Current Steel Structures Research

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Sustainability has become a major world issue over the past few years. Due to the impact of the construction market on the gross domestic product (GDP)—approximately 12 to 13% for the United States—sustainability is becoming a key consideration in all architectural designs. By direct extension, this is now affecting the work of structural engineers in general, although much of the current influence is almost hidden among the many and complex issues of construction. Various rating schemes, such as the Leadership in Energy and Environmental Design (LEED) system in the United States, are used extensively to assess architectural and engineering designs; but, of course, the issue goes much beyond the efforts of the design profession, insofar as structures are concerned.

However, it is a fact that codes and standards will be significantly affected, and structural engineers need to recognize the importance of the subject and take a proactive role in the overall design process. Since steel is the most recycled of all materials, the industry and AISC alike have long recognized the critical nature of the subject and are on record as pursuing sustainability aggressively. Intensive research efforts are now under way in a number of countries, and it is already clear that construction techniques and materials are changing significantly to meet the needs of future societies. There is no question that steel and steel structures occupy a central and advantageous position in all of these undertakings.

A major international research and development effort on the part of the world steel industry is under way in several locales, and one of the projects reported in this paper reflects current European approaches and where the developments may lead. In many ways, the sustainability work is also tied to seismic research efforts, since such studies must take into account efficient construction techniques and economies, and that goes hand-in-hand with sustainability. A seismic study that is examined in this paper focuses on effective composite construction for members and frames, and another study looks at the development of novel and innovative fastening solutions for steel in combination with structures using other materials. Of course, bridges have major effects on local and regional communities, and two studies discussed in the paper examine the improvements that can be achieved by advanced load analyses as well as different structural systems and details.

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

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SUSTAINABILITY OF STEEL STRUCTURES

Sustainability of Steel Structures: This is a major, long-term project that is being conducted at the Institute for Sustainability and Innovation in Structural Engineering (ISISE) at the University of Coimbra in Coimbra, Portugal, with Professor Luis da Silva as the director.

In addition to the development of a sustainability assessment protocol for a variety of practical construction cases, the project aims at expanding, identifying and quantifying the influence of the following features (Gervásio, 2008):

- The key advantages of steel and steel construction
- Energy efficiency of steel production
- The effects of various structural and non-structural details
- The time needed for high-quality and safe fabrication and construction
- Functional requirements and potential changes over life cycle
- Construction material waste and recyclability
- Durability of steel, the life span of the structure, and the eventual rehabilitation or demolition

Construction provides approximately 7% of world employment and 28% of industry employment. At the same time, it is known that the construction industry consumes nearly 50% of all resources extracted from the earth, and a significant percentage of the total energy consumption and greenhouse gas emissions (GHG) (= CO_2) can be identified as related to construction. Construction and demolition waste account for a large percentage of the total waste, and it is especially high in wealthier nations.

It is recognized that the influence of several of the preceding features has been documented reasonably well, but not always in the context of steel construction. For example, addressing steelmaking by itself, it is essential to note the shift from basic oxygen furnaces (BOF) to electric arc furnaces (EAF) that has taken place in the United States over the past 20 years. Specifically, all American structural shape producers now use EAF and ladle metallurgy technology, along with continuous casting, to give the most efficient steel production in the world. In Europe and other areas of the world this is much less so, to the effect that BOF production is still used for approximately two-thirds of worldwide steel production.

Considering energy consumption and CO_2 emissions for BOF and EAF illustrates in part how far the industry has come. Based on data from the International Iron and Steel Institute (IISI), the energy consumption is reduced by 67% and the CO_2 emissions are reduced by 82% when the change is made from BOF to EAF. Further, another European research project is aiming at the development of steel production with ultra-low CO_2 emissions, with a reduction of 50% compared to the numbers of today.

The efficiency of steel construction is a major advantage, in terms of significantly reduced fabrication and construction time, construction site organization, high-quality workmanship, and reduced construction site waste. But the greatest advantages of steel for sustainability are the facts that

1. Steel is 100% recyclable.
2. EAF-based products are based on steel scrap rather than iron ore and coke, hence reducing the environmental and natural resource impacts of steel construction.
3. Steel has a high strength-to-weight ratio, for high construction efficiency.
4. Steel frames are highly adaptable to changes in functional requirements over the life span of the structure.

The current rating systems for steel structures, including the American-based LEED, all emphasize (1) materials and resources (MR) and (2) innovation and design processes (ID). In these respects, the MR advantages of steel as outlined earlier are very clear. For ID, the ability of steel to adapt to a variety of uses, including changes that are needed during the life cycle of the structure are major advantages. So is the use of cold-formed elements and pre-engineered buildings, as well as composite construction and other systems that make the most efficient use of different materials. And finally, the relative ease with which a steel structure can be taken down and the elements reused for other structures or simply recycled is a plus that does not enter into most considerations at the pre-construction stage.

In essence, therefore, the full sustainability capacity of structures can only be assessed realistically by considering the complete life cycle. As would be expected, the recommendations of the researchers focus on the eminent performance of steel in all elements of the life cycle analyses.

STRUCTURAL BEHAVIOR AND STRENGTH UNDER SEISMIC LOADS

Seismic Design and Analysis of Rectangular Concrete-Filled Steel Tube (RCFT) Members and Frames: This project is conducted at the University of Illinois at Urbana, with Professor Jerome F. Hajjar as the director. It has been funded by the National Science Foundation and the University of Minnesota (Tort and Hajjar, 2004, 2008).

The study aims at developing a performance-based design technique for structures with RCFT columns and steel girders and includes a reliability assessment procedure. The work is very advanced, specifically by incorporating two- and three-dimensional evaluations with seismic and nonseismic loads, as well as nonlinear time-history analyses. The mechanisms of load transfer and composite interaction have been examined in comparison with experimental data from other studies, and the correlation with the finite element formulation was found to be very good. Using the ground motions from a range of earthquake records, the researchers were able to establish realistic assessments of the progression of damage in a series of RCFT structures. This is critical for an eventual, practice-oriented, performance-based design approach.

It will be useful to see how these results compare to some previous studies of damage and damage accumulation in structures (for example, Bažant and Cedolin, 1991; Chi, Deierlein and Ingraffea, 2000). Extensive damage accumulation studies have been conducted at numerous locations, particularly in France by Lemaitre, Pijaudier-Cabot and others.

PERFORMANCE OF NOVEL FASTENING SYSTEMS

Market Opportunities for Innovative Fastening Solutions for Steel Structures: This is a major three-year (2007–2010) project undertaken jointly by three European universities and three European companies. Funding is provided by the Research Fund for Coal and Steel under the auspices of the European Union. The lead effort is taking place at the University of Stuttgart in Stuttgart, Germany, with Professor Ulrike Kuhlmann as the director. The other two universities are the Czech Technical University in Prague, the Czech Republic, and the University of Coimbra in Coimbra, Portugal.

The primary emphasis of the project is to provide fastening techniques and solutions for structures where reinforced concrete has been the traditional choice of material. Economical approaches focus on connections between steel elements and concrete structures, with the fairly large construction tolerances for the latter creating significant problems at the construction sites. Specifically, the connection details that are being developed provide for easy fabrication, quick and accurate erection in the structure, high load capacity, and sufficient ductility. The primary focus is on methods that can be readily adopted by practicing engineers. Two examples are shown in Figures 1 and 2, with steel beams attached to a concrete wall with simple and practical connections.

It is important and interesting to note that the European codes that address steel and concrete structures, EC3 and EC2, respectively, both have to accept the proposed solutions.

PERFORMANCE OF BRIDGE STRUCTURES

Size Effects in the Fatigue Behavior of Tubular Bridge Connections: This study is part of a major, long-term project that has been conducted at the Federal Institute of Technology (EPFL) in Lausanne, Switzerland, with Professors Alain Nussbaumer and Manfred Hirt as the directors.

Bridges such as the one shown in Figure 3 have become very common in Europe. This has happened in spite of the complex tubular connections, difficult welding fabrication, and fatigue considerations in design that require extremely detailed evaluations. But the elegance and simplicity of these solutions and the long-term successful construction and service record have made these structures into signature bridges.

One of the major considerations in the design of tubular bridges is the fatigue resistance and service life of the connections. Early studies found that connections for tubes with a larger wall thickness tended to fail earlier than small thickness members. This is referred to as the size effect, and a variety of solutions were developed over the years. Part of the problem was that very few studies of the size effect had actually been conducted. Even more troublesome is the fact that today's projects have typically been based on geometries that are typical for offshore structure, since bridges utilize entirely different sizes and geometries. This is especially the case for the lower chords of the tubular trusses. Further, many current design recommendations are based on the stress at the weld toe of the failing member, the so-called hot-spot, a number of which are illustrated in Figure 4. The hot-spot approach tends to be very punitive for the thicker wall tubes that are used in bridges. Finally, designs based on static loads produce member sizes that are outside the range of the current design recommendations.

The primary aim of the EPFL research project was to establish the fatigue behavior of K-joints with circular hollow sections (CHS) (Costa Borges, 2008). Specifically, the influences of the various geometric parameters on the fatigue strength had to be determined. To that end, a number of full-scale tests were conducted where crack depths were monitored and measured. An advanced three-dimensional crack propagation model was also developed to establish a broad base for the design criteria that would be forthcoming. The model was based on linear elastic fracture mechanics, using an incremental crack growth strategy.

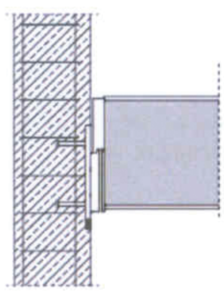

Fig. 1. Steel beam connected to concrete wall with anchor plate and shear studs.

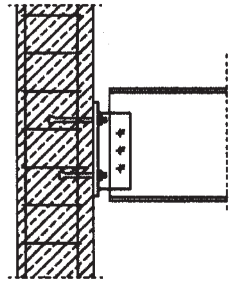

Fig. 2. Steel beam connected to concrete wall with anchor plate and shear tab.

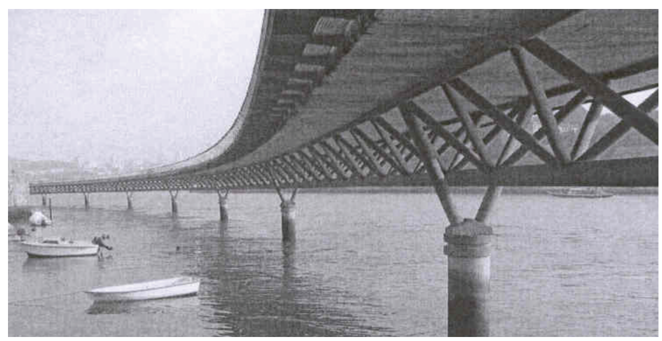

Fig. 3. The Cas das Piedras Bridge in Portugal (photograph courtesy of Alain Nussbaumer).

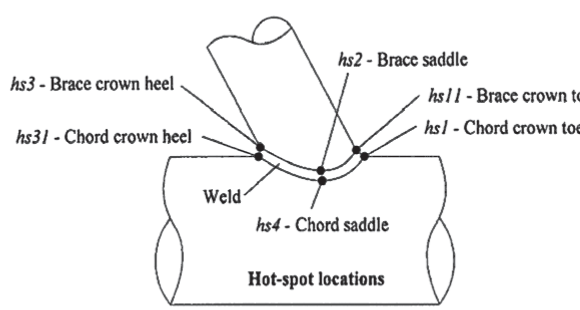

Fig. 4. Definitions of hot-spot locations for a tubular connection (courtesy of Alain Nussbaumer).

A full-blown parametric study was conducted, using typical bridge connection details and three basic load cases. Specifically, the connections had a low chord radius-to-wall thickness ratio. A geometry correction factor that is a function of the relative crack depth for such joints has been introduced, whereby the absolute size of the connection is accounted for. The absolute size of the joint is also known as the "size effect." Finally, the researchers have shown that the size correction factors for the fatigue strength can be expressed as a function of the non-dimensional geometric parameters, the chord wall thickness, and the load cases that have been used.

A Methodology for an Integral Life Cycle Analysis of Bridges in View of Sustainability: This study is currently going on at the Institute for Sustainability and Innovation in Structural Engineering at the University of Coimbra in Coimbra, Portugal. The project director is Professor Luis da Silva.

The study was started relatively recently, following the project that addresses sustainability for building structures, as reported earlier in this paper. The procedures are similar insofar as the steel is concerned; extensive simulation studies will be conducted to assess life cycle considerations and the factors that are unique to bridge structures. These will include risk analyses.

Finally, two case studies will be done, focusing on a composite highway bridge and a bridge with integral abutments.

Load Rating of Curved Composite Steel I-Girder Bridges through Load Testing with Heavy Trucks: This project has been conducted at the University of Minnesota, with financial support provided by the Minnesota Department of Transportation and the Center for Transportation Studies. Professor Jerome F. Hajjar directed the project.

Load rating of bridges is a major and very important effort on the part of all U.S. states, and the procedures for such ratings have been developed by the American Association for State Highway and Transportation Officials (AASHTO, 2003). The ratings are used extensively by transportation officials and the trucking industry. Curved girders are particularly difficult to rate under the current provisions, since these are based on straight-line girder evaluations with a correction factor for the curvature as well as a reduction of the flange yield stress. Improved methods that are based on grillage analyses have been developed, and these are now being applied to curved girders. The purpose of the analyses and the heavy truck testing of the project was to assess the accuracy of the grillage analysis and to develop rating procedure recommendations for these types of bridges (Krzmarzick and Hajjar, 2006).

Extensive parametric evaluations of a range of bridges and models were conducted, finding that the predicted bending stresses were very accurate, whereas warping normal stresses were less so, although still acceptable. The final rating recommendations include how to take composite action into account in the stiffness and stress computations, determining effective widths and modular ratios, and how to incorporate lateral bracing effects. Finally, work is continuing to develop rating procedures that can be used with and without load testing.

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