Current Steel Structures Research

REIDAR BJORHOVDE

For many years AISC and other American code-writing bodies for structural engineering purposely avoided criteria that required or even just mentioned analytical techniques or approaches. This was done to allow the designer the maximum amount of freedom in selecting the mathematical and mechanistic procedures that were thought to be the most appropriate for the problem at hand. But things have changed a great deal over the past 20 years, mostly due to the availability of computing tools and accompanying theoretical developments: things can be done today that could not even be imagined a few years ago. Three-dimensional analysis is now common for major structures, as is the use of time-history analyses, and modeling of members, connections and frames in various materials has become very efficient. This does not mean that the traditional, simpler methods that were suitable for low-rise and many other structures have been invalidated. Far from it: the design of a continuous beam or a one-story portal frame and many other structures can still be accomplished "on the back of an envelope," as the saying goes. There is no need to utilize sophisticated 3D frame analyses or finite element solutions for many types of structures, especially in nonseismic regions.

All of the above being said, however, it is also clear that advanced analytical techniques are capable of taking into account geometric and other effects that may play major roles in the performance of a structure. This is particularly evident in the stability analysis that must be undertaken for a great many structures. Second order influences are required by design specifications today, and they impose stability effects that must be recognized in the sizing of the elements of the frame. The accuracy of these effects is analysis-dependent, and the specification has to recognize this. This is part of the reason why the stability chapter of the 2005 AISC *Specification for Structural Steel Buildings* (AISC, 2005) provides numerous references to analytical treatment, including the use of notional loads and reduced stiffness effects (Nair, 2007). Although there is no question that these approaches are much more accurate, the level of complexity of many designs makes it very difficult to assess realistic causes and effects. But analysis now is an integral part of many parts of the Specification.

The projects that are presented in this paper reflect a broad range of state-of-the-art work. Connections in very high strength steel continue to be a subject that is looking to novel applications in structural rehabilitation, in particular. Similarly, advanced connection modeling is essential for seismic regions, including such important systems as those that are used for rack structures. In this context the energy-absorption capacity of semi-rigid (PR) connections and frames continue to be examined for practical implementation. Studies of composite construction are looking to provide significant advances over the next few years, and the work that is currently taking place in the United States is particularly exciting.

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.

CONNECTIONS FOR STEEL STRUCTURES

Tests on Bolted Shear Connections in High Strength Steel: This is a project being conducted at the University of Ljubljana in Ljubljana, Slovenia, with Professor Darko Beg as the director.

A series of 26 double shear connections using 10-mm (approximately ⅜-in.) S690 plate steel were conducted to examine failure modes and the potential influence of a very high yield-to-tensile ratio. The S690 steel grade corresponds to ASTM A514; the average actual yield and tensile properties were 796 MPa (115 ksi) and 844 MPa (122 ksi), with the yield-to-tensile ratio equal to a very high 0.94. It is noted that these properties are well in excess of the specified minima for S690 as well as A514. The elongation at fracture was 17%.

Attempting to avoid bolt failures in the connection assemblies, it was decided to use ¾-in. bolts of the European high strength grade 12.9, for which there is no American counterpart. The nominal tensile strength of the 12.9 bolt material is 175 ksi. Further, in addition to using the 12.9 bolt grade, it was decided to utilize smaller bolt spacing and end distance than what is required by Eurocode 3 (CEN, 2005). This would also contribute to the connection failure mode, to the effect that the plate material would fail in some fashion.

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

Despite the very high strength and yield-to-tensile ratio of the plate material, all of the connections failed in ductile modes. As an illustration, Figures 1 and 2 show two of the specimens after testing. Using hole diameters of 22 mm (⅞ in.), and recognizing that Eurocode 3 specifies bolt placement on the basis of the hole diameter, the connections that are shown have the following bolt placement data (d_h is the hole diameter):

Figure 1	Pitch = 2.5 d_h	End distance = 1.5 d_h
Figure 2	Pitch = 2.5 d_h	End distance = 2.5 d_h

The researchers observed that the connections exhibited large plastic deformations in the areas around the bolt holes, which facilitated the stress redistribution. In fact, the failure demonstrated in Figure 2 is similar to what was experienced for high-strength cold-rolled material in a study of block shear characteristics in gusset plates (Hardash and Bjorhovde, 1985). This would appear to indicate that a high yield-to-tensile ratio and lower ductility may not be as detrimental to bolted connections as has been perceived in several studies. However, this is the subject of continuing research.

SEISMIC RESPONSE OF STEEL STRUCTURES

Development of a Hysteretic Model with Pinching for Steel Connections: This is a very large investigation of the rotation and energy absorption characteristics of a number of beam-to-column connections, carried out at the University of Coimbra in Coimbra, Portugal, under the direction of Professor Luis da Silva.

Modeling of cyclic connection response, as illustrated by the hysteresis curves in Figure 3 is a very complex task. In particular, the pinching effect that is reflected in Figure 3b has been very difficult to model. However, a suitable model was developed by the Italian researchers Della Corte, De Matteis, and Landolfo (2000), and the study by Professor

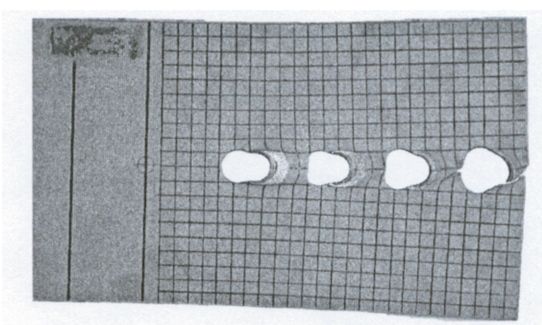


Fig. 1. Shear failure of bolted connection (photo courtesy of Darko Beg).

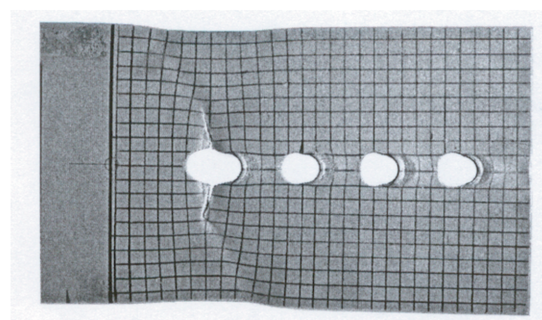
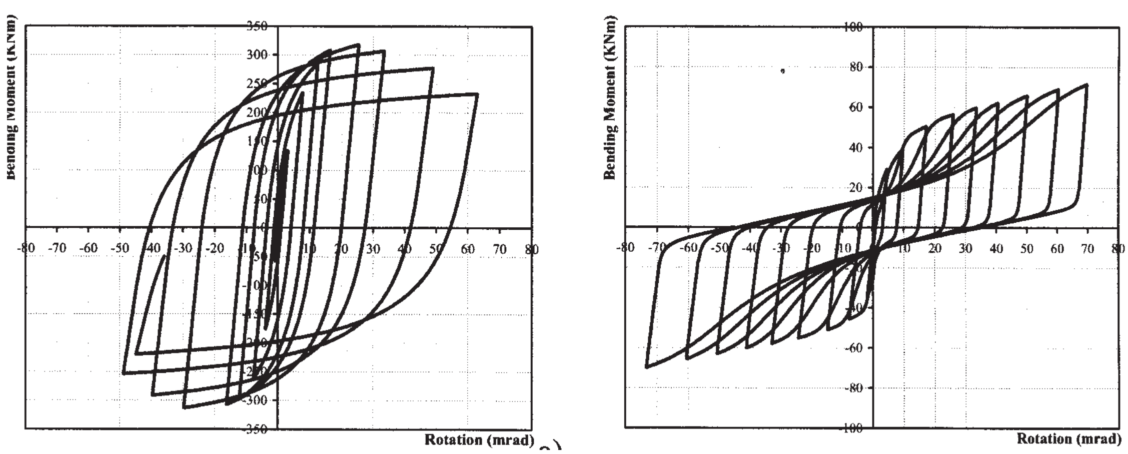


Fig. 2. Net cross section plate fracture (photo courtesy of Darko Beg).



(a) (b)

Fig. 3. Typical connection hysteresis curves without (a) and with (b) pinching response (courtesy of Luis da Silva).

da Silva and his team has now evaluated and categorized a total of 216 connection tests from a variety of international sources (Nogueiro, da Silva, Bento, and Simoes, 2007).

The study examined the connections for primary response parameters, with the aim of developing a model for a generic connection subjected to seismic loads. It also included the effects of different cyclic load protocols. The key observations and conclusions are:

1. The connection types that were included are: (i) fully welded beam-to-column connections; (ii) connections with welded flanges and bolted webs; (iii) top and seat angle connections; (iv) bolted end-plate connections; and (v) dogbone connections.

2. 21 different kinds of loading histories were represented in the connection test data base.

3. The parameters that are necessary for appropriate analysis are detailed for all of the connection types

4. Connections with and without pinching effects are included. The pinching effect is critical for a number of common connections, such as various European end-plate types.

The research project is continuing, looking to establish acceptable standardized connections with stable hysteresis loops. Parametric studies aim to determine the sensitivity of the various connection types to the strength and stiffness effects that control their behavior.

Estimation of Cyclic Characteristics for Thin Web Plates after Shear Buckling: This project has been conducted at the Tokyo Institute of Technology in Tokyo, Japan, under the direction of Professor Kikuo Ikarashi.

This study aimed at clarifying the post-shear-buckling characteristics of thin webs of girders, specifically by examining the influence of the width-thickness ratio of the web and the size of the flanges.

The test specimens were built into a loading assembly as shown in Figure 4, where the shear element is centrally located. The loads are applied as indicated by + and – signs at the far ends of the assembly, producing an antisymmetric shear distribution. The researchers observe that once shear buckling has occurred and an incomplete tension field has been formed, the web shear is maintained at a certain "shelf" level even though the deformation increases. This is similar to the plastic moment that is developed in a compact beam, for example. The magnitude of the shelf shear value increases when the flange area increases. This is as would be expected.

Figure 5 shows one of the specimens after failure. The post-buckling load-deformation characteristics consist of three parts, as follows: (i) unloading part; (ii) shelf (plateau) part; and (iii) tension field part. The researchers have used the failure model to establish a multilinear model which in turn is used to define the post-buckling load-deformation relationship.

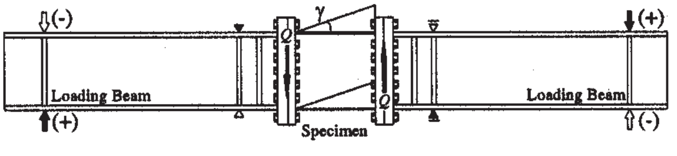


Fig. 4. Loading assembly and shear post-buckling specimen (courtesy of Yoshihiro Kimura).

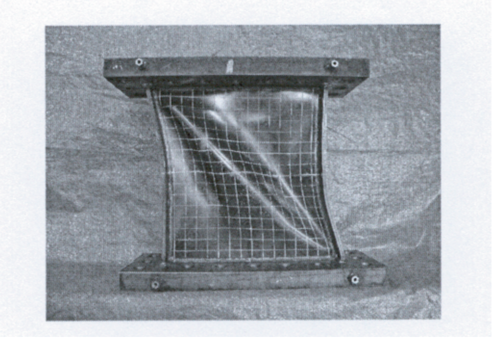


Fig. 5. Post-buckling appearance of test specimen (photo courtesy of Yoshihiro Kimura).

COMPOSITE CONSTRUCTION FOR BUILDINGS

System Behavior Factors for Composite and Mixed Structural Systems: This is a major, three year project that is funded by the NEES program of the National Science Foundation and AISC. It is a joint effort between Georgia Institute of Technology and the University of Illinois at Urbana. Professors Roberto T. Leon (Georgia Tech) and Jerome F. Hajjar (University of Illinois) are the project directors.

The project has three main objectives, as follows:

1. Develop comprehensive guidelines for determination of the equivalent stiffness of composite columns, to be used in seismic analysis and design of composite frames

2. Upgrade the computational models that are available for the analysis of complete composite systems, incorporating connection modeling and previous studies of composite beam-columns

3. Determine improved system response factors for composite framing systems

In addition to the facilities of Georgia Tech and the University of Illinois, the experimental and data acquisition facilities of the NEES-supported MAST Laboratory at the University of Minnesota will be used for testing of a wide range of composite beam-columns under three-dimensional realistic loading. The experimental work at the University of Minnesota will be complemented by the development of component models for beam-to-column connections and column base connections. A total of 18 full-scale beam-column tests will be run, using rectangular and circular concrete-filled hollow structural sections. The tubular members will have high wall *b*/*t* ratios, going beyond what is currently allowed under the AISC Specification (AISC, 2005). Further, they will utilize various concrete strengths and column slenderness ratios, and the specimens will be tested for bending about both of the major axes.

The project's focus on construction will likely be buildings in the five to 20 stories range. These constitute a major share of the market. It is therefore anticipated that the results of this unique, large-scale project will have significant and early impact on design and construction practices for composite structures in the US. There is great industry and designer interest in the project, and the researchers are working closely with the AISC Research Committee and the Committee on Specifications.

MODELING ELEMENTS FOR STEEL FRAMES

Practical Design Methods for Steel and Composite Frames with Semi-Rigid Connections: This study has been conducted at the University of Navarra in Pamplona, Spain, under the direction of Professor Eduardo Bayo.

Semi-rigid (PR) connections and frames have been the subject of numerous studies over the past 20 years, with design recommendations provided by the Commentary of the AISC Specification (AISC, 2005) and by Section 1.8 of Eurocode 3 (CEN, 2005). A number of practical approaches have been developed, but the application in practice continues to be very limited. There are many reasons for the limited market penetration, but the lack of practical computer software is certainly the major influence. The complexity of the issues of frame analysis and stability, coupled with the very large number of connections with greatly varying stiffness properties, are paramount effects of the limited acceptance among designers.

The primary aim of Professor Bayo's research project has been the development of a simplified, design-oriented method of analysis that carries the work of the engineer efficiently from global analysis through the final design of the connections. In this respect, the so-called component method of connection design that is detailed in Eurocode 3 (and 4) has been a major advantage.

Two procedures have been developed for steel and composite framing systems, as demonstrated by the flowcharts of Figures 6 and 7. Figure 6 provides the outline for elastic analysis; Figure 7 gives the data for plastic analysis. It is emphasized that European codes are based entirely on limit states approaches.

Following a preliminary sizing of members and connections, the critical step of assessing the initial connection stiffness is taken. Using these properties, the structural analysis is then performed, and the necessary moment capacity and other connection properties are derived from the results of the analysis. The final sizing of the semi-rigid connections is done as the last step in the design process, as illustrated by the examples in two papers prepared by the researchers (Cabrero and Bayo, 2005; Gil and Bayo, 2007). Extensive parametric studies were conducted as part of the research project. Specifically, detailed data are given for extended end-plate steel connections, and for flush end-plate composite connections.

OTHER STRUCTURES

Storage Racks in Seismic Areas: Project SEISRACKS, as it is referred to by the researchers, is being conducted at the University of Liège in Liège, Belgium. The project directors are Dr. Hervé Degée and Professor André Plumier. The work is supported by the European Research Fund for Coal and Steel.

The study is another major, multi-country effort within the European Union. Thus, parts of the project have been carried out at the Technical University of Lisbon in Lisbon, Portugal, and some tests have been run at the central European experimental laboratory JRC at Ispra, in Italy. Shaking table tests were performed at the National Technical University of Greece in Athens, Greece.

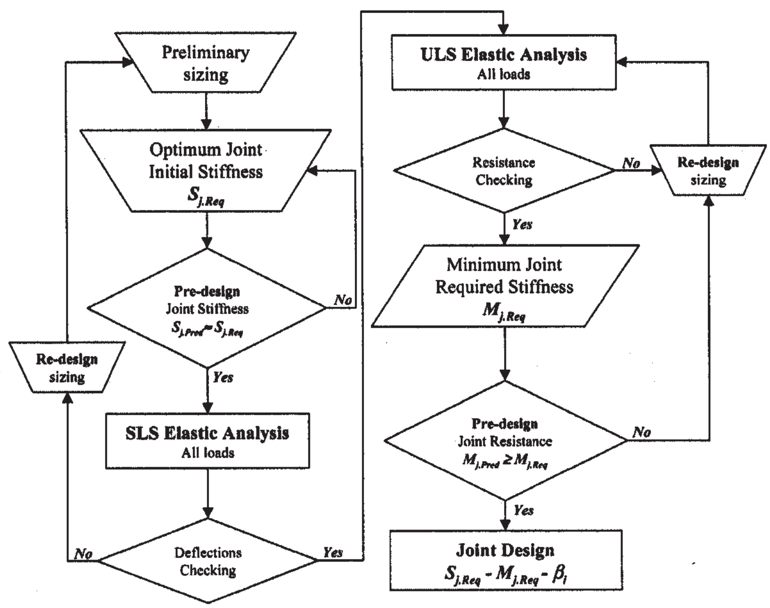


Fig. 6. Elastic analysis procedure for semi-rigid frames (courtesy of Eduardo Bayo).

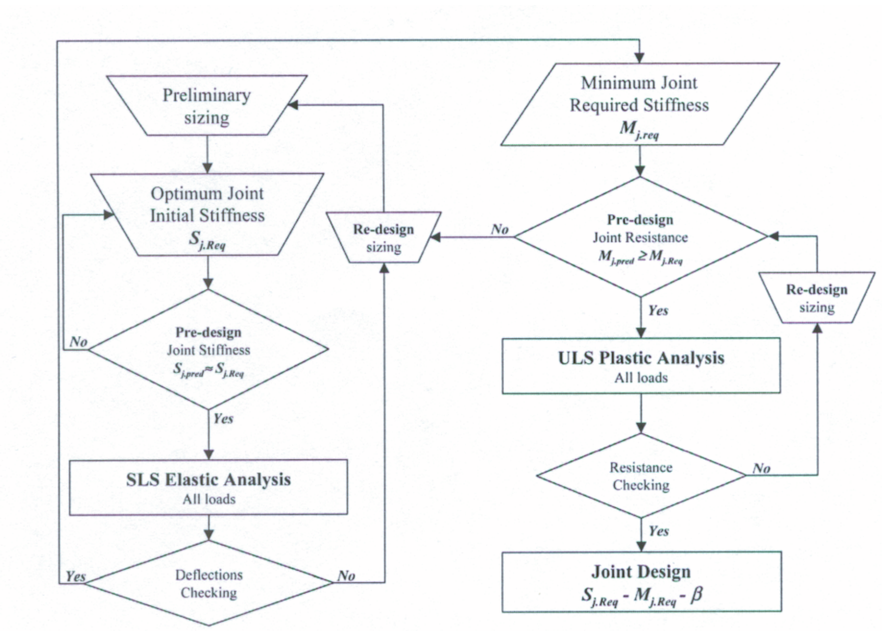


Fig. 7. Plastic analysis procedure for semi-rigid frames (courtesy of Eduardo Bayo).

Storage racks can be major multi-story structures; they utilize unique beam-to-column connections that are needed for easy assembly of the racks. As a result, the connections tend to be very flexible, with unique response characteristics and limit states. In seismic regions the behavior and strength of these structures is a major issue. The main aims of the project have been to increase the database for the dynamic behavior of the racks, specifically towards the development of the European design requirements. Advanced numerical models have been developed by the research team at the University of Liège, which is now conducting extensive parametric evaluations.

The loads for rack structures are unique, through the use of pallets that carry the products that are to be stored by the rack. The sliding of pallets during earthquakes is a critical issue; this was part of the shaking table tests conducted in Athens. The numerical procedures have been calibrated to take into account such sliding; although the researchers also note that the sliding in some cases will affect the rack in a positive fashion. However, the phenomena are very complex.

Figure 8 shows a rack that was tested for pushover response. The importance of connections and members in the first level of the structure is critical, as can be envisioned.

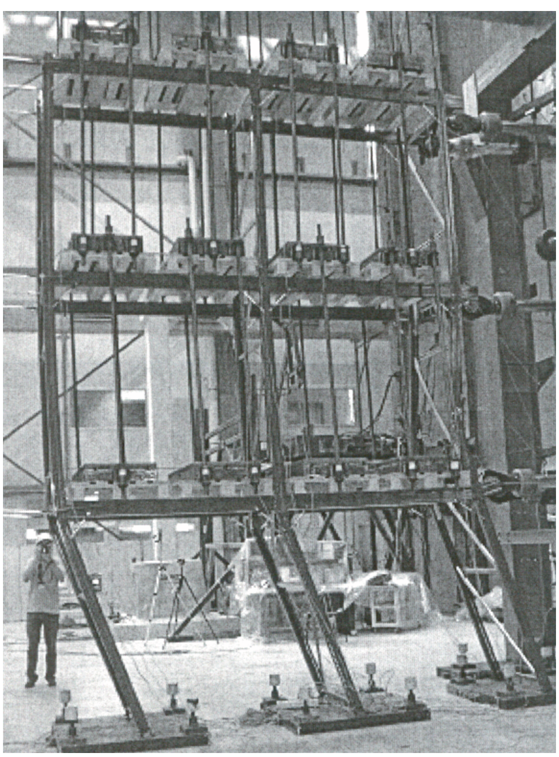


Fig. 8. Rack structure subjected to pushover test (photo courtesy of Hervé Degée).

REFERENCES

AISC (2005), *Specification for Structural Steel Buildings*, ANSI/AISC 360-05, American Institute of Steel Construction, Inc., Chicago, IL.

Cabrero, J.M. and Bayo, E. (2005), "Development of Practical Design Methods for Steel Structures with Semi-Rigid Connections," *Engineering Structures*, Vol. 27, No. 8, pp. 1125–1137.

CEN (2005), *Eurocode 3: Design of Steel Structures— EN 1993*, Comité Européen de Normalisation, Brussels, Belgium.

Della Corte, G., De Matteis, G., and Landolfo, R. (2000), "Influence of Connection Modelling on Seismic Response of Moment Resisting Steel Frames," in "Moment Resistant Connections of Steel Building Frames in Seismic Areas," F.M. Mazzolani, ed., E. and F.N. Spon Publishers, London, England.

Gil, B. and Bayo, E. (2007), "Practical and Efficient Approaches for Semi-Rigid Design of Composite Frames," *Steel and Composite Structures*, Vol. 7, No. 2, pp. 161–184.

Hardash, S.G. and Bjorhovde, Reidar (1985), "New Design Criteria for Gusset Plates in Tension," *Engineering Journal*, AISC, Vol. 22, No.2, pp. 77–94.

Nair, R. Shankar (2007), "Stability Analysis and the 2005 AISC Specification," *Modern Steel Construction*, May, pp. 49–51.

Nogueiro, Pedro, da Silva, Luis, Bento, Rita and Simoes, Rui (2007), "Numerical Implementation and Calibration of a Hysteretic Model with Pinching for the Cyclic Response of Steel Joints," *Advanced Steel Construction*, Vol. 3, No. 1, March, pp. 459–484.

ACKNOWLEDGMENTS

Special thanks are due the following members of the International Structural Steel Research Advisors (ISSRA) who provided input to this paper:

Eduardo Bayo, University of Navarra, Pamplona, Spain

Darko Beg, University of Ljubljana, Ljubljana, Slovenia

Yoshihiro Kimura, Nagasaki University, Nagasaki, Japan

René Maquoi, University of Liège, Liège, Belgium

Luis da Silva, University of Coimbra, Coimbra, Portugal

Additional assistance has been provided by Hervé Degée, University of Liège, Liège, Belgium; Roberto Leon, Georgia Institute of Technology; and Thomas Schlafly, AISC Director of Research.