Current Steel Structures Research

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INTRODUCTION

This issue of "Current Steel Structures Research" for the *Engineering Journal* focuses on a selection of research projects at universities in Europe and New Zealand. Not all current projects at each school will be discussed. Instead, selected studies provide a representative picture of the research work and demonstrate the importance of the schools to their respective home countries—and indeed their importance to the efforts of industry and the profession worldwide.

The universities and many of their researchers are very well known in the world of steel construction: the Czech Technical University in Prague, the Czech Republic; the University of Ljubljana in Ljubljana, Slovenia; and the University of Auckland in Auckland, New Zealand. Segments of some of the projects at these institutions have been discussed in previous research papers, but the studies that are presented here reflect additional elements of the projects as well as other significant long-time efforts. All of the projects are multi-year efforts, emphasizing the need for careful planning and implementation of research needs and applications, including the education of graduate students and advanced researchers. As in the United States, the outcomes of the studies focus on design standards and industry needs.

The lead researchers have been active for many years, as evidenced by their leading roles in the design standards development of their countries, but they have also been frequent participants in the work of other countries and regions. Large numbers of English-language technical papers and conference presentations have been published, contributing to a collection of studies that continue to offer solutions to complex problems for designers as well as fabricators and erectors. Many of the projects also complement current work in the United States and elsewhere. The broad sharing of knowledge that is taking place promises significant results, not the least because of issues of finances and the sheer cost of research: synergism is a critical feature of multi-institutional, indeed multinational, activities.

References are provided throughout this paper when they 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.

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SOME CURRENT RESEARCH WORK AT THE CZECH TECHNICAL UNIVERSITY IN PRAGUE, THE CZECH REPUBLIC

The Czech Technical University (CTU) has been one of the leading academic institutions in Europe for many years. The faculty has pursued an aggressive development of technical programs and research facilities. In spite of its location "behind the Iron Curtain" for many years, with somewhat limited access and communication with researchers in other areas of the world, a number of the faculty members at CTU pursued contacts with colleagues in the West. However, the amount of activity that has taken place since the early 1990s has been impressive, particularly after the Czech Republic joined the European Union (EU). There have been numerous significant projects addressing the performance of steel materials, members and connections for steel structures, steel and composite frames, bridge structures, and the response of steel structures subjected to fire.

Design of Connections to Composite Columns for Improved Fire Robustness: Professor Frantisek Wald is the director of this project, which has been sponsored by the Research Fund for Coal and Steel (RFCS), an arm of the European Union. Additional support has been provided by TATA Steel Tubes Europe. The CTU staff has been working together with researchers from the University of Coimbra (Portugal), the universities of Manchester and Sheffield in England, and the University of Luleå in Sweden.

Focusing on the behavior and robustness of practical beam-to-column connections between wide-flange beams and both concrete-filled tubular (HSS) columns and partially encased wide-flange columns, the project aims to determine the following criteria for the connections and related design requirements:

1. Thermal effects in composite connections under different types of fire loading, including the cooling phase.
2. Component behavior in composite connections under arbitrary internal stress resultants and imposed displacements at elevated temperatures.

3. The influence of the connections on the global behavior of frames at elevated temperatures.

4. Using full-scale demonstrations, determining the influence of improved connection designs on the structural robustness under realistic fire conditions.

5. Development of connection design guides for practical applications.

The connections that are being examined are flush end-plate types and so-called reverse channel types, both of which are commonly used in European construction practice. Current results are partial and only tentative; the project will be completed by the end of 2012.

Modeling of Membrane Action of Floor Slabs Exposed to Fire: Professor Frantisek Wald is the director of this project, which has been funded by the Grant Agency of the Czech Republic, an institution similar to the National Science Foundation in the United States.

Using fiber-reinforced concrete for the slab, a yield line model was developed and tested computationally by finite element analyses. Interestingly, in addition to the traditional steel and concrete composite slab, a composite system using glulam beams was also designed and tested, in recognition of the use of wood for certain structures in the Czech Republic.

At this time, four steel-concrete composite floor assemblies have been tested at ambient temperature and two have been tested for fire-level temperatures (Bednar et al., 2011). Figure 1 shows the appearance of the floor system at the completion of the ambient temperature test and Figure 2 shows a collapsed slab during the fire test. As expected, the yield line modeling predicted the ambient results very well, and the fire test demonstrated the ductility of the fiber-reinforced slab and steel system. The final results will be available in 2012.

Composite Beams with High Ribbed Concrete Deck: Professors Jiri Studnicka and Stepan Thoendel direct this project.

Using trapezoidal steel deck 135 mm (5.3 in.) high and IPE 200 (200 mm high or 8 in.) steel shapes for the composite beams, the system violates the maximum 80-mm (3.1-in.) steel deck height criteria of the current Eurocode 4 (EC4) (ECS, 2004). Two full-scale tests were conducted using simply supported beams with a 6-m (20-ft) span. The tentative results indicate that it may be possible to expand the EC4 criteria to include such deep decks (Thoendel and Studnicka, 2011). The project will complete by the end of 2012, at which time suitable design recommendations will be made.

Performance of Small-Diameter-Headed Stud Shear Connectors: Professor Josef Machacek is the director of this project.

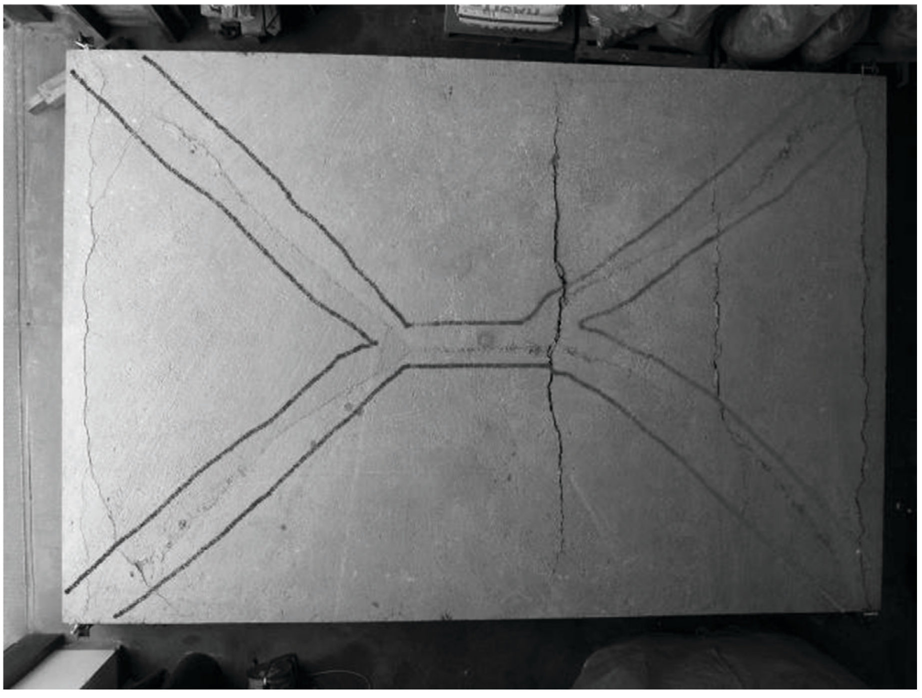

Fig. 1. Yield line failure mode of ambient temperature composite slab test. (Photograph courtesy of Professor Frantisek Wald)

Using pushout tests with 10- and 13-mm (⅜- and ½-in.) shear studs, with concrete strengths of 20 and 30 MPa (nominally, 3 and 4 ksi), the representative strength parameters and variability characteristics were determined. Applied to partially encased composite members subjected to bending and axial force, as shown in Figure 3, the tests have demonstrated that the connectors behaved as ductile elements (Nguyen and Machacek, 2011). Nonlinear response of such beam-columns was evaluated using the ANSYS software. Overall, the results showed that the use of the Eurocode 4 criteria for the plastic distribution of the longitudinal shear force may be used.

Composite Beams with High-Performance Concrete and High-Strength Steel: Professors Jakub Dolejs and Ivan Tunega are the directors of this project.

Four composite beams have been tested, using 150-mm (6-in.) 70-MPa (10-ksi) concrete slabs with HE260A rolled steel shapes (250 mm or 10 in. high) in S460 steel (65-ksi yield stress). Pushout tests were also conducted to verify the behavior and performance of the shear connectors in the high-strength concrete. Finite element analyses and additional tests were also conducted to determine the capacity of the shear connection with its distribution along the length of the beam.

Overall, the aim of the project is to confirm or to modify the applicability of the Eurocode 4 criteria, if necessary, for shear connectors in high strength concrete. The final results will be available in late 2012.

Development of Innovative Steel-Glass Structures for Architectural and Structural Applications: This project has been funded by the Research Fund for Coal and Steel (RFCS), with Professors M. Netusil and M. Eliasova as the

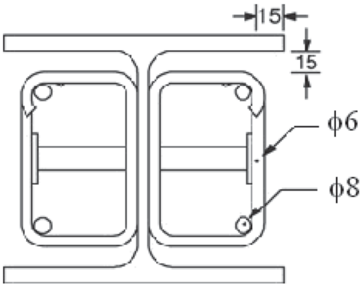

Fig. 3. Partially encased composite beam cross-section with small-diameter shear studs. (Drawing courtesy of Professor Josef Machacek)

Fig. 2. Collapsed composite slab assembly during fire test. (Photograph courtesy of Professor Frantisek Wald)

directors of the Czech component of the overall project. It is part of a larger-scale development of steel and glass structures and is operated as a joint effort among CTU, the German technical universities of Aachen and Dortmund, and the Steel Construction Institute of the United Kingdom. The lead research institution is the Technical University of Aachen.

Aiming for optimal interaction between glass and steel, various steel-glass structures have been examined. In particular, steel-supported glazing systems for use in façades, roofs and other parts of buildings have been explored, leading to the development of hybrid steel-glass beams, as illustrated in Figure 4. The web-to-flange connections are provided by polymer adhesive joints and the details of the joints may vary in accordance with the preferences of the architect and the structural engineer (Netusil and Eliasova, 2010).

At this time, analytical procedures have been used to develop practical design approaches, and a full-scale test has been conducted at CTU, as shown in Figure 5. Additional data will be available as the project progresses.

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF LJUBLJANA IN LJUBLJANA, SLOVENIA

The University of Ljubljana is a premier European university with a broad program in all areas of civil engineering. Following the separation of the various regions of Yugoslavia, the western area became the country of Slovenia, with the city of Ljubljana as the capitol. The faculty of the university have been very aggressive in their efforts to join the European research community, and the structural engineering efforts have been particularly successful under the leadership of Professor Darko Beg. The structural steel research program has featured a number of important projects that have been conducted as single studies and a number of efforts that are jointly pursued with other European schools.

Fig. 4. Hybrid steel-glass beam with adhesive web-to-flange connections. (Figure courtesy of Professor Frantisek Wald)

Behavior and Strength of Bolted Connections in Bearing: The director of this project has been Professor Darko Beg.

The aim of the project is to clarify and expand the bearing criteria that are used in Eurocode 3 (ECS, 2005). Specifically, the design criteria are very conservative but also vague and impractical. Previous studies were focused on the strength and behavior of connections in high-strength steel, such as S690 (similar to ASTM A514); the current project addresses the performance of connections with up to 6 bolts in the mild S235 steel grade (for all practical purposes, the same as ASTM A36). The bolts are of the European 8.8 grade, which is comparable to A325.

Interestingly, the results to date show that the bearing criteria that were developed for connections in S690 steel are also suitable for mild steel (Može and Beg, 2011). Specifically, although the tests demonstrated that different limit states were observed for the connections that were tested, the bearing resistance was always the governing one. The final version of the design criteria will include suitable ductility considerations.

Longitudinally Stiffened Plate Girders Subjected to Moment and Shear Interaction: Darko Beg is the director of this project, which is jointly operated with the University of Stuttgart in Germany.

A series of large-scale tests were conducted in 2010, aiming to determine the behavior characteristics of plate girders subjected to high moment and shear. Figure 6 shows the test setup for the girders. A numerical model was developed for analysis using ABAQUS, and the results compared to within 5% of the test data. Once the numerical model has been fully verified, extensive parametric evaluations will be performed.

Further, the numerical results were compared to those predicted by the criteria of Eurocode 3, Part 1-5 (ECS, 2006). The largest difference was found for girders having one longitudinal stiffener in the compression zone, where the positive effect of the tensile stresses due to the bending moment is not considered in the computation of the shear capacity of the largest panel. Various resistance models have been developed, including two that are based on an interaction treatment and one that is based on the strength of the gross cross-section.

Extensive statistical analyses are now under way, correlating the physical and the numerical results. Among recent findings, higher "partial safety factors" must be applied for several cases. It is anticipated that a number of changes will

Fig. 5. Full-scale test of a steel-glass beam.
(Photograph courtesy of Professor Frantisek Wald)

Fig. 6. Test setup for a large-scale plate girder.
(Photograph courtesy of Professor Darko Beg)

be proposed for Eurocode 3, once the results from Ljubljana and Stuttgart have been fully evaluated.

Intermediate Transverse Stiffeners in Plate Girders: Darko Beg is the director of this project, which is also jointly operated with the University of Stuttgart.

Over the past several years, various authors have claimed that the influence of tension field action on the transverse stiffeners is much smaller than what is predicted by the EC3 design criteria. Two large, full-scale tests, as shown in Figure 7, were conducted to verify these results, if possible. The physical tests have now confirmed that the numerical findings are correct. On this basis, a new model has been developed, and an extensive parametric study has been performed. A simplified approach based on stiffness criteria has been developed for the design of the transverse stiffeners. The approach incorporates all relevant loading cases. The proposed approach has not yet been published, and it is anticipated that extensive discussions will be conducted by the EC3 technical committee.

Flame Straightening of Structural Steel Elements: This project has been sponsored by the Research Fund for Coal and Steel (RFCS), with Professor Darko Beg as the director

Fig. 7. Plate girder test to assess the influence of tension field action on the transverse stiffener. (Photograph courtesy of Professor Darko Beg)

of the study component that is being conducted at the University of Ljubljana.

The work to be conducted at Ljubljana focused on determining the residual stresses in steel plates of various grades of steel, as illustrated in Figure 8. Water-jet cutting was used for the traditional method of sectioning that provides the basis for the measurement of the strains associated with the residual stresses. It was also essential to evaluate the welding deformations in tee elements ahead of the flame straightening.

The primary effort of the research team was to provide numerical simulations of the flame-straightening process using the actual temperature field that was introduced. Further, an analytical method was developed to estimate the deflections of beams that had been straightened by heating in the usual V-shape. The principle of this approach is based on the fact that the heated area will yield in compression due to an external force, in the form of a strip across the flange and the V in the web. The neutral axis then forms in the apex of the V, and the tensile stresses in the unheated part of the shape will be in equilibrium with the heated part of the cross-section. Finally, the temperature that causes the yielding of the heated part is defined as the critical value. It has been determined that this temperature provides a good estimate of the rotation of the V that will occur under these conditions. This gives a realistic value of the contraction due to the cooling of the V.

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF AUCKLAND IN AUCKLAND, NEW ZEALAND

The University of Auckland has had a prominent civil engineering program for many years, and the faculty members have enjoyed good relations with local designers and industry. The Heavy Engineering Research Association (HERA) of New Zealand effectively played the role of AISC for many years, and New Zealand has also benefited from close collaboration with the resources and market of Australia. In fact, design standards for the two countries are now developed and published jointly.

For several years, Dr. G. Charles Clifton worked as the chief technical officer of HERA. Upon joining the faculty of the University of Auckland, he started an aggressive research and development program for the Department of Civil Engineering, which is now the leading "steel university" in the country. It is particularly important to observe that seismic activity can be quite strong in New Zealand, as demonstrated by numerous larger and smaller earthquakes every year. Further, as examples of the steel research work at the university, it is interesting to note the following recently completed studies:

- Development and behavior of a new, long-span composite floor system.

- Development and behavior of a new, long-span composite floor system, with special emphasis on the use in a building with a riveted steel frame.
- Seismic assessment and retrofit of riveted steel-framed buildings, including beam-to-column connections with high deformation capacity but very low rotational strength.
- Composite slab strengthening solution with carbon fiber strips in the slab.
- Lightweight, low-cost buckling restrained braces for developing countries, with the potential of using bamboo tubes in lieu of an expensive solution with steel tubes.

Current research efforts are detailed in the following.

The Self-Centering Sliding Hinge Joint: The project is sponsored by the New Zealand Earthquake Commission. Professor G. Charles Clifton is the project director; the team researchers are H.H. Khoo and John Butterworth, as well as Greg MacRae from the University of Canterbury in New Zealand.

The sliding hinge joint (SHJ) is a New Zealand invention. It is a beam-to-column connection intended for use in low-damage, steel moment-resisting frames. It has a pinned connection between the top flange of the beam and the column, with asymmetric friction connections in the bottom flange and web base. This allows for large inelastic rotations with limited connection and floor slab damage. Further, the SHJ decouples connection strength and stiffness, with significant advantages over conventional moment connections. The joint does lose strength during sliding, due to bolt tension losses in the asymmetric friction connections. It also does not always return the frame to the pre-earthquake position, delaying the immediate occupancy of the structure after the earthquake.

A self-centering sliding hinge joint (SCSHJ) with ring springs (RS) has also been developed to reduce strength losses and improve the dynamic recentering properties of the connection (Khoo et al., 2011). This will ensure that the frame residual drift is within post-construction tolerances. It involves connecting a ring spring to the beam bottom flange and the column flange of the SHJ, as shown in Figure 9a. Because the springs are only effective in compression, suitable detailing of same, as shown in Figure 9b, ensures that the spring will compress in both directions. Thus, the ring spring will:

Fig. 8. Sectioning of the flange plate by water-jet cutting.
(Photograph courtesy of Professor Darko Beg)

1. Develop moment resistance, reducing the number of bolts required in the asymmetric friction connection.

2. Store energy, which will contribute to recentering upon release.

3. Maintain the sliding joint strength due to limited degradation.

Five 10-story frames with different spring sizes were studied analytically, with up to 50% ring spring contribution to the moment resistance. This demonstrates that the dynamic recentering properties can be significantly improved, despite the absence of more favorable hysteretic curves in most self-centering systems. Finally, a full-scale subassemblage test is currently under way, as shown in Figure 10.

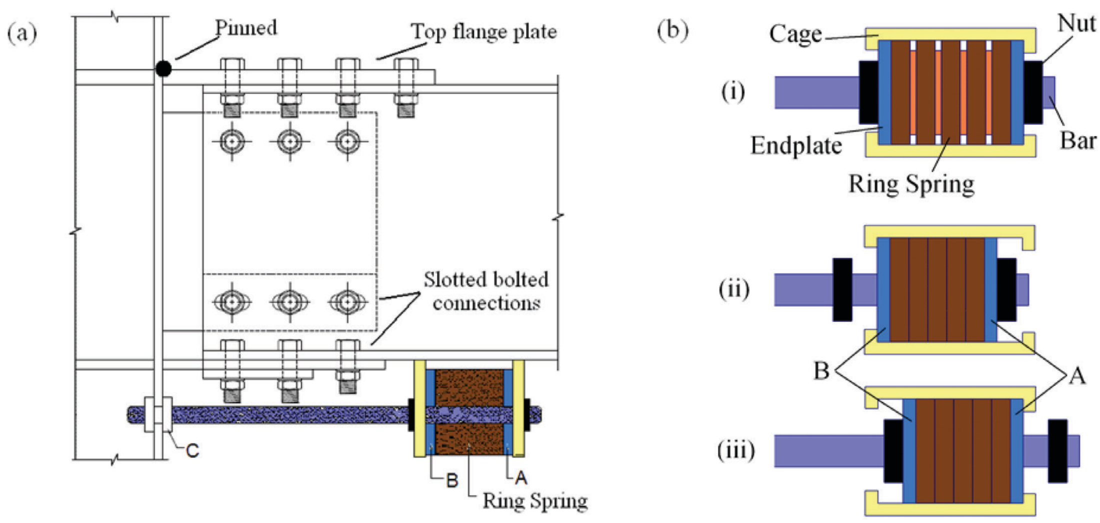

Fig. 9. (a) Self-centering sliding hinge joint; (b) ring spring layout. (Figure courtesy of Professor G. Charles Clifton)

Fig. 10. Full-scale frame subassemblage test setup. (Photograph courtesy of Professor G. Charles Clifton)

Effects of Floor Slab Resistance on the Inelastic Behavior of Chevron-Type Eccentrically Braced Frames: The director of this project is Professor G. Charles Clifton; the team researchers are D. Volynkin and C. Mathieson.

Following the February 2011 New Zealand earthquake, several examinations showed that eccentrically braced frames (EBFs) that were compositely connected to the floor slab experienced self-centering as well as less-than-expected active link yielding (Bruneau et al., 2011). A numerical model was created to study the effect of a floor slab on the out-of-plane resistance of the EBF structures. The deformation was modeled by a translational spring with a stiffness derived from yield line theory. Figure 11 shows the assumed yield line collapse mechanism formed under loading at the collector beam ends.

The analysis demonstrated that the floor slabs reduce the rotation of the active links. This caused additional forces to be distributed into the secondary elements of the EBF, leading to yielding in an increased number of elements. Following the earthquake, the structure exhibited self-centering as a result of the restoring force from the floor slabs. Without such a restoring force, EBFs have no inherent tendency to produce self centering. The researchers are now working to improve the floor slab model as well as to develop a design procedure that will take into account the out-of-plane resistance of the slab.

ACKNOWLEDGMENTS

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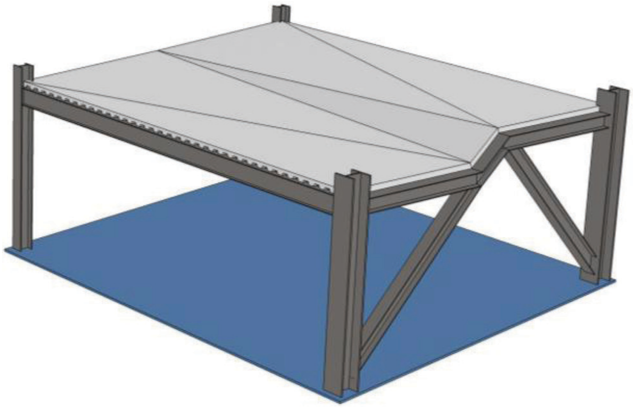

Fig. 11. Yield line model of structural system.
(Drawing courtesy of Professor G. Charles Clifton)

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