Current Steel Structures Research

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INTRODUCTION

With this issue, the *Engineering Journal* enters its second year of publication of papers presenting ongoing steel structures research around the world. The subject matter details hot-rolled steel and composite construction as it applies to buildings and bridges. Details of approaches and findings and how they apply to American practice are provided as much as feasible, and the locations of the researchers and their institutions are identified whenever such data have been given. Topics vary from issue to issue, but steel properties and characteristics, member and frame performance and stability, connections, composite structures, and bridge design and construction are the major areas of interest.

Behavior, strength, design criteria, and fabrication considerations for connections continue to be among the most active research areas. Two of the projects discussed in this paper present novel findings and requirements for high-strength bolted connections in very high-strength steel. Another study provides interesting observations regarding bolt hole preparation using plasma cutting. A major project in China aims at determining the response characteristics of end-plate beam-to-column and beam-to-beam connections subjected to fire conditions. And in an area of work that is likely to have significant impact on the practice of engineering, many European efforts now focus on the need for design guidelines and manuals, and several projects will yield such products.

A cooperative effort between researchers in Australia and Belgium has resulted in design recommendations for tension and compression for circular hollow cast iron members. This may be very useful for engineers doing renovation work in older structures. Current knowledge on the material properties of cast iron for structural applications is limited, and design recommendations are essentially nonexistent.

Composite construction continues to be another major area of work, for buildings as well as bridges. So are studies addressing behavior characteristics of stiffened plate structures, with obvious applications to bridges and certain industrial types of installations.

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References are provided throughout the paper, whenever such are available in the current public domain. However, most of the work presented is still in progress, and reports or publications have not yet been prepared.

CONNECTIONS

High-Strength Bolted Connections in High-Strength Steels: This is a project being conducted at Delft University of Technology in Delft, The Netherlands, with Professor Frans Bijlaard as the project director (de Freitas, de Vries, and Bijlaard, 2005). Professor Bijlaard is also the current chairman of the Eurocode 3 steel design code committee for the European Union.

The study was premised on the fact that most of the criteria that are currently used for high-strength bolted connections have been derived on the basis of tests and analyses with shape and plate material of mild- (36 ksi) to medium-strength (50 ksi) steel. The question that needed resolution was especially whether it was suitable to apply the same end and edge distances when 100 ksi or even higher strength steel were to be used. Although it is not very common to use A514 and similar grades of steel for building applications in the U.S., such is becoming more acceptable in other locales. Steels with yield strengths as high as 140 ksi are available in Europe, for example.

The European HS bolt grades 8.8 and 10.9 are closely comparable to ASTM A325 and A490, respectively. The original tests with these bolts in mild steel connection material could be classified as "strong bolts in weak steel," as observed by Professor Bijlaard. Using 100-ksi-yield steel with the same types of bolts changes the connection to "weak bolts and strong steel."

Thirty single-bolt, double-shear physical tests were conducted, using the two grades of HS bolts in 100 ksi steel, with three tests for each of the 10 different connection configurations. The specimens were designed to fail in bearing, using end distances of $1.0d_0$, $1.2d_0$, $2.0d_0$, and $3.0d_0$, and edge distances of $1.0d_0$, $1.2d_0$, $1.5d_0$, $2.0d_0$, and $2.5d_0$, where d_0 is the hole diameter. Some of the thinking that went into the test planning focused on the perceived smaller deformation capacity of higher strength steels, which would seem to indicate that a larger end distance, for example, would be needed. On the other hand, the material strength is higher, which would require a smaller end distance to meet the same level of limit state capacity.

Comparing the findings to the requirements of Eurocode 3 (EC3), it was determined that the EC3 rules are conservative for 100 ksi steel, especially when the edge distance is less than $1.5d_0$. Further, it was found that the minimum end and edge distances can be reduced from $1.2d_0$ to $1.0d_0$.

For American practice, it is emphasized that EC3 uses bolt end and edge distances in terms of the hole diameter, as opposed to the bolt diameter. Further, the bearing limit state capacity is determined on the basis of a somewhat complex relationship involving end and edge distances in comparison to the hole diameter, as well as the ratio of the tensile strength of the bolt material to the tensile strength of the plate or shape material The distances given above are therefore not directly comparable to those of U.S. practice, although the sense of the findings is correct.

Bolted Connections Made with High-Strength Steel S690: This project is conducted by Professor Darko Beg at the University of Ljubljana in Ljubljana, Slovenia. Somewhat more comprehensive than the HS bolt project in Delft, the initial results have just become available through a presentation at a technical committee meeting of the European Convention of Constructional Steelwork (ECCS).

One- and two-bolt double-shear connections were tested to evaluate bearing limit states, using ⅞ and 1⅛ in. HS bolts in the grades 10.9 and 12.9. The nominal tensile strength of the 12.9 bolts is 175 ksi; there is no comparable American structural bolt grade. The 12.9 grade was used in the tests specifically to avoid bolt shear failures; in practice the grade is currently used primarily to renovate and strengthen existing structures. Additional tests were conducted on plain plate specimens in 100 ksi steel with no holes and with single holes of diameters from 5 to 50 mm (0.2 to 2 in.), as well as three mild steel (yield stress 235 MPa = 35 ksi) control tests.

The purpose of the plain plate tests was to evaluate the failure strength and ductility demands on the basis of net section failure. The purpose of the single and double bolt tests was to evaluate the influence of a range of end and edge distances in the S690 100-ksi steel. Overall, the findings of the Ljubljana researchers agree with those of the Delft project, particularly that somewhat smaller end and edge distances can be used for connections in the 100-ksi steel, although it is noted that the net section limit state will prevail at the smaller end distance magnitudes.

Future work on connections in high-strength steel will focus on welded assemblies as well as long joints.

Behavior of Beam-to-Beam and Beam-to-Column End-Plate Connections under Fire Conditions: This project is conducted at Tongji University in Shanghai, China, under the direction of Professor G.-Q. Li.

End-plate connections are used extensively in China for a variety of applications, including for portal frames and as beam-to-column connections in highrise structures. The study includes the development of finite element connection models for fire conditions; the models will be applied in the analysis of multistory structures. Physical testing will also be conducted. The project is relatively recent; results will be critical in the development of suitable design code requirements.

Use of Plasma Cutting in the Preparation of Bolt Holes: This study has been carried out at the Helsinki University of Technology, under the direction of Aleksander Potapenko and Ming Qi.

Hole preparation in Finland is normally done by drilling. In U.S. practice, hole punching is almost always used, as long as the punching equipment has sufficient capacity for the given material thickness and strength. Nevertheless, the Finnish researchers noted that plasma cutting leads to fairly clean holes with little roughness; it was felt that this procedure would be faster and more economical than drilling. Further, the researchers wanted to examine the effect of the type of hole fabrication on the static as well as the fatigue strength of certain types of single-shear connections.

A number of static and dynamic (fatigue) tests were carried out with 50-ksi-steel plates and ⅝ in. bolts. Briefly, the static tests demonstrated that there is no difference in strength and behavior between specimens with drilled holes and specimens with plasma cut holes. The fatigue tests exhibited a drop in the resistance of approximately 50% when plasma cut holes were used in lieu of drilled holes. It is emphasized that the connections were not tested for seismic conditions.

Design Manual for the Design of Weak-Axis W-Shape Beam-to-Column and W-Shape to HSS Column Connections: This manual is under development by Professor Luis da Silva at the University of Coimbra in Coimbra, Portugal, under the auspices of Task Committee 10 of the European Convention for Constructional Steelwork.

As illustrated in Figure 1, the manual will focus on the design criteria and procedures for end-plate connections,

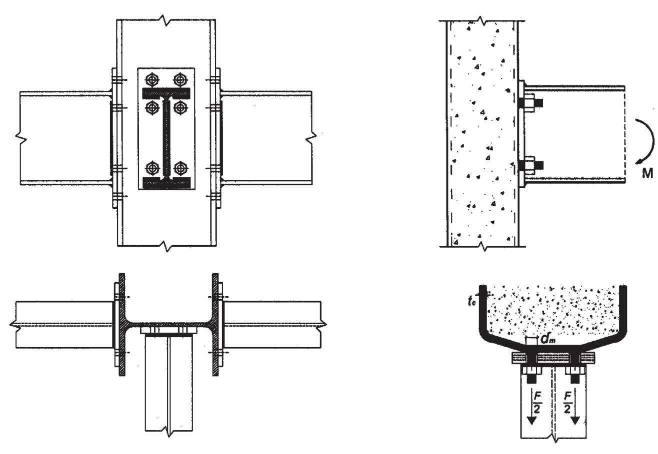

Fig. 1. W-shape weak axis and W-shape to HSS beam-to-column connections.

which are very common in European practice. Specifically, the manual will provide detailed design examples for a range of connections of both types, including different shapes (European designations H and IPE) and sizes in bolted and welded configurations.

In addition, the manual will provide the background information and procedures for connection and frame modeling, including classification according to the criteria for strength and stiffness that are specified by EC3. This is the approach that has been chosen by Eurocode 3 for the incorporation of semi-rigid (PR) concepts, the general applicability of which certainly is translatable to American conditions.

STRUCTURAL MEMBERS

Design of Cast Iron Columns, Including Tension Fracture Capacity: This study has been conducted by Professor Jacques Rondal of the University of Liège in Liège, Belgium, and Professor Kim Rasmussen of the University of Sydney in Sydney, Australia (Rondal and Rasmussen, 2005).

Cast iron columns were used extensively in structures in the 19th century, before the advent of the Bessemer process in steelmaking and the development of what today is considered as structural steel. A number of historical structures that are still in use today contain cast iron columns, and the aim of the study was to develop rational limit states evaluation criteria for such members. In particular, cast iron as a material has a tensile strength that is much lower than the compressive strength, and the modulus of elasticity is about 40 percent of that of today's steels. Further, the limit states criteria need to incorporate realistic measures of out-of-straightness, as well as the effects of a stress-strain relationship that is completely nonlinear.

Figure 2 shows a typical cast iron column cross section. For a variety of practical production reasons, the cross sections were tubular, and the wall thickness tended to vary significantly, especially as a result of the fact that the members were cast in the horizontal position. The criteria developed by Rondal and Rasmussen take these effects into account. They also observe that the initial out-of-straightness for a wide range of 19th-century wrought iron columns had a maximum value of $L/750$ and a mean of $L/1{,}500$, based on actual measurements (Salmon, 1921). By similarity in production techniques and fabrication tolerances, these data also apply to cast iron members. It is interesting and important to note that the $L/1{,}500$ value is what forms the basis for the AISC column design requirements of 2005, although these are based on research and were formulated for hot-rolled and welded built-up shapes in steels from the second half of the 20th century (Galambos, 1998).

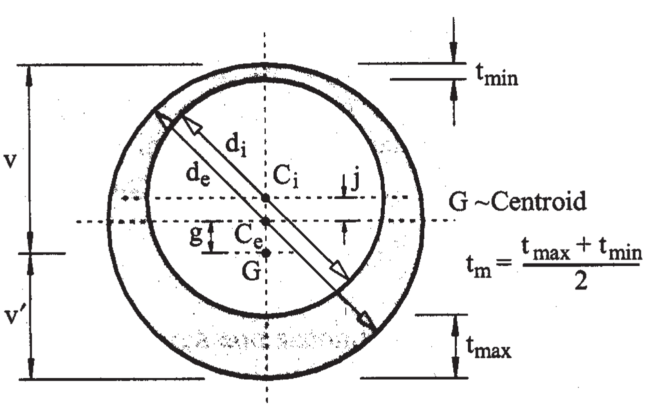

Fig. 2. Cast iron column cross section.

Because of the significant difference between the compressive and the tensile strength of cast iron, the design equations that have been developed take both limit states into account. The 300 19th-century column tests of Hodgkinson and Tetmayer were evaluated to provide the correlation to physical limit states as well as the criteria that were used at that time. The proposal gives equations that limit the strength on the basis of compressive and tensile strength, with no criteria that focus on slenderness limits. It is therefore a procedure that lends itself to evaluations under state-of-the-art limit state (LRFD) terms. No other approach is realistic for such members.

FABRICATION ISSUES

Cracking in Galvanized Steel Elements: This study has been conducted by Dr. Markus Feldmann at the Technical University of Aachen (RWTH Aachen) in Aachen, Germany (Feldmann, 2005).

Cracking in galvanized steel structures has been observed in the U.S. and other countries, and a number of studies have endeavored to resolve causes, effects, and remedies. Structural details that appear to present problems include copes in various forms, certain other connection areas and, in general, where significant changes in cross section occur. Originally it was surmised that hydrogen stress corrosion was the cause of the cracking, but it has now been determined that liquid metal embrittlement is the primary cause, as prompted by the zinc in the galvanizing bath.

Four parameters are the main indicators of galvanized steel cracking:

- Higher dipping speed into the galvanizing bath (higher speed appears to lower the incidence of cracking)
- Steel element geometry (stress concentration details; surface treatment; thinner plate and larger height create larger heat-induced stress gradients and hence higher probability of cracking)
- Heat transition coefficient (depends on zinc alloy details and flux)

- Material strength (it appears that higher steel strength may make the element more susceptible to cracking, although this is only a weak correlation, since residual stress due to rolling and welding is independent of material strength)

COMPOSITE STRUCTURES

Effective Width of Composite Girders with Reduced Height for the Calculation of Deflections: This project is being conducted at the University of Stuttgart in Stuttgart, Germany, with Professor Ulrike Kuhlmann as the director.

Shallow composite beams and girders are becoming the norm in many types of structures, especially when it is critical to reduce the floor-to-floor height. Traditional composite bending member analysis does not suffice under these conditions, since neither the bending moment capacity nor the bending stiffness of the slab are negligible. Further, for such members the slab will have cracked in the positive moment region at service loads. Figure 3 illustrates the stress resultants in a shallow composite beam, as well as the variation of the slab effective width for pure bending and pure membrane response. The membrane response is what is commonly used for composite beams today, and the corresponding effective width is a lower bound.

A series of shallow composite girder tests was conducted to examine the variability of the effective width and the deflection of the beams. It was found that

- Current codes give effective widths that are much smaller than actual conditions
- The effective width increases as the tensile strength of the concrete goes up
- The effective width increases with increasing slab width and thickness
- The effective width decreases as positive moment region slab cracking continues

Effective width criteria are very similar in the codes of various countries, and the effects outlined by the researchers are known in principle. For traditional (not shallow) composite beams the AISC Specification several years ago removed the effective width criterion that incorporated the slab thickness. However, the slab bending and therefore the thickness effect are much more important for shallow beams, especially with thick slabs. On the other hand, the correlation to concrete tensile strength is not very pronounced. Since the tensile strength of concrete is highly variable and difficult to determine, it is most likely that an effective width that incorporates this term will not prove practical.

Positive moment region slab cracking prompts a gradual reduction in the bending stiffness of the slab. This means that the effective width is reduced and eventually approximates that of the pure membrane condition. This is illustrated by the curve in the lefthand part of Figure 4.

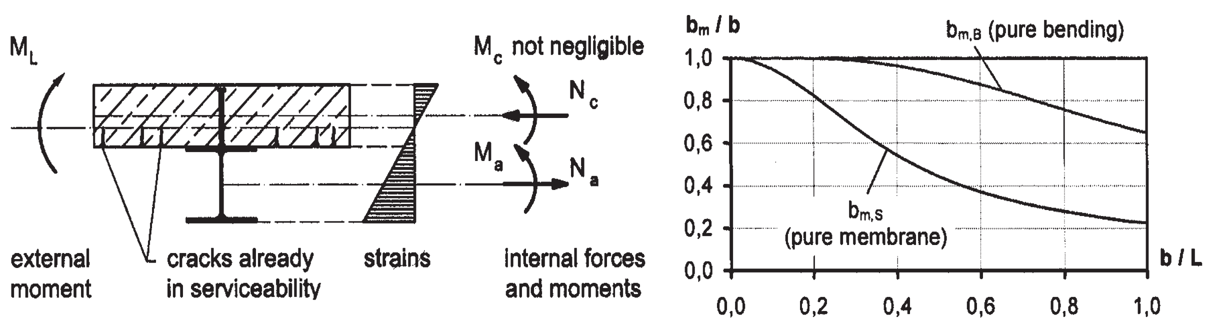

Fig. 3. Composite beam stress resultants and effective width variation.

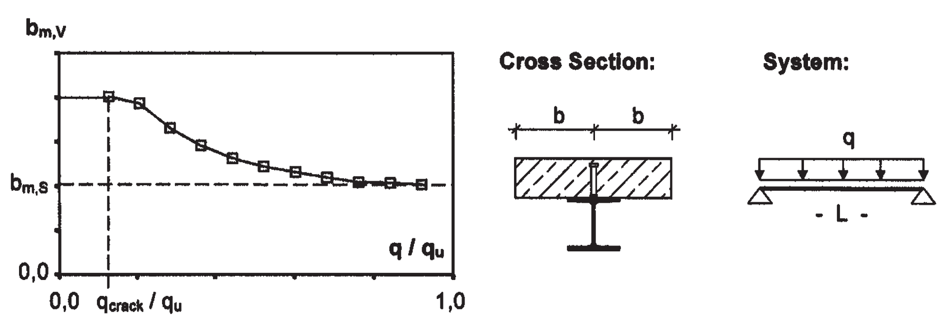

Fig. 4. Transition of effective slab width from bending to membrane condition.

The project eventually will provide a complete set of composite beam criteria that will benefit composite floor systems that make use of shallow beams with heavy slabs.

INDUSTRIAL STRUCTURES

Overhead Traveling Crane Support Structures: This study is under way at the University of Stellenbosch in Matieland, South Africa. Professors Peter Dunaiski and Johann Retief are the project leaders.

The project is a major research effort that involves full scale testing at the University of Stellenbosch and the development of an in-depth numerical model that incorporates the combined behavior of the crane and the supporting structure. For example, parameters such as the wheel spacing of the end carriage of the crane, the boundary conditions of the crane supporting columns and the stiffness of the portal frame are represented in the numerical model.

In a unique cooperative venture with industry, crane manufacturers and operators will provide field measurements on hoist loads for three representative crane types and support structures to assist in the development of a comprehensive reliability analysis. Statistical data and models for four classes of hoist loads have been developed, including arbitrary point-in-time and extreme value data. These are also being considered in combination with wind and roof loads. Finally, the reliability models examine ultimate and accidental limit states as well as fatigue for crane girders and columns, roof columns, roof trusses, and longitudinal crane bracing.

The project aims at providing improved load models for vertical, horizontal longitudinal, horizontal transverse loads, and accidental loads for crane structures in general. The approach and modeling will lend itself to application in many other areas of the world.

Storage Racks in Seismic Areas: This study is part of an extensive program that is funded by the European Union, to determine the strength, stiffness, and behavior of various structural systems for rack structures under seismic loads. The intent is to develop a seismic design code for such structures. The research work is being conducted in Italy (ACAI), Portugal (Technical University of Lisbon), Greece (National Technical University, Athens), and Belgium (University of Liège) and at the European Laboratory for Structural Assessment (ISPRA). Project directors are provided at each of the institutions. The Belgian project of the study is led by Dr. Hervé Degée and Professor René Maquoi at the University of Liège.

There is currently no design code for rack structures in Europe, similar to what is now known as the Eurocodes. In the United States the standard of the Rack Manufacturers Institute (RMI) has been used for many years; it has served as the model for such codes in several countries. The European project will address the conditions in the seismically active areas of the continent, including site-specific foundation and structural requirements.

BRIDGE STRUCTURES

Competitive Steel and Composite Bridges through Improved Steel-Plated Structures: This is a very major undertaking of the European Union, involving a total of nine research and industrial partners from Belgium, Germany, France, Spain, and Sweden. The Belgian project of the study is led by Dr. Hervé Degée and Professor René Maquoi at the University of Liège; it is carried out in collaboration with the Technical University of Aachen (RWTH Aachen) in Aachen, Germany, and the University of Luleå in Luleå, Sweden.

The project aims at developing bridge girder cross sections that have been optimized for efficient fabrication and erection procedures. One of the primary objectives is to reduce the number of stiffeners, since such elements increase fabrication costs and complicate structural assembly. Open and closed stiffener cross sections are being examined.

The influence of shear lag and longitudinal stress gradients also requires detailed study, since current design provisions offer three, not necessarily all practical, options for the bridge designer. Further, the present provisions in Eurocode 3 are based on column-like and plate-like limit states, using an interpolation procedure between the two models. It is not known which of the two models is the most realistic, and the project aims at resolving any uncertainties.

Finally, work is also being done to examine the behavior of longitudinally stiffened I- and box girders under shear. The intent is to include relevant torsional stiffness contributions of closed cross section web stiffeners and to examine the potential interaction with longitudinal stresses due to overall bending of the girder.

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