Current Steel Structures Research

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Structural steel research touches a number of closely related and sometimes maybe not so closely related subjects. For example, columns are connected to concrete footings by anchor rods, the joint action of which affect the response of the steel member and the steel frame. Steel beams may be connected to a concrete shear wall or to a glulam rafter, all of which require special considerations because of the use of significantly different materials. And the material response characteristics must be taken into account, both with respect to short- and long-term behavior aspects. Conditions such as humidity (for example) affects the steel for corrosion, but it may play a major role at all times during the service life of the structure, because wood and concrete both shrink and/or expand as a function of humidity. How do façade attachments influence the response of the spandrels or other steel members to which they are connected? What about the use of cold-formed steel elements or stainless steel? Standards are certainly available, but practical and intelligent designs go well beyond computations in accordance with structural code requirements.

The preceding observations reflect some real conditions for the constructed project, and the designers and fabricators and general contractors have to be able to address the diverse needs of the structure. And what must be done about loading conditions that come at the designer in literally hundreds of combinations? What about floor vibrations, which can be a serious issue, even though they may not endanger the stability or strength of the structure? What about roof deflections or strength needs under the conditions of ponding? Numerous questions of these kinds arise every year, and it is the engineer's responsibility to ensure that all realistic conditions have been addressed.

It is interesting and most useful to note that the Canadian Institute of Steel Construction (CISC) is currently undertaking an effort to examine the issues surrounding steel and other materials as used in combination in buildings. The first two articles have been published (Leckie, 2007a, 2007b); the third will appear in 2008. Design and construction practices in Canada are extremely similar to what is used in the United States, and American practitioners will clearly benefit from these evaluations.

The findings that are presented in this paper reflect a broad range of state-of-the-art work. A recent project in Spain is one of the first to examine the tested behavior of two-dimensional (2D) versus three-dimensional (3D) connections and how they compare and influence each other. A Canadian study focuses on connections to rectangular hollow sections (RHS), using various plate attachments. An unusual project in Finland examines a novel approach to optimization of steel beam design, attempting to cover all feasible parameter ranges and limit states. Fatigue in tubular structures is a major, long-term effort in Switzerland, as part of an intensive bridge design and construction program. The study discussed here examines micro- and macro-structural size effects. Orthotropic bridge decks are used extensively in Europe; the French "Orthoplus Project" applies advanced concepts to these types of bridge decks, including surfacing solutions. Finally, a multi-year major effort in the Netherlands dealing with the numerous issues of ponding of roof structures has come to fruition, and a detailed analysis and design report has now been published.

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.

CONNECTION BEHAVIOR AND STRENGTH

Three-Dimensional Behavior of Semi-Rigid Connections: This project has been conducted at the University of Navarra in Pamplona, Spain, with Professor Eduardo Bayo as the director (Cabrero and Bayo, 2007a, 2007b).

The most common approach to steel frame analysis and design is based on planar (2D) modeling, although realistic assessments should reflect 3D behavior. Further, most, if not all connections are semi-rigid (Type PR), and the effect on frame response can be significant. Unfortunately, most analyses have focused on 2D behavior with perfectly pinned or rigid connections, and almost all physical tests have been conducted in various forms of 2D representation.

Using extended end-plate beam-to-column connections for the strong as well as the weak axis of the column, Figure 1 shows the test specimen that was developed by the researchers in collaboration with several fabricators. The joints into the column are all bolted, but the end plates are welded to the beam ends. It is noted that the weak-axis connection is

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not framed into the column web, but rather to plates that are welded to the column flange tips. The researchers observe that this solution means that the weak- and strong-axis connections will not interact, and the design can therefore be done individually for the connections. Finally, the weak axis plates are partial end plates, as can be seen in Figure 1. This was done to allow for easier tightening of the bolts.

The member dimensions are somewhat smaller than what is typical North American practice. The column shape for all specimens was an HEB 160 (160 mm = 5½ in. deep). The *x*-axis beam was an IPE 330 (330 mm = 13 in. deep); the *y*-axis beam was an IPE 240 (240 mm = 9½ in. deep). The shape steel grade was S350 (yield stress 350 MPa = 50 ksi); all plate material was grade S275 (yield stress 275 MPa = 40 ksi). Two end plate thicknesses were used: 16 mm (⅝ in.) and 10 mm (⅜ in.).

Figure 2 shows two of the connections following testing, with the one on the left having the thicker (16 mm) end plates and the one on the right with the thinner (10 mm) plates.

As would be expected, the connection strengths and stiffnesses were reduced when the smaller end plate thickness was used. Interestingly, the connections in both axes exhibited higher initial stiffness when 3D proportional loading was applied, meaning that there is a certain amount of coupling effects between the *x*- and *y*-directions. The stiffness increase due to coupling was about 15% for the *x*-axis connections; it was 8 to 23% for the *y*-axis connections.

The project has also provided an analytical component model for these connections, in line with the typical approach of Eurocode 3 (CEN, 2005). An extensive parametric study used a finite element evaluation with different loading conditions and geometric configurations, giving good correlation with the experimental results.

Behavior of Longitudinal Double Plates-to-RHS Connections: This project has been conducted at the University of British Columbia in Vancouver, BC, Canada, with Professor Siegfrid Stiemer as the director.

The aim of the project has been to evaluate the response characteristics of T-connections with longitudinal double plates connected to a rectangular hollow structural section. Seven double-plate and two single-plate connections were tested in a setup as shown in Figure 3. The primary test parameters were (1) the ratio of the width of the plates to the width of the RHS and (2) the type or number of plates.

As expected, the strength of the double-plate connection increased as the spacing between the plates was increased, and the double-plate connection had higher strength than the design using single plates with the same plate area. This is attributed to the fact that the width ratio for the double-plate connections is larger than that of the single-plate case. Further, the double plates are welded to the RHS in locations where the stiffness is greater than at the centerline of the section.

Yield-line analyses were performed for different locations of the plastic hinges that typically developed in the RHS, including in the wall next to the plate fillet welds and close to the corner radius. An example of such plastic hinge locations is shown in Figure 4. The connection strengths predicted by the yield-line model are in good agreement with the experimental data.

Continuing project work will address the effect of a range of width-to-thickness ratios for the main chord, and for double-plate connection width ratios larger than 0.80.

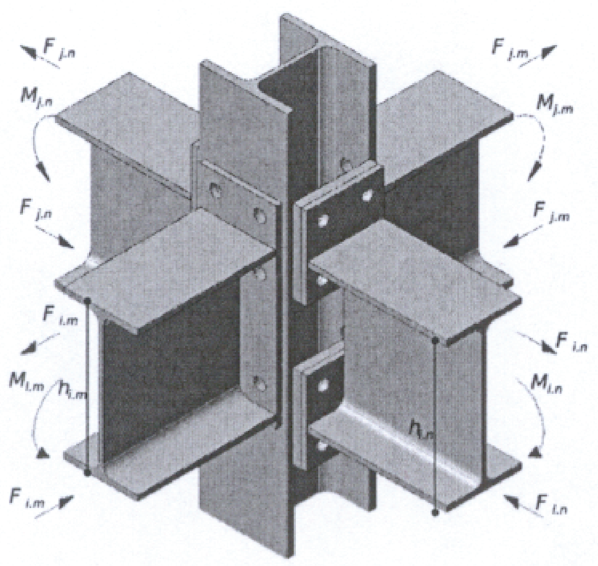

Fig. 1. Three-dimensional type PR connection (figure courtesy of Eduardo Bayo).

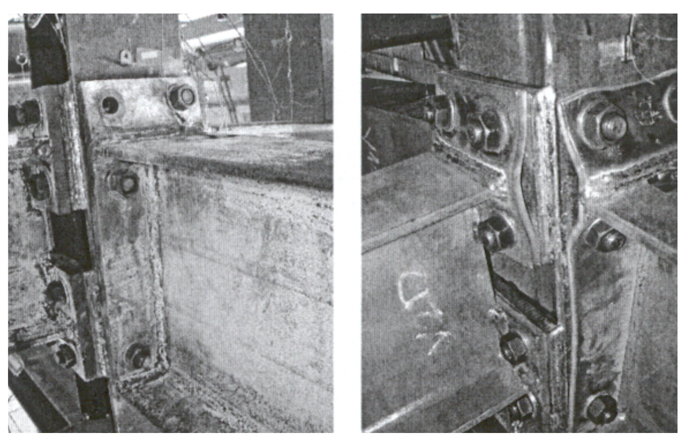

Fig. 2. Two specimens after testing (photo courtesy of Eduardo Bayo).

OPTIMIZATION OF WELDED BUILT-UP BEAM DESIGN

Welded Steel Beam Design Using Particle Swarm Analysis: This research project has been conducted at Tampere University in Tampere, Finland, in collaboration with Cardiff University in Cardiff, United Kingdom, as well as with two Finnish companies. Professor Markku Heinisuo has been the project director.

Particle swarm analysis or particle swarm optimization (PSO) is a relatively new approach to optimization, which has not found many applications in engineering at this time. However, it offers significant potential for analysis and design situations where there are a great many variables that control the final solution. Part of the problem is clearly that although it is feasible to arrive at acceptable solutions in terms of engineering theory, practice-oriented designs may not have come from the PSO algorithm.

The researchers first solved a carefully structured example, using a comprehensive search. On this basis the optimum design solution was found *a priori*, with the aim of examining the PSO approach through a scientifically valid test. At this stage of the research work it is noted that PSO does not perform well unless it is used as part of a multilayer procedure.

The study will be expanded to include comprehensive structural and fabrication features, as well as parameters that reflect design, transportation, erection, building use, life cycle costs and other relevant issues. The focus will be on the development of efficient search engines that can handle extremely large numbers of variables. Only time can tell whether the PSO approach will produce solutions that can be used in practice.

CONSTRUCTION AND PERFORMANCE OF BRIDGE STRUCTURES

Modeling of Micro- and Macro-Structural Size Effects for Fatigue of Welded Tubular Structures: This project reflects part of a major, long-time effort that has been carried out at the Federal Polytechnic University of Lausanne (EPFL) in Lausanne, Switzerland, under the direction of Professor Manfred Hirt and Senior Scientist Dr. Alain Nussbaumer.

The focus of this study has been the development of an accurate probabilistic fatigue crack growth model for tubular joints, and large-scale fatigue tests of relevant tubular connections with multiple possible crack sites have also been conducted (Walbridge and Nussbaumer, 2008). A novel approach to crack monitoring has been utilized—the researchers believe it is the first time it has been applied to a large-scale tubular truss beam. The method is known as the alternative current potential drop (ACDP), and it has proven to be very accurate and efficient. Fatigue cracks were found both in tension chords as well as in compression joints, and residual stresses were therefore incorporated into the ABAQUS finite element model. The approach also included sizing effects for different geometric parameters, to arrive at suitable stress intensity factors for different basic load cases. Further, proportional and nonproportional sizing effects were developed from the experimental database.

The research work is continuing, and emphasis will now be placed on various residual stress (RS) effects. This will include RS measurements on tubular truss beams and will

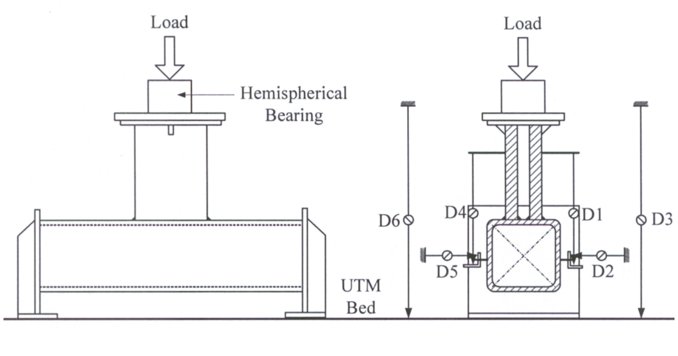

Fig. 3. Double plates to RHS connection test setup (figure courtesy of Siegfrid Stiemer).

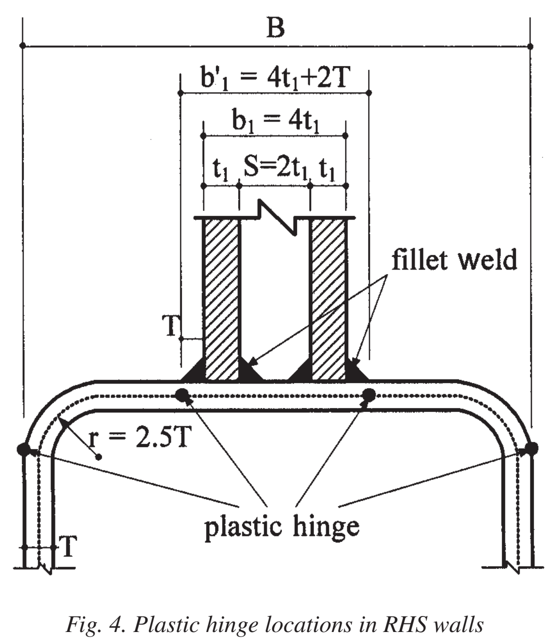

Fig. 4. Plastic hinge locations in RHS walls (figure courtesy of Siegfrid Stiemer).

eventually be extended to incorporate welding and post-weld treatment influences, to allow for scaling effects. It is expected that the design of a wide range of tubular structures will be significantly enhanced as a result of this project.

Advanced Engineering for Orthotropic Bridge Decks and Surfacing Solutions: This is a three-year research project now under way in France, known by the name Orthoplus. It is funded by the French national research agency (ANR) and involves efforts by seven public and private partners. The project director is Dr. Claude Le Quéré of the bridge organization Sétra.

The primary aim of Orthoplus is to provide criteria for the optimization of the design of orthotropic bridge decks (Le Quéré, 2007). Figure 5 shows a typical example from such decks, using the solution that was utilized for the famous bridge Viaduc de Millau south of Clermont-Ferrand. The modeling includes the composite action of the surface layer of the deck as well as the steel deck plate, including the fatigue mechanism in the steel plate.

New orthotropic plate theoretical approaches will be developed, along with tools of analysis that will give practical and realistic assessments of the duration (life) of the deck. The methodology will incorporate the influence of the type and thickness of the surfacing material.

PONDING OF ROOF STRUCTURES

Ponding of rain water can be a major problem for flat or near-flat roof structures (or even not so flat roofs if the drains are clogged), and most design codes include some form of criteria for the analysis and design for such loads. Appendix 2 of the AISC *Specification for Structural Steel Buildings* contains simplified and more advanced recommendations for ponding (AISC, 2005). The basis for these criteria were developed by Marino (1966), and they have functioned adequately since their introduction in the late 1960s.

However, work at Delft University of Technology in Delft, the Netherlands, has resulted in a major report with case studies, failure analyses, and recommendations for improved design checks and methods of evaluation. The 200-page report has been published as part of the university's long-standing HERON report series (Heron, 2006), and it contains analyses and practical design suggestions on the following subjects:

- "Roof failures due to ponding—a symptom of underestimated development," by J.N.J.A. Vambersky
- "Ponding collapse analyses of light weight roof structures by water raising capacity," by S.N.M. Wijte
- "Structural design for ponding of rainwater on roof structures," by F. van Herwijnen, H.H. Snijder and H.J. Fijneman
- "Ponding on flat roofs: a different perspective," by J. Blaauwendraad
- "Evaluation of ponding analysis methods using 3-D finite element modeling," by A. Schouten, J. Locht and J.P.B.N. Derks

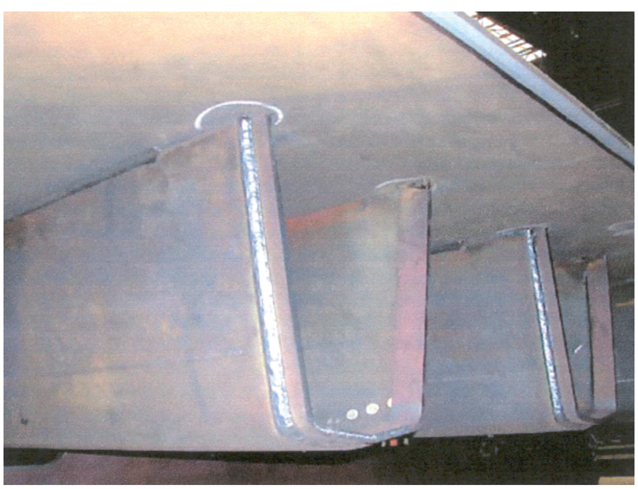

Fig. 5. Troughs of the deck of the Viaduc de Millau (photo courtesy of André Colson).

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