Current Steel Structures Research

REIDAR BJORHOVDE

Seismic strength and performance of steel structures and structural elements continue to be the focus of a very large number of studies all over the world, but probably nowhere as vigorously as in the United States. Apart from the fact that extensive areas in the U.S. now can be seismically active and are treated as such by the International Building Code, this is in part caused by the close relationship between design specifications (= standards) and building codes. Thus, all of the major U.S. materials-based design codes are now incorporated into the building code by reference. Further, the relationships between these groups and organizations such as the Building Seismic Safety Council (BSSC) and various efforts under the auspices of the National Science Foundation emphasize the state-of-the-art character of current code developments in the United States.

Similar efforts are under way in Europe, under the umbrella of the European Union (EU) and its code commission CEN and various funding groups. The standardization work in Europe is greatly complicated by the fact that the EU now has 27 members, but several additional countries are also active participants in these programs. It would not be unreasonable to assume that these efforts would have limited probability of success, but such is not the case at all. So-called National Annexes to the various Eurocodes are prepared by each country before the standards can be put to practical use, but numerous research projects feed relevant information to the individual specification committees. The years 2009 to 2010 are when all national codes are supposed to be ready for implementation, and the design profession is working diligently to ensure that the change-over from old standards can take place with a minimum of technical problems.

Research and development groups in Australia, Chile, China, Japan, Korea, New Zealand, and Taiwan are equally and aggressively seeking improvements to their national design standards for seismic effects. There are many similarities between the practices in these countries and code activities elsewhere, mostly because seismic effects are fundamentally the same. Some differences exist because of differing construction techniques and engineering preferences. It is therefore critical to be able to draw upon the expertise in all locales. At the same time it must be recognized that local approaches may make the application of solutions from other areas difficult, whether it is because of traditions in any form or it is simply impractical to bring in novel construction forms or otherwise expensive solutions.

The research efforts discussed in this paper examine the behavior and strength of braced frames under seismic conditions, emphasizing the advantages of this very common structural system but also the needs for unique performance criteria. Similarly, the energy absorption characteristics of various types of PR connections may offer significant advantages for seismic response, as examined in another project. Using the so-called direct strength method for slender hot-rolled members is being studied by an American researcher who developed the concept for cold-formed steel structures. A major Chinese investigation of structural performance under fire conditions has real applications everywhere, in particular because of its assessment of the efficiency of certain fireproofing techniques and the removal of part of the protection. Composite structures continue to play a major economic role for buildings, and a novel system using precast hollow-core slabs is being studied in England. Finally, stainless steel continues to attract attention for several applications, and Spanish researchers aim to provide practical criteria for plate girders of such materials, as well as novel requirements for hybrid girders.

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.

STRUCTURAL BEHAVIOR AND STRENGTH UNDER SEISMIC LOADS

Special Concentrically Braced Frames (SCBF): This project has been conducted at the University of Washington in Seattle, with Professor Charles W. Roeder as the director. Funded by the NEES-SG program of the National Science Foundation, the project also functions with numerous subcontracts to other institutions in the U.S. as well as in Japan and Taiwan.

Braced frames have been used extensively for steel structures in nonseismic regions, and they offer significant advantages insofar as analysis techniques and economies of

Reidar Bjorhovde is the Research Editor of the AISC *Engineering Journal*.

construction are concerned. Under the designation special concentric braced frames, they are now frequently used in seismically active areas because of their inherent lateral stiffness and strength. The increased use of SCBFs is tied to the performance problems that have been experienced with moment resisting frames. However, unique aspects of the braced frames require more information about their inelastic post-buckling behavior; in particular, the response of the gusset plates and the bracing members.

The researchers at the University of Washington have conducted extensive analytical and experimental investigations of various SCBF gusset plate connections. The analyses are based on inelastic, cyclic deformation evaluations. The 23 large-scale single-story frame specimens that have been tested so far include diagonal braces, beams, columns and gusset plates, as shown in Figure 1.

The tests have been run to reach the full deformation capacity of the frame. Extensive and severe yielding and post-buckling displacements have been found in the brace as well as the gusset plate and the framing members, as shown in Figure 2. Considering that connection design variations have been implemented for each test to examine the impact on the performance of the frame, it is clear that the gusset plate design has a very significant impact on the frame. The study has led to proposals for improved design procedures for the gusset plate and other connection elements.

In addition to the single-story single-bay SCBF tests that have been performed at the University of Washington, two full-scale two-story frame tests have been conducted at the research laboratory of the National Center for Research on Earthquake Engineering (NCREE) at the National University of Taiwan. Professor K.-C. Tsai is the director of NCREE. Figure 3 shows one of the test frames, noting that the test specimen is the structure enclosed within the blue color frame. The blue frame provides the lateral support for the test structure, which has a two-story X-brace system along with a composite floor slab. The tests were conducted under inelastic cyclic displacements until two or more of the braces failed. In addition to the overall system performance, these tests also provided information on the effect of the multi-story bracing configuration as well as the design and performance requirements for the midspan gusset plates.

Fig. 1. Single-story SCBF test specimen (photo courtesy of Charles W. Roeder).

Fig. 2. Post-buckling deformations in the SCBF test frame brace and gusset plate (photo courtesy of Charles W. Roeder).

Fig. 3. Two-story SCBF with a two-story X-brace configuration (photo courtesy of Charles W. Roeder).

Additional SCBF research work will be conducted by the participants at the University of California at Berkeley and the University of Minnesota. These sub-projects will examine the influence of different bracing systems, composite slabs, and the three-dimensional response of the frames. It is anticipated that the research work will continue for an additional three years, offering significant changes and improvements in the design methods for braced frames.

Energy Dissipation Characteristics of Semi-Rigid Connections: This project was conducted some time ago at the University of Oklahoma in Norman, OK, with Professor Anant Kukreti as the director.

Based on the data from 48 full-scale cyclic tests, the project has provided energy dissipation data and characteristics for a range of practical PR (semi-rigid) connections (Abolmaali, Kukreti, Motahari and Ghassemich, 2008). The following types of connections were included in the study:

- Bolted-bolted double web angle connections
- Welded-bolted double web angle connections (welded to beam web)
- Top and seat angle connections
- Flush end-plate connections
- Extended unstiffened end-plate connections

All of the connections used slip-critical bolts. The test assembly columns were W14×159 shapes in 50 ksi yield stress steel; the beam sizes varied, depending on the individual types of connections.

In particular, using an appropriate cyclic testing protocol, the total energy absorption of the connections was determined on the basis of the hysteresis loops. Rather than looking at the maximum rotation or story drift capacity of the connections, focusing on the complete energy absorption distills the connection performance into the most important performance measures. This is what has been recommended by Nakashima, Suita, Morisako and Maruoka (1998) and Bjorhovde, Goland and Benac (2000). The procedure is now utilized in Japanese seismic performance assessment criteria.

The data have been assembled in connection performance tables, which can be useful for designers considering frames with PR connections. Other studies have shown that such frames offer potential advantages for seismic construction (Astaneh, Nader and Malik, 1989), although overall building drifts may be relatively high.

LOCAL STABILITY OF STRUCTURAL MEMBERS

Cross-Sectional Stability of Hot-Rolled Shapes: This is an ongoing study by Professor Benjamin Schafer at Johns Hopkins University in Baltimore, MD. It is performed as part of his responsibilities under the AISC Faculty Fellow program.

Cross-sectional stability or resistance to local buckling of many forms is an essential feature of analysis and design of cold-formed steel members. These types of elements have very high width-to-thickness ratios and various forms of edge support conditions, and local buckling checks are extensive and fairly complicated. The American Iron and Steel Institute (AISI) issues the *North American Specification for the Design of Cold-Formed Steel Structural Members* (AISI, 2007), and this standard and its predecessors give the authoritative criteria for all forms of local buckling.

Known primarily for his work on the strength and stability of cold-formed steel structures, Professor Schafer developed the direct strength method (DSM) for such elements, making the checks for local buckling significantly more robust and all-encompassing (Schafer, 2006). He is now working to provide a similar approach for slender (noncompact) hot-rolled members, which will take into account the post-buckling reserve strength. This appears to offer economies for the use of slender members, and also to provide designer-friendly criteria for highly complex problems. Finally, in addition to developing improved local buckling design criteria and methods for the AISC *Specification for Structural Steel Buildings* (AISC, 2005), he has also developed tutorials for DSM and how the method can be used for hot-rolled steel.

STEEL STRUCTURES UNDER FIRE CONDITIONS

Behavior and Strength of Steel Columns with Partial Damage of the Fire Retardant Coating: This project is a major effort of the Chinese National Natural Science Foundation, taking place at Tongji University in Shanghai, China. The director is Professor G.-Q. Li.

At this stage of the research work, two full-scale tests of wide-flange steel columns have been completed. Coated with 20-mm (¾-in.)-thick fireproofing material, the fireproofing was purposely removed from each end of the columns, to assess the performance of such damaged members under laboratory fire conditions. The 140-mm (4½-in.) deep H-shape column specimens were 2.7 m (9 ft) long; the fireproofing was removed from 190 mm (72 in.) of each end of one of the specimens, and from 380 mm (15 in.) from each end of the other specimen (see Figure 5). The columns had flush end-plates at the ends; they were loaded to 55% of their axial capacity while the temperature in the furnace was set to follow the criteria of the ISO 834 code. Figure 4 shows the test setup with the furnace; Figure 5 gives the dimensional data for the column specimens.

As expected, the tests showed that the fire resistance of the damaged columns was reduced, and the reduction was significantly larger for the member with the largest amount of fireproofing removal. Further details of the tests are not yet available, but it is noted that the column failure was initiated by the local buckling that took place at the unprotected column ends. Examples are shown in Figure 6.

COMPOSITE CONSTRUCTION

Composite Beams with Precast Hollowcore Slabs: This research project is conducted at the University of Leeds in England, with Dr. Dennis Lam as the director.

The study was undertaken on the premise that the use of precast slabs could offer reduced construction time, cost of concrete materials, etc. The hollowcore slab also offers reduced weight and the advantage of readily available conduits for cables and similar.

At this time the research work focuses on the use of simple beam-to-column connections with the hollowcore slabs, and a number of tests and analyses have been carried out for the system. The correlation between finite element evaluations and the physical tests is good; detailed moment capacity and rotation characteristics are being assembled for eventual use toward the development of design criteria. Figure 7 shows an example of one of the finite element models.

PLATE GIRDER RESEARCH IN SPAIN

The steel structures research activities in Spain have expanded significantly over the past few years, for several reasons. The country is benefiting from an active economic climate, and a large number of companies in the national and international market are aggressively looking for novel applications

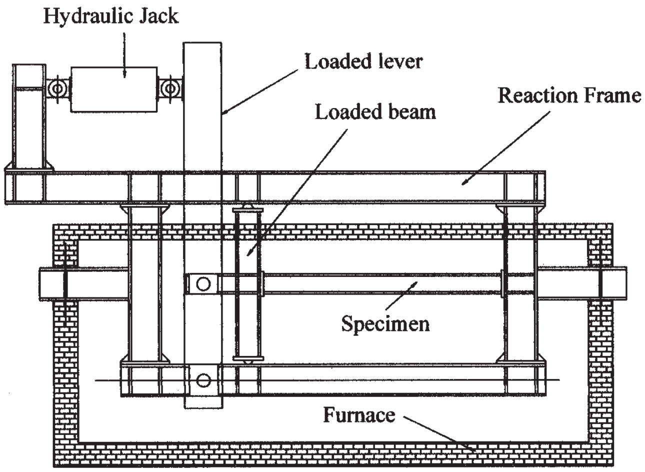

Fig. 4. Test setup for columns with damaged fireproofing (figure courtesy of G.-Q. Li).

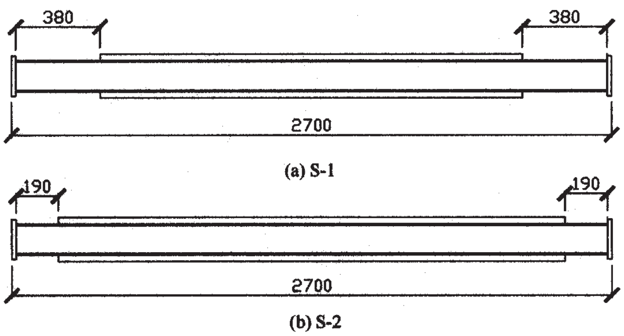

Fig. 5. Column specimens with damaged fireproofing (figure courtesy of G.-Q. Li).

(a) End A

(b) End B

Fig. 6. Local buckling within unprotected column ends (photo courtesy of G.-Q. Li).

of structural materials and systems. This applies to buildings as well as bridges, and is greatly assisted by prominent architects and engineers such as Calatrava and Moneo, and university researchers such as Professors Eduardo Bayo (University of Navarra) and Enrique Mirambell (Polytechnic University of Catalonia). The projects described in the following are but two examples of current research work.

Hybrid Steel Plate Girders: This research project is funded by the Spanish "National Agency," with Professor Mirambell as the director.

Based on the concept of more efficient use of materials of different strengths in the various elements of the cross section, hybrid girders have been studied in the U.S. and other countries with a view toward increased construction economies. Some of the problems of hybrid girders are those of the higher slenderness of high strength webs, for example, as well as the different limit states that may govern the ultimate strength of the tension flange. Fatigue is, of course, always a consideration for girders that are to be used in bridges and crane structures.

The current study at the Polytechnic University of Catalonia focuses on two main subject areas, namely, shear buckling and the response of the girder to concentrated loads. Based on extensive parametric evaluations, the results are now being translated into design requirements (Chacón, Mirambell and Real, 2006). It is clear that current approaches tend to be conservative for girders with stocky panels. Further, initial imperfections must be taken into account, and such is being done within the criteria that have been developed.

Design of Stainless Steel Plate Girders for Shear: Stainless steel offers certain aesthetic advantages for structural applications, although the use of such materials in construction is still very limited, primarily because of cost. Nevertheless, under some environmental and exposure conditions the use of stainless steel may be economically feasible. The plate girder project described here is being conducted at the Polytechnic University of Catalonia, with Professor Mirambell as the director. It is financially supported by the Spanish ministries of Education and Culture, and Science and Technology.

The primary aims of the project are (1) to communicate with engineers and architects and enhance the fundamental understanding of stainless steel properties and behavior, with special emphasis on the nonlinear response; (2) to detail the primary limit states of stainless girders, but especially those associated with shear response and stability; and (3) to develop an efficient and practical design approach for such girders subjected to shear.

Three experimental groups of tests have been done, and 27 girders have now been physically tested, with the first and second groups focusing on the general behavior while subjected to shear loading. The first group used girders with low-to-medium web slenderness; the second group had members with slender webs. The third group aimed at determining the effect of longitudinal stiffening of the girders. Finite element analysis has added to the fundamental understanding of the behavior of these girders, and the correlation between tests and theory is generally very good. Figure 8 compares the ABAQUS finite element model at shear buckling with the physical specimen—the data are very good. A new shear design procedure has now been developed, including the effects of transverse and longitudinal stiffeners, end posts, and actual boundary conditions (Estrada, Real and Mirambell, 2007a, 2007b).

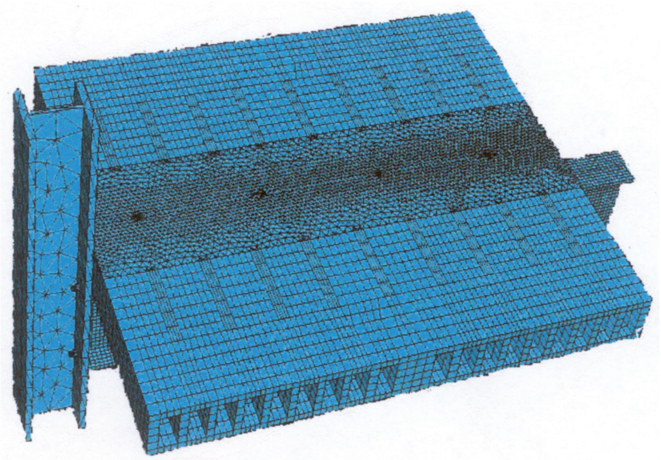

Fig. 7. Composite connection with hollowcore slab (figure courtesy of Dennis Lam).

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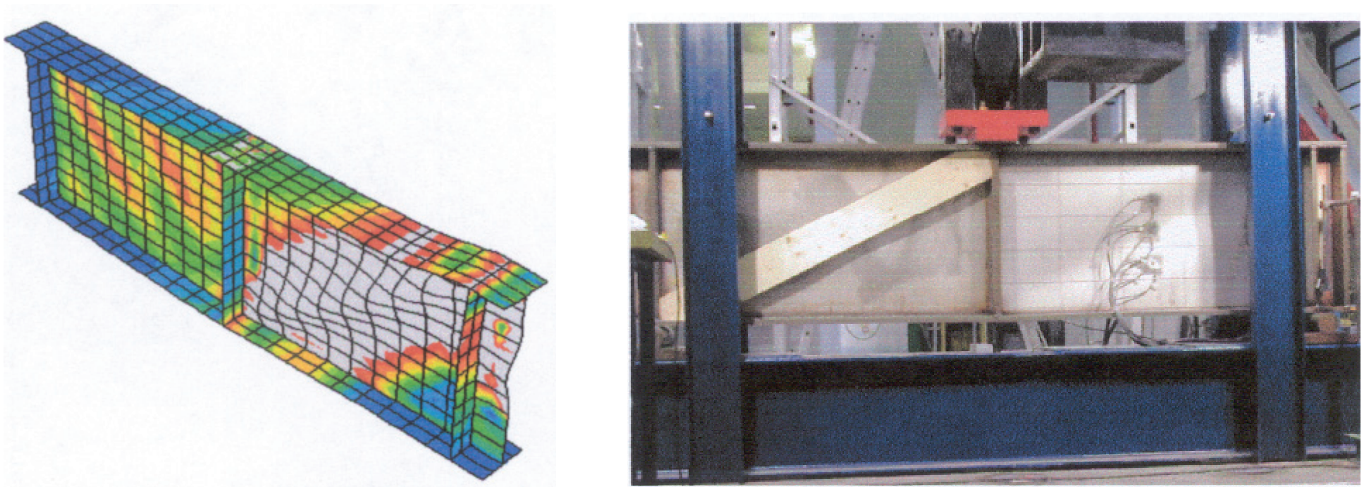

Fig. 8. Finite element model and test specimen of stainless steel plate girder (photos courtesy of E. Bayo and E. Mirambell).