Current Steel Structures Research

No. 25

REIDAR BJORHOVDE

This issue of the *Engineering Journal* focuses on a selection of current research projects at a number of Canadian universities. The descriptions will not discuss all of the current projects at the schools. Instead, selected studies give a representative picture of the research efforts and demonstrate the importance of the schools to the efforts of industry and the profession. The close relations between AISC and CISC, the Canadian Institute of Steel Construction, have provided significant benefits to researchers, designers and industry on both sides of the border. The standards for materials, design and fabrication of both countries reflect mutual accomplishments that have offered benefits to all.

The universities and many of their structural steel researchers are very well known in the world of steel construction: University of Toronto, University of Waterloo, University of Ottawa, Dalhousie University in Halifax and Carleton University in Ottawa. Some of the many projects at the University of Alberta were discussed in the "Current Steel Structures Research" paper that was published in the second quarter 2010 issue of the *Engineering Journal* (Bjorhovde, 2010). Some of the ongoing work at the University of British Columbia will be featured in a future paper. For example, a project directed by Professor Siegfried Stiemer is providing novel approaches to the performance considerations for hybrid structures. The work at École Polytechnique in Montreal, whose leading steel researcher is Professor Robert Tremblay, will also be discussed in a future paper. Professor Tremblay has played a significant role in the understanding and development of seismic design criteria for braced frames in Canada as well as the United States.

All of the projects presented in this paper are funded in full or in part by the Steel Structures Education Foundation (SSEF) of Canada.

In true forward-looking fashion, the researchers at the institutions that are featured here have been active for many years, as evidenced by their participation and leading roles in the design standards development efforts of Canada and the United States and many other countries. Large numbers of technical papers, reports and conference presentations have been published, contributing to a collection of studies that continue to offer practical solutions to complex problems for designers as well as fabricators and erectors.

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

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF TORONTO

Over the years, the University of Toronto has been a leader in many areas of structural engineering research. For steel construction, the principal contributors have been Professors Peter Birkemoe and Jeffrey Packer, with studies that have included innovative solutions to the strength, behavior and design of connections of various kinds, column strength and stability, and the behavior of structures subjected to high-energy loading conditions.

The famous study of Birkemoe and Gilmor on block shear (1978) defined a new and very important limit state; the subject has since been examined by a large number of researchers in various locales around the world. The recent work of Professor Packer on the strength and performance of certain cast steel connections has offered a novel solution to some of the complex problems associated with braced frames and the gusset plates that are the most typical for such frames. This was discussed in some detail in the "Current Steel Structures Research" paper that was published in the fourth quarter 2008 issue of the *Engineering Journal* (Bjorhovde, 2008).

Among the best known of the research work at the University of Toronto has been the extensive and long-term research efforts of Professor Packer on the strength and behavior of a great variety of connections for hollow structural sections. The results and recommendations have been adopted in numerous design specifications around the world, included in several editions of the AISC *Specification* (Packer et al., 2010).

Elliptical Hollow Structural Sections (EHSS): Studies have been under way for some time at the University of Toronto to develop member and connection characteristics for elliptical shapes. Professor Packer is the project director.

Reidar Bjorhovde, Dr.-Ing., Ph.D., P.E., Research Editor of the *Engineering Journal.* Tucson, AZ. Email: rbj@bjorhovde.com

Starting with round hollow structural sections (RHSS), square and rectangular sections (RHSS) were developed and, eventually, elliptical sections (EHSS). EHSS shapes have been produced in Europe since 1994; there is currently no producer of these sections in North America, although the material meets the 2007 requirements of ASTM A501 Grade B. Cross-sectional properties of a variety of sections have been developed, using an equivalent circular shape approach (Packer, 2009). Typical dimensions generally have major-to-minor axis ratios of 2:1.

Architecturally, the elliptical sections offer certain advantages, and originally they were used for the supporting framework for a number of glass roofs and façades. They would usually be placed such that the narrow view of the member would be visible through the glass. This was the preferred orientation for the architectural solution.

Stub column tests have shown that the failure mode of EHSS members is much more like plate buckling than cylinder buckling. Such results were used by the Toronto team to develop criteria for an equivalent RHSS rather than a CHSS cross section. Further evaluations will be made to provide improved strength data for design.

At this time, various EHSS-to-EHSS connections are being examined, through analyses and tests. An example is shown in Figure 1.

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF WATERLOO

Steel-Precast Concrete Composite Girders with Nonconventional Shear Connectors: This project has been directed by Professors Scott Walbridge and Jeffrey West.

This project was undertaken in an effort to solve the issues associated with the use of precast deck panels for steel bridges, where the concrete deck has deteriorated sufficiently to warrant replacement, and also for certain temporary bridges. The original designs had been based on composite action; the solution required composite action between the precast panels and the steel girders. One study focused on the use of high-strength bolts as shear connectors (Iszauk and Bjorhovde, 2002); other solutions examined various other shear connection solutions (Thomann and Lebet, 2007).

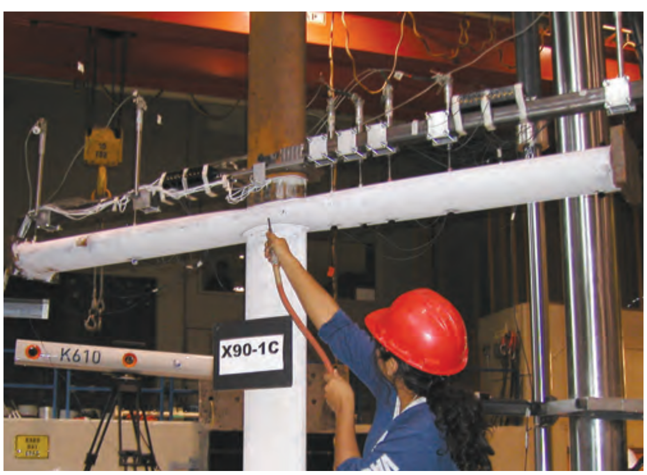


Fig. 1. Test of an elliptical HSS connection (courtesy of Professor J.A. Packer).

Two shear connection approaches were developed for the project, as follows:

1. Using post-installed shear connectors with bearing or slip-critical connections combined with various friction-enhanced surfaces (Kwon et al., 2010).

2. Using discrete stiffened bearing plates at the ends of the precast panels.

Both of these approaches were designed *not* to rely on field grouting to achieve the composite action.

For the first approach, small-scale push-out tests with various configurations of connector placement were used, along with finite element analyses. Design recommendations for this procedure are being developed. The second approach was specifically developed for various applications with remote location bridges, including varying discrete shear connector spacing and bridge dimensions. A finite element modeling procedure has been developed for this approach. Figures 2 and 3 illustrate the details of the shear connector systems.

Predicting the Effect of Post-Weld Treatment Applied under Load: This project has been directed by Professor Scott Walbridge.

Various techniques of post-weld treatment have been examined by a number of researchers, designers and fabricators with the goal of improving the fatigue life of welded bridge structures that are currently in service. One of the most important methods involves reducing the tensile residual stress that is found in the vicinity of the toe of fillet welds, or even to change this stress from tension to compression. This will reduce or arrest the growth of small fatigue cracks. The most common approach to reducing the tensile residual stress is to use peening of some sort, such as needle peening, hammer peening or ultrasonic peening.

A number of small-scale fatigue tests were run (where the specimens were first prestressed) to simulate the tensile stresses due to the dead load. The specimens were then needle peened. The propagation (depth) of the cracks was monitored by several techniques, including microhardness measurements. The results were then used to validate the assumptions used in the fracture mechanics analysis, based on linear elastic and strain-based models.

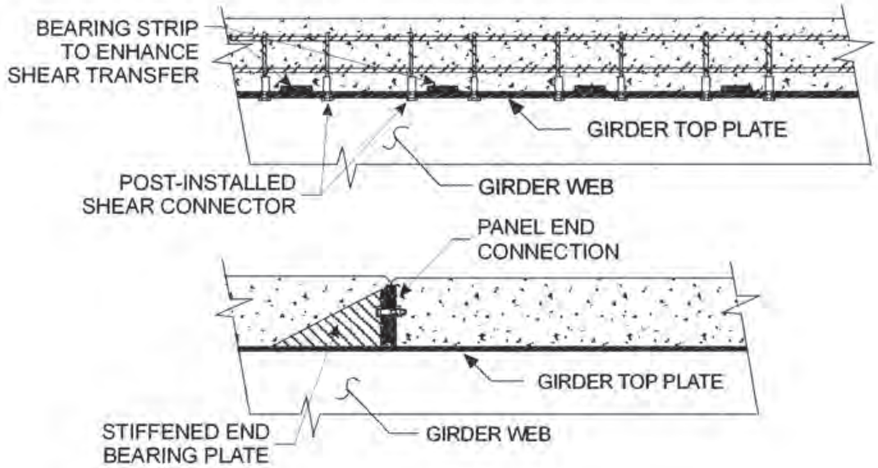


Fig. 2. Shear connection with post-installed shear connectors (top) and stiffened end bearing plate (bottom) (courtesy of Professor Scott Walbridge).

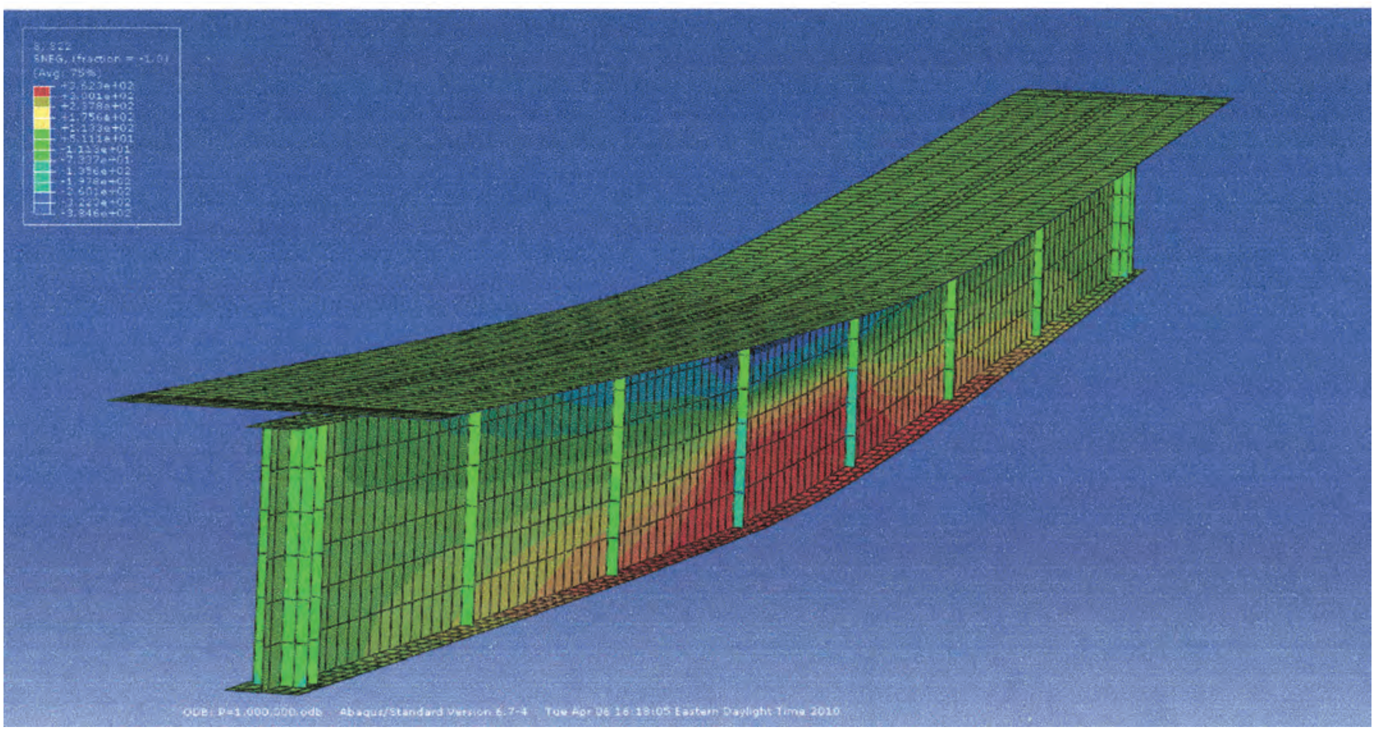


Fig. 3. Finite element stress image for girder with discrete shear connections (courtesy of Professor Scott Walbridge).

The following findings have been reported by the researchers (Ghahremani and Walbridge, 2010):

1. Needle peening can produce significant increases in the fatigue life of welds. For a given stress range, a category C detail will have a fatigue life equal to or greater than a category B detail when it has been normally peened. The fatigue life will be even larger than that of a category A detail when the peening has been applied under load.
2. Laboratory measurements of crack growth, microhardness and microstructure analysis show that the needle peening will have favorable effects up to a depth of 0.5 to 1.0 mm (0.02 to 0.04 in.) below the weld surface.
3. The fracture mechanics models provide very good data for the fatigue lives of untreated welds and treated welds for a variety of prestressing levels.

Some of the fatigue test results are illustrated in Figure 4, along with the requirements of the Canadian steel bridge design standard CSA-S6.

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF OTTAWA

Full-Scale Testing of Gerber Frames: The project director for this study has been Professor Magdi Mohareb.

As illustrated in Figures 5 and 6, the project aims at determining the effects of the load distribution and the lateral support conditions for seven full-scale, so-called Gerber-type steel frames. This framing system is economical and very common for one-story commercial buildings in Canada. Specifically, the overhang of the roof girders (see Figure 5) is approximately 20 to 30% of the span, and the beams ("drop-in beams") for the main span are simply supported from the cantilevered overhangs (Kulak and Gilmor, 1998).

For the seven test specimens, the bracing conditions were as follows:

1. Four did not have any lateral bracing.
2. One specimen had open web steel joists at the tops of the columns as well as five uniformly spaced joists that were connected to the top flange of the beam.

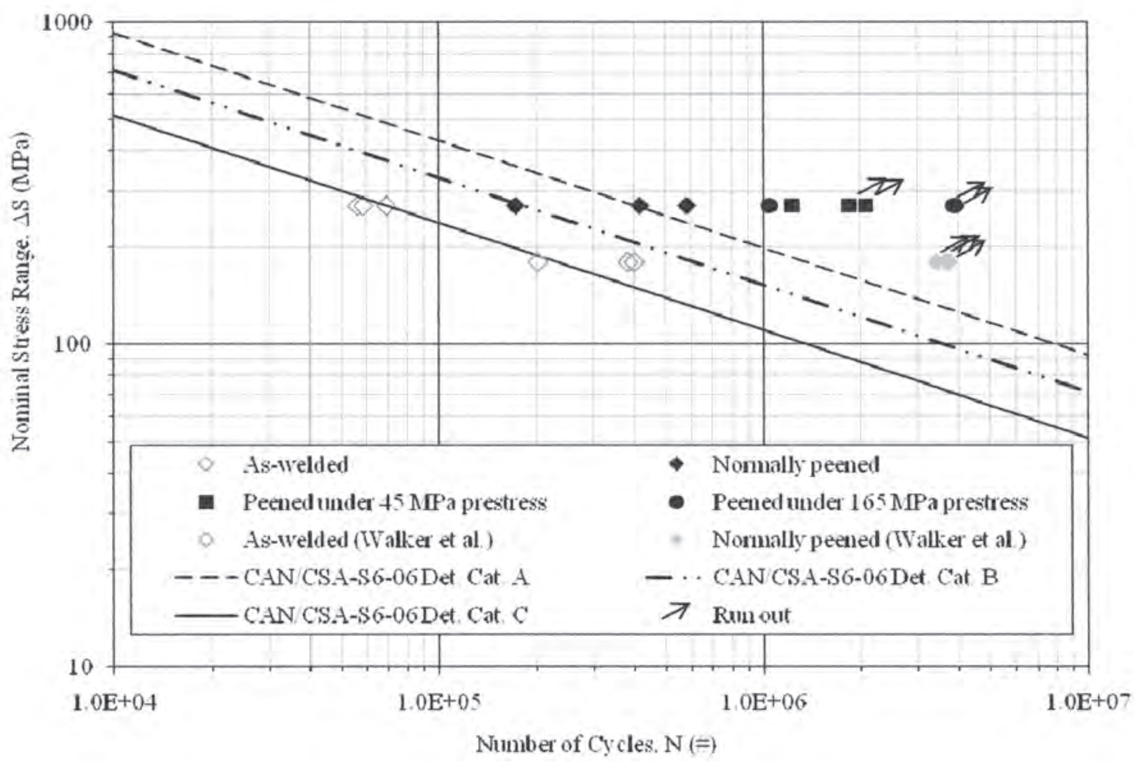


Fig. 4. Fatigue test results for peened welds and comparison with the criteria of CSA-S6 (courtesy of Professor Scott Walbridge).

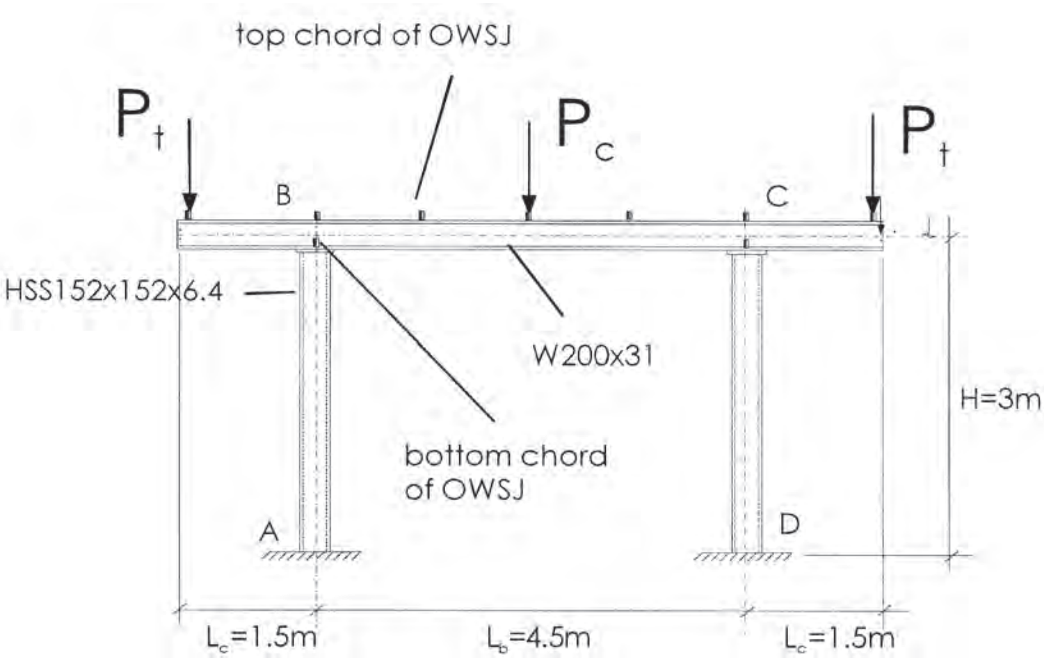


Fig. 5. Configuration of Gerber test frame specimen (courtesy of Professor Magdi Mohareb).

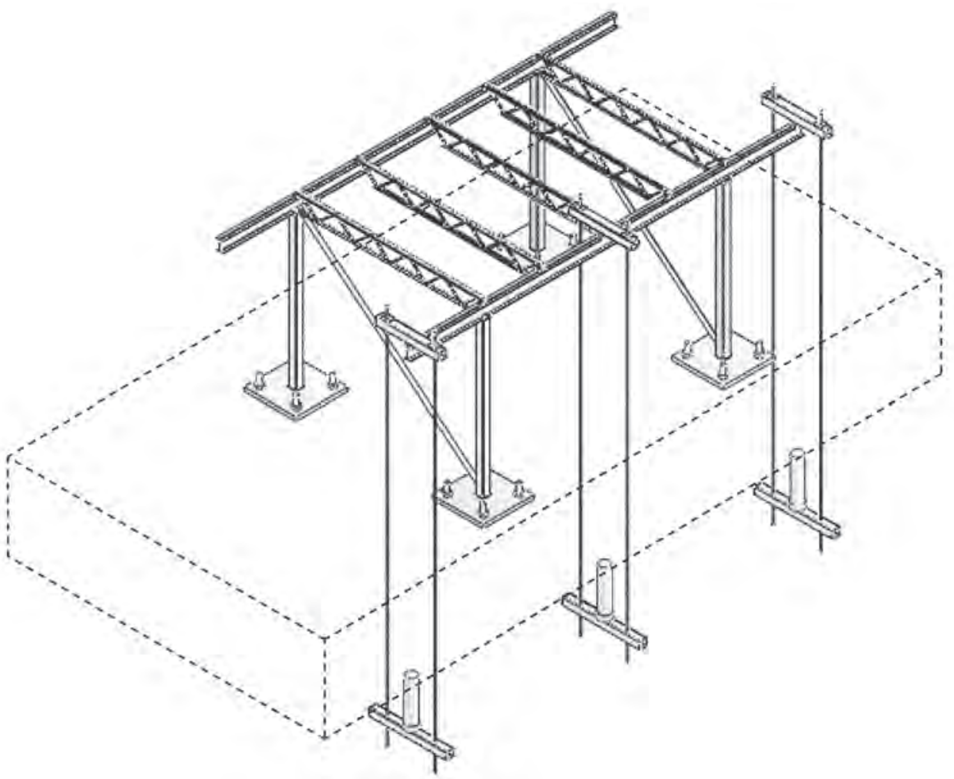


Fig. 6. Gerber test frames and load application system (courtesy of Professor Magdi Mohareb).

3. One specimen had open web steel joists at the tops of the columns (points B and C).

4. One specimen had columns laterally restrained at B and C.

The overhang tip load was P for frames 1, 2, 5, 6 and 7; 0 for frame 3; and $0.25P$ for frame 4. The beam midspan loads were P for all frames, except frame 2, for which it was 0.

In addition to the full-scale physical tests, finite element models were developed for the frames. At this time, six of the tests have been concluded; the test results and the predicted capacities agree to within 2 to 10%.

SOME CURRENT RESEARCH WORK AT DALHOUSIE UNIVERSITY, HALIFAX, NOVA SCOTIA

Behavior and Design of Steel Single-Angle Beam-Columns: This project has been directed by Professor Yi Liu.

In view of the fact that the current beam-column criteria for single angles is based on what was developed for doubly symmetric shapes, this study aims at providing requirements that reflect the unique characteristics of single-angle members. In particular, significant differences have been observed between tested capacities and the largely conservative strengths prescribed by the AISC and the CSA code values.

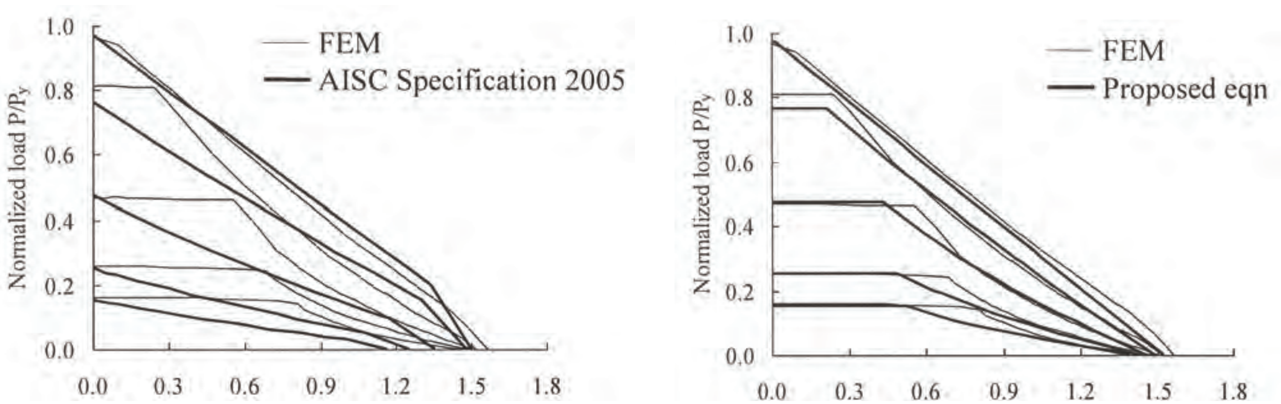
A total of 52 equal- and unequal-legged, single-angle columns were tested, using loads applied with various eccentricities. A finite element model was developed for a comprehensive parametric evaluation, taking into account practical design considerations. Following the initial evaluations, a new concept—in the form of a critical eccentricity—was developed and entered into the formulation of an improved design equation. This allowed for the determination of the various sources of the conservatism of the American and the Canadian single-angle criteria and also showed the somewhat unconservative design capacities for several cases.

Details of the proposed single-angle equation continue to be examined for eventual presentation to the specification committees. In the meantime, Figures 7a and 7b show the comparison between the finite element results and the current AISC criteria, as well as the comparison between the finite element results and the proposed single-angle equation. The horizontal axes denote the values of the normalized moment, M/M_y.

Strengthening of Steel Beams under Load: This project has been directed by Professor Yi Liu.

It is interesting to note that Professor Liu makes the observation that there is very little experimental and analytical research that addresses strengthening of beams while in service. Largely, that is correct, but there are certainly a number of important studies that deal with the subject (Nagaraja Rao and Tall, 1963; Ricker, 1988; Tide, 1990). Nevertheless, these issues are very important to designers, fabricators and contractors, and clear guidance needs to be offered. The key problems are related to the residual stresses that will be introduced during the strengthening operation, as well as the preload from the service operations of the structure.

The experimental segment of the research project used nine steel W12×19 beams with three types of reinforcing plates, as shown in Figure 8. The shapes were tested in flexure, while the reinforcing plates were welded to the beam at different preload levels. Three strengthening patterns and two beam lengths were used, and the residual stress distributions for each were measured. A numerical model was also developed. It was found that strengthening under load had a significant effect on beams that failed in lateral-torsional



(*a*) (*b*)

Fig. 7. Comparison of finite element predictions and the capacities predicted by (a) the AISC Specification *(2005) and (b) the proposed single-angle equation (courtesy of Professor Yi Liu).*

buckling. The effects can be offset by providing lateral restraints along the length of the beam, reducing the detrimental effect of the welding residual stress and the distortion that often accompanies the welding under such conditions.

SOME CURRENT RESEARCH WORK AT CARLETON UNIVERSITY, OTTAWA, ONTARIO

Structural Performance of HSS Steel Frame Assemblies with Moment Connections in Fire: This project has been directed by Professor G. Hadjisophocleous.

Recognizing the increasing use of hollow structural sections for columns and even beams in steel structures, the project aims to test a total of 10 beam-to-column connections in the new fire test laboratory of Carleton University. For several reasons, it was decided to use end-plate connections for the test specimens, examining the influence of the thickness of the end plate, the degree of axial restraint of the beam and the beam cross-sectional properties. Further, an extended end-plate connection that is expected to perform better under elevated temperatures will also be tested.

Fig. 8. Placement of reinforcing plates for W*12 × 19 beams to be tested under load (courtesy of Professor Yi Liu).*

Figure 9 shows the appearance of two of the connections after the fire test. As expected, the one with the thinner (½ in.) end plate responds significantly different than the one with the thicker (¾ in.) end plate. Specifically, for the thinner case the rotations are largely provided by the deformations of the plate. For the connection with the thicker end plate, the deformations are provided through deformations of the column, where it appears that a plastic hinge has formed. This may not be advantageous for the overall response of the structure, but the issues continue to be studied.

REFERENCES

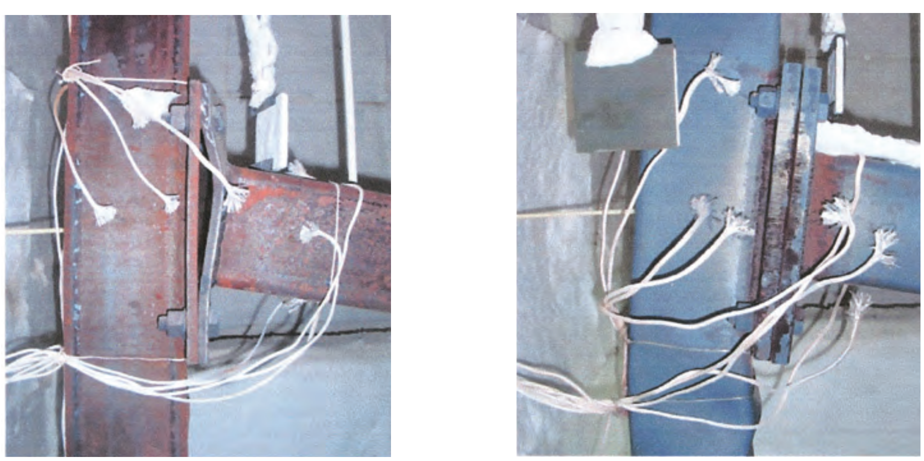
Birkemoe, P.C. and Gilmor, M.I. (1978), "Behavior of Bearing-Critical Double-Angle Beam Connections," *Engineering Journal*, AISC, Vol. 15, 4th Quarter, pp. 109–115.

Bjorhovde, R. (2008), "Current Steel Structures Research," *Engineering Journal*, AISC, Vol. 45, 4th Quarter, pp. 287–292.

Bjorhovde, R. (2010), "Current Steel Structures Research," *Engineering Journal*, AISC, Vol. 47, 2nd Quarter, pp. 123–130.

Ghahremani, K. and Walbridge, S. (2010), "Predicting the Effect of Peening Treatments Applied under Load on the Fatigue Performance of Welds in Existing Steel Bridges," *Proceedings, 8th International Conference on Short and Medium Span Bridges*, Niagara Falls, Canada.

Iszauk, S.I. and Bjorhovde, R. (2002), "High Strength Bolts as Shear Connectors: Composite Steel Girders with Precast Bridge Deck," *Proceedings, FHWA Steel Bridge Conference*, Salt Lake City, UT, December 13–15.



(*a*) (*b*)

*Fig. 9. Deformations of two HSS end-plate beam-to-column connections after fire tests: (a) test 1 end plate (*t = ½ *in.); (b) test 2 end plate (*t = ¾ *in.) (courtesy of Professor G. Hadjisophocleous).*

Kulak, G.L. and Gilmor, M.I. (1998), *Limit States Design in Structural Steel*, 6th ed., Canadian Institute of Steel Construction, Toronto, ON, Canada.

Kwon, G., Engelhardt, M.D. and Klingner, R.E. (2010), "Behavior of Post-Installed Shear Connectors under Static and Fatigue Loading," *Journal of Constructional Steel Research*, Vol. 66, No. 4, pp. 532–541.

Nagaraja Rao, N.R. and Tall, L. (1963), "Columns Reinforced under Load," *Welding Journal*, Vol. 42, April, p. 177-s.

Packer, J.A. (2009), "Elliptical Sections—Part Two: EHS Member Design," *Advantage Steel*, Canadian Institute of Steel Construction, Toronto, ON, Canada.

Packer, J.A., Sherman, D.R. and Lecce, M. (2010), *Design Guide No. 24, Hollow Structural Section Connections*, American Institute of Steel Construction, Chicago, IL.

Ricker, D.T. (1988), "Field Welding to Existing Steel Structures," *Engineering Journal,* AISC, Vol. 25, No. 1, pp. 1–16.

Tide, R.H.R. (1990), "Reinforcing Steel Members and the Effects of Welding," *Engineering Journal,* AISC, Vol. 27, No. 4, pp. 129–131.

Thomann, M. and Lebet, J.-P. (2007), "Design Methods for Connections by Adherence for Steel-Concrete Composite Bridges," *Structural Engineering International*, Vol. 1, pp. 86–93.

ACKNOWLEDGMENTS

Significant special assistance has been provided by ISSRA member David MacKinnon of the Steel Structures Education Foundation of Canada.