specification for the design, fabrication, and erection of structural steel. The committee had five members: Milo S. Ketchum, Dean of the College of Engineering at the University of Illinois; George F. Swain, Professor of Civil Engineering at Harvard University; E.R. Graham of Graham, Anderson, Probst & White Architects, Chicago; W.J. Thomas, Chief Engineer of Geo. B. Post & Sons Architects, New York; and Wilbur J. Watson, President of Watson Engineering Company, Cleveland.

On June 1, 1923 the committee submitted a 9-page document entitled *Standard Specification for Structural Steel for Buildings*. After adopting it, AISC made the *Specification* available to the profession as a part of a book entitled *Steel Construction*. That was the beginning of the now ubiquitous design aid that has, over the years, become known as the AISC *Manual of Steel Construction*. In 1925, the AISC Board of Directors conferred the AISC’s first honorary memberships on the five authors of the *Specification*.

Composite beams were not included in the 1923 document. Requirements for their use appeared for the first time in the AISC *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings* adopted in 1936. They were applicable to any rolled or fabricated steel floor beam entirely encased in concrete and meeting certain dimensional and reinforcing steel requirements. Loads applied before hardening of concrete were assigned to the steel beam alone while the assumption of composite action was applicable to loads applied after the hardening of concrete. The maximum tensile stress in the steel section was limited to 20 ksi. For the allowable concrete stress and the modular ratio, reference was made to the specification governing the design of reinforced concrete for the specific structure under consideration. Another short paragraph dealt with the design of the end connections of the steel beam.

Design rules for composite beams remained basically unchanged until 1961 when the document included design of composite beams without concrete encasement of the steel section. It called for connecting the beam to the slab by mechanical shear connectors welded to the beam and embedded in the slab. Basing the design on the conditions at ultimate strength and providing allowable loads for the design of shear connectors were two other significant new features of the 1961 text.

Tests and theory have shown that the ultimate strength of a composite beam is independent of shoring during construction. Thus, even though the design was carried out at the working load level, it was permitted to assume that all loads were resisted by the composite section regardless of the presence or absence of shoring. The design of shear connectors was based on the assumption of fully plasticized cross-section of the composite beam and on the maximum strength of shear connectors determined from tests. The allowable horizontal shear load per connector was tabulated for three sizes of stud, channel and spiral connectors and three cylinder strengths of concrete.

In 1969, provisions were added for the design of beams with incomplete composite action and those for spiral shear connectors were dropped. Requirements for beams with incomplete interaction were expanded in 1978. Two major extensions were introduced in that edition: shear connectors embedded in lightweight concrete slabs and composite beams built with stay-in-place steel forms. Except for minor adjustments primarily of an editorial nature, and reorganization in 1989 consistent with the LRFD format, the allowable stress design provisions of 1978 have been retained to this day.

Load and Resistance Factor Design

In 1969, the American Iron and Steel Institute (AISI) awarded a research project to T.V. Galambos at Washington University in St. Louis. Galambos' first task was to review the practices in the design of steel-framed buildings and to propose a path for further advancements. Shortly after the beginning of the project, a symposium on Concepts of Safety and Methods of Design was held in London. The papers presented at the meeting confirmed that the worldwide trend in the development of structural design specifications was toward explicit consideration of multiple limit states in combination with the theory of probability. Galambos then proposed that these two concepts, the explicit consideration of multiple limit states and the theory of probability, should serve as the corner stones of a new method for the design of structural steel for buildings. Six years of exhaustive studies brought the project to completion.

At the beginning of the project, the new method was referred to as Load Factor Design for Buildings. George Winter of Cornell University objected on the grounds that the proposed method was to introduce not only load factors but also resistance factors. The method was named Load and Resistance Factor Design (LRFD).

The final report of the project at Washington University was issued in May 1976. To convert it into a specification, portions of the text were assigned to eleven subcommittees of the AISC Committee on Specifications. When the subcommittees completed their work, the results were assembled into a draft for a thorough review by the whole Committee. The resulting preliminary report, labeled "For Trial Use Only," was released by AISC on September 1, 1983 for a one-year period of review and trial use.

During the course of the subcommittee work, due attention was given to the organization of the prospective document. Steven J. Fenves of Carnegie-Mellon University studied the logic of the organization of the manuscript and prepared proposals for consideration by an editorial committee. The adopted format was based on the need for clarity and ease of use of the new specification as well as on the familiarity of the design community with the organization of the allowable stress design (ASD) specification. The subsequent (1989) issue of ASD was reorganized using the format adopted for LRFD.

The *Load and Resistance Factor Design Specification for Structural Steel Buildings* was adopted by AISC on September 1, 1986. The fundamental feature of LRFD was the dimensioning of members and connections at ultimate strength level. The design was based firmly on the wealth of knowledge obtained over several decades of structural research. LRFD furnished the designer with information that can serve as a basis not only for routine designs but also for solutions to unusual problems outside the applicability of ASD. Furthermore, a clear path was provided for updating based on new research findings and for adopting design rules for new products.

The first update of LRFD for buildings was issued in 1993 and the third edition became available in 1999. To avoid the need for maintaining two separate documents, the AISC Committee on Specifications at its meeting on November 10, 2001 adopted a new format that will accommodate the LRFD and the ASD requirements within the same common text. The target year for publication of the unified document was set as 2005.

Besides the method of approach and form, the 1986 LRFD expanded the scope of the AISC requirements for composite construction by incorporating rules for compression members in a form fully compatible with that used in the design of bare steel columns. Another significant innovation was the replacement of tabular values for the design of shear connectors with equations, one for studs and another for channels. Both accommodated lightweight aggregate concrete implicitly. The 1993 edition increased the maximum spacing of stud shear connectors to 36 in. and moved the requirements for the design of shear connectors in hybrid beams from a footnote into the body of the text. Otherwise the changes introduced in this second edition of LRFD were mostly editorial.

Further editorial adjustments and four substantive changes were made in the 1999 edition. The highest permitted minimum yield strength of steel used in calculations was raised to 60 ksi, new requirements were included for the transfer of loads to axially-loaded encased composite columns, a provision was added for concrete-encased beams with shear connectors and the design load was reduced by 25 percent for a single stud connector placed in the rib of a formed steel deck running perpendicularly to the supporting beams.

Despite the innovations and expanded composite design provisions incorporated into LRFD, the new method is not used universally by the design community even though adopted more than 15 years ago. One of the last steps in the original development of the entire *LRFD Specification* was a calibration of the design results with ASD. Despite the urging by the sponsor of the research project that in view of the improvements introduced by LRFD the new method should provide some small but definite savings, the researcher's preference was for LRFD to result on the average in the same designs as ASD. This last point was accepted by the AISC Committee on Specifications. Because the two methods produce similar results, designers have little incentive to replace the traditional ASD method with something unfamiliar and, in many cases, have continued using ASD.

Studs in a Steel deck

Formed steel decks are used universally for construction of floor slabs in steel-framed buildings. The decks are roll-formed into a corrugated shape. Except when very shallow, the corrugations are usually of trapezoidal cross-section. Decks 2 in. and 3 in. deep are the most common. They are welded to the supporting steel beams. In composite construction, stud shear connectors are located in the troughs of the deck. They are welded to the supporting beam through that portion of the deck sheet that is placed flat on the top flange of the beam.

In commercially produced decks, the flat portion has a stiffener in the middle between the two adjacent corrugations. Thus the studs cannot be centered in the rib but must be placed closer to one of the walls of the corrugations. Recent laboratory tests have shown that for ribs running perpendicularly to the supporting steel beams there can be a significant reduction in the strength of such a stud from that placed in a solid slab. As a stopgap measure, adopted before the supporting research was completed, the 1999 *LRFD Specification* reduced by 25 percent the design strength of a stud shear connector placed singly in a deck rib oriented perpendicular to the beam.

Reduction in the strength of a stud shear connector in the rib of a steel deck is readily understandable. If the stud were bearing directly against the wall of the deck, with no concrete between the sheet and the stud, it would be essentially unconnected to the slab. Thus it could transfer hardly any load from the steel beam into the concrete flange of the composite beam. On the other hand, in practice there will always be some concrete between the stud and the deck for reasons such as the inclination of the wall of the deck, need for space for the welding gun at the base of the steel deck trough, etc. Furthermore, it is highly improbable that all studs would be welded in the most unfavorable position. Finally, current deck profiles have been in use for decades and millions of square feet of composite floors have been built using current AISC design loads for stud shear connectors. The structural performance of these floors has been uniformly satisfactory. No difficulties, let alone failures, could be attributed to the AISC design loads for studs.

It seems, however, desirable to point out that a redesign of the shape of commercially produced decks could result in an improved product. Placing the horizontal stiffener of the flat portion of the deck off center would permit welding the studs along the centerline of the trough. Such a step would also facilitate stud welding and the inspection of the product. Decks manufactured in Australia have two stiffeners located off center, leaving enough space for welding the studs between them.

AASHTO Requirements

Composite beams were the principal load carrying elements in practically all ordinary steel highway bridges built in the United States during nearly the past half century. They were designed in accordance with the *Standard Specifications for Highway Bridges* issued by AASHTO. The compilation of the *Specifications* began in 1921 with the organization of the AASHO Committee on Bridges and Structures. The specifications were developed gradually during the following years until issued by AASHO in printed form in 1931. As parts of the document were approved, they were made available in mimeographed form to the state highway departments and other bridge builders.

A printed version of the *Standard Specifications for Steel Highway Bridges* was issued by the United States Department of Agriculture on October 9, 1924. According to the introduction,

> The standard specifications for steel highway bridges set forth in this bulletin are those recommended by the subcommittee on bridges and structures of the American Association of State Highway Officials. They were presented to the association at its annual meeting at Kansas City, Mo., December 4 to 7, 1922 and were subsequently adopted by the association by letter ballot. They have since been approved by the Secretary of Agriculture for use in connection with the administration of Federal appropriations for construction of the Federal aid highway program.

The introduction included a list of subcommittee membership. One member each came from fourteen states and two from the U.S. Bureau of Public Roads. One of the two was from Washington, D.C., the other from Portland, Oregon. The Bureau representative from the east coast, E.F. Kelley, served as chairman of the committee and E.E. Brandow of the Pennsylvania State Highway Department as secretary. The well known expert on the design of arch bridges, Conde B. McCullough of Oregon, was among the fourteen members from the states.

Forty-eight pages long, the document consisted of a brief introduction, design requirements divided into three divisions, and an index. The first division dealt with materials, the second with general considerations, and the third with design. The division on design covered 28 of the 48 pages and was subdivided into subsections on general features, loads, unit stresses, distribution of loads and structural steel design. The last item covered close to 100 different topics, starting with dimensions for stress calculations and ending with approval of plans. Among these numerous design topics, there were requirements for reversal of stress, combined stresses, secondary stresses, compression members, tension members, connections and connecting devices, floor systems, bracing, plate girders, trusses, and viaducts. The text ended with the following sentence:

> "No deviation from the approved plans will be permitted without the written order of the engineer."

The Government Printing Office produced the 1924 document and sold it for 10 cents per copy.

The earliest ancestor of the highway bridge specifications was issued in 1871 by Clarke, Reeves & Company, the forerunner of the Phoenix Bridge Company, in their initial annual circular. It was the first general specification for the design of railroad bridges issued in this country. One page long, it consisted of four parts: design, properties specified for the iron, fabrication requirements, and limits on deflections of the finished structure.

Standard Specifications for Highway Bridges and Incidental Structures issued by AASHO in 1931 was the first broadly recognized standard for the design and construction of highway bridges in the United States. With the advent of the automobile, highway departments were established in all states just before the end of the nineteenth century. They handled all aspects of a substantial majority of bridges in the whole country. The responsible individual within each department was the chief bridge engineer. It was natural, therefore, that these engineers acting collectively as the AASHO Committee on Bridges and Structures would become the author of this first broadly recognized standard. Furthermore, maintaining the document became a continuing task of the Committee.

Within a short time, the *Specifications* became a de facto national standard. It was adopted and used not only by the state highway departments but also by other bridge-owning authorities and agencies in the United Stated and in several other countries. The last three words of the original title were soon dropped and the document was reissued under the same title in consecutive editions at approximately four-year intervals. The sixteenth edition appeared in 1996.

The body of knowledge related to the design of highway bridges has grown enormously during the half century following the original issue of the document. In 1986, the Subcommittee on Bridges and Structures requested the research committee of AASHTO to undertake an assessment of bridge design specifications. The work was accomplished under the National Cooperative Highway Research Program (NCHRP) administered by the Transportation Research Board. Completed in 1987, the principal result of the assessment was a recommendation to develop an entirely new bridge design standard. A multi-year, exceptionally comprehensive NCHRP project was awarded to the consultants Modjeski & Masters. With their administrative input and under the guidance of a 50-member project panel, composed of some of the country's best bridge engineering talent, an entirely new bridge design standard was produced and released under the name LRFD.

Section 9, Composite Beams of the 1944 edition of the AASHO bridge specifications called for proportioning "by the moment of inertia of the net composite sections." It included rules for the effective flange width, the effect of shoring on stresses in the composite beam, computation of horizontal shear between the slab and the beam, and deflections. It also required the use of mechanical shear devices for the transfer of horizontal shear and for preventing uplift between the slab and the beam. The spacing of the mechanical devices was limited to a maximum of 2 ft. A significant expansion took place in 1957 with the addition of design equations for channel, stud, and spiral shear connectors. Further changes in the design of shear connectors followed in the ninth and tenth editions. The tenth edition dropped the rules for spiral shear connectors and included provisions for the design of composite box and hybrid girders.

By 1977 the designer had the choice between the working stress design and the load factor design. The LFD, adopted by the AASHO Committee on Bridges and Structures in 1971 for steel bridges, represented a milestone in the development of design specifications for highway structures. It enabled the designer to determine routinely the ultimate strength of a composite beam and other structural elements of a bridge. Another major change came a couple of decades later with the introduction of LRFD. Following the phaseout of the WSD and LFD, hopefully before the end of the first decade of this millennium, the LRFD should become the sole method in structural design of ordinary steel highway bridges. That will mark the completion of an early path on the road toward explicit evaluation of the strength and deformability of a bridge as a part of the design process.

COMPOSITE COLUMNS

AISC Column Design

Over the years, the design of composite columns was covered in the ACI Code and that of composite beams in the AISC Specification. In 1976 the AISC *Engineering Journal* included Furlong's paper "AISC Column Logic Makes Sense for Composite Columns, Too." Shortly afterward George Winter, who was at that time chairman of the Structural Stability Research Council, formed an ad hoc group called the Structural Specification Liaison Committee (SSLC). Composed of at least one member from each of the structural specification committees of the ACI, AISC and AISI, its purpose was to work toward unifying the approaches to structural design in reinforced concrete, structural steel and cold-formed steel. Winter chaired the group. William A. Milek, Clarkson W. Pinkham, and a few others served as its members. In addition, SSLC called on several experts as consultants on specific issues.

One of the subjects taken up by the SSLC was the design of composite columns. Furlong's paper was written in terms of working stress design. In cooperation with Furlong, the committee transformed the method into the ultimate strength design format and proposed its inclusion in the new specification for structural steel design that was then under development. The new document, adopted by AISC in 1986 as the *LRFD Specification*, included the modified Furlong method for concentrically loaded composite columns as well as provisions for composite columns subjected to combined compression and flexure.

In essence, the Furlong method was a modification of the addition formula for reinforced concrete columns derived from experimental research at the University of Illinois and Lehigh University during the 1930s. The modification consisted of the addition of a new term accounting for the contribution of the structural steel shape or the steel pipe to the overall strength of the column. The new term was given as a function of the product of the structural steel or steel pipe cross-sectional area and the yield strength of steel.

AISC design of composite columns was developed without any new supporting experimental evidence. Therefore, the provisions were made purposely very conservative especially for combined compression and flexure for which experimental evidence was practically nonexistent. The transition from concentric compression to bending was based on two straight lines rather than on the obviously more correct, but also less conservative and less certain, convex curve.

Another reason for the conservative approach was the desire to provide incentives for research on composite columns. Unfortunately, proposals to the National Science Foundation by academic institutions for research projects in this field were unsuccessful. Furthermore, commercial incentives were insufficient for conducting the work under the sole sponsorship of the industry. The requirements for composite columns remained essentially unchanged in both the 1993 and the 1999 editions of the *LRFD Specification*. They remain a fruitful field for academic research, particularly now that powerful computer programs drastically reduce the number of experiments necessary to verify theoretical approaches.

Joint Committee Reports

Perhaps the earliest broadly based recommendations for the design of reinforced concrete in the United States were contained in the final report of the first Joint Committee on Concrete and Reinforced Concrete.

Two engineering societies, the American Society of Civil Engineers (ASCE) and the American Society for Testing and Materials (ASTM), and two industry-wide associations, AREA and the Portland Cement Association, appointed in 1903 and 1904 special committees for the purpose of preparing a recommended practice for the design of concrete and reinforced concrete structures. In June 1904 the special committees merged into the Joint Committee on Concrete and Reinforced Concrete and in 1915, ACI was added to the roster of constituent organizations. Progress reports were presented in 1909 and 1912. The final report, adopted on July 1, 1916, stated that it was not a specification but that it may be used as a basis for such documents.

Less than a year after the adoption of the final report, the ASTM Committee on Reinforced Concrete initiated steps toward forming a successor to the Joint Committee. The second Joint Committee held an organizing meeting in February 1920. It produced tentative specifications and submitted them to the constituent organizations. The document was then presented in several cities and remained open for public criticism and discussion for more than two years. As a result of the feedback, verification tests followed. The final report was issued on August 14, 1924 under the title *Standard Specifications for Concrete and Reinforced Concrete*. The final document included provisions for materials, construction, and design. The design was based on working stresses and the elastic cracked-section theory.

Requirements for composite columns were included for the first time in the 1924 specifications. A composite column was defined as a structural steel shape thoroughly encased in circumferentially reinforced concrete or a cast iron pipe filled with concrete. The allowable stress for concrete for both of these column types was $0.25f'_c$ considering only the area within the circumferential reinforcement or inside the pipe. The allowable stress for structural steel and cast iron sections was a function of the slenderness of the column with a maximum of 16 ksi for structural steel and 10 ksi for cast iron.

The third Joint Committee was organized in 1930 to study the extent and character of the advances in knowledge since the 1924 report. In December 1932, the American Institute of Architects was added to the five constituent organizations of the earlier Joint Committee. The Committee issued a progress report that was presented and discussed at the ACI meeting of February 1937. Their final report issued to the constituent organizations in June 1940 retained the elastic cracked-section theory for the design of flexural elements, but the provisions for concentrically-loaded columns were based on their maximum attainable strength.

Column equations of the 1940 report used the so-called addition formula that was developed from extensive tests of reinforced concrete columns completed at the University of Illinois and Lehigh University in the early 1930s under the direction of Frank E. Richart and Inge Lyse, respectively.

The addition formula was first adopted by ACI as a part of its 1936 Code. Although service load design was retained in the 1936 ACI Code and the 1940 Joint Committee report, both the magnitude and the form of the column design equations were derived from conditions characteristic of the ultimate strength of the column.

The 1940 Joint Committee report included substantially expanded provisions for composite columns, added provisions for combination columns and made the provisions for pipe columns applicable to steel rather than the cast iron pipe referred to in the 1924 report. The single most important change from the earlier Joint Committee reports was the adoption of the addition formula for the design of concentrically loaded composite and pipe columns. The allowable compression in flexure was increased from 0.4 to 0.45 f'_c and the allowable steel stress from 16 or 18 to 18 or 20 ksi depending on the type of steel.

ACI Building Code

National Association of Cement Users (NACU), which became known in 1913 as ACI, issued in 1908 a report of its Committee on Laws and Ordinances that included six pages entitled *Requirements for Reinforced Concrete or Concrete-Steel Constructed Buildings*. While it is not clear whether this document achieved any official standing, it was the earliest predecessor of the ACI Code. In February 1910, *Standard Building Regulations for the Use of Reinforced Concrete* were adopted as NACU Standard No. 4. The next major revisions were adopted in 1920 and the revised report issued under its earlier name during the same year. The 1920 *Regulations* included recommendations of the 1916 Joint Committee report.

Following several revisions issued as preliminary drafts or tentative standards, another version of the code was adopted and published in the 1936 ACI proceedings under the title *Building Regulations for Reinforced Concrete* (A.C.I. 501-36-T). It was the first ACI Code that included provisions for composite columns. The permissible load on a composite column was given as the sum of separate contributions of concrete, the longitudinal bar reinforcement and the structural steel core. Each of the three terms was independent of the other two because the Illinois and Lehigh tests of reinforced concrete columns have shown that a column fails by crushing of concrete only after yielding of the longitudinal steel components. The part of the report dealing with composite columns included requirements concerning the details of the steel core and reinforcement, and for splices and connections of the core. It also stipulated that the core must be designed to carry safely any construction loads placed upon it prior to its encasement in concrete.

Also included were provisions for two types of combination columns listed as "Steel Columns Encased in Concrete" and "Pipe Columns." The first of these two elements was defined in the same way as the combination column of the 1940 Joint Committee report. Its design load was specified as a function of the permissible stress for an unencased steel column, the cross-sectional area of the steel section and the cross-sectional area of the concrete section. The permissible load for a pipe column was given by two additive terms, one representing the contribution of concrete and the other that of the steel pipe. Slenderness reduction was required whenever the column length exceeded ten times the least lateral dimension.

Except for the transition to ultimate strength design and for some minor adjustments, the equations for the design of composite, combination, and pipe columns remained essentially unchanged through at least 1963. In line with the changes introduced in subsequent years into the design of reinforced concrete columns, by 1977 the code provisions for composite compression members stated simply that the "strength of a composite member shall be computed for the same limiting conditions applicable to ordinary reinforced concrete members." Furthermore, by 1977 no differentiation was made among various types of composite compression members. They were defined as "members reinforced longitudinally with structural steel shapes, pipe, or tubing with or without longitudinal bars." On the other hand, the section on composite compression members was expanded by the addition of requirements that may be categorized as detailing. The provisions in force at the time of writing this article remain essentially the same as those in the 1977 issue.

CONCLUDING REMARKS

Extensive practical experience has demonstrated that composite construction is a system suitable for areas of high seismicity. It has been used in Japan for decades but on the west coast of the United States its use spread only relatively recently. The first U.S. seismic provisions for composite construction were included in the 1994 version of the National Earthquake Hazards Reduction Program's *Recommended Provisions for Seismic Regulations for New Buildings* issued by the Federal Emergency Management Agency in 1994. AISC included composite construction in the 1997 *Seismic Provisions for Structural Steel Buildings* and the provisions were also included by reference in the 2000 edition of the *International Building Code*.

Design rules for composite construction have been developed gradually over the years and have been undergoing improvements and updating to this day. These progressive changes resulted in more efficient uses of the constituent materials and led to better, less expensive structures. There is no doubt that the search for further improvements and for application of new materials in the field of composite construction will continue into the future.

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