Current Steel Structures Research

REIDAR BJORHOVDE

This is the third contribution in the *Engineering Journal's* series of papers that address ongoing research activities around the world. The subject matter details hot-rolled steel and composite construction as it applies to buildings and bridges. The topical areas vary somewhat from one issue to the next, but studies of steel materials, fabrication issues, connections, member and frame performance and stability, composite structures, structural systems, and bridge design and construction are the primary fields. Details of approaches and findings and their applicability to American practice are provided as much as feasible, and the locations of the researchers and their institutions are identified.

The subjects presented in this paper reflect an interesting blend of research into member behavior and strength and the addition of new results for the database that has been used to develop steel design codes for the past 30 years. In addition, several major studies around the world are now aiming to resolve the design issues related to fire and blast, a subject of great interest to the American design profession for a number of years. These investigations are significantly aided by advanced software, to allow the modeling of structures for high temperatures and very large deformations and deformation-induced forces. The response characteristics of structural systems for frames and bridges are always relevant, as are connection techniques and methods. One of these studies is looking at the behavior and strength of steel elements with glued joints, redefining and bringing novel adhesives into efforts that were started more than 40 years ago.

It is important to note that several of the projects reflect collaborative efforts between universities, research laboratories and firms from private practice and industrial companies. This is a project approach that is unusual in the United States, but it may offer significant advantages insofar as practical applications and code developments are concerned. Further, since the design of complex structures goes well beyond "normal" solutions, practicing engineers may be able to offer critical input to engineering research activities.

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

STRUCTURAL MEMBERS

Characteristics and Behavior of Plasma-Cut Welded H-Shaped Steel Columns

Siva Sivakumaran at McMaster University in Hamilton, Ontario, Canada has directed this project.

Welded built-up columns have commonly been used in various locales and projects around the world. Hot-rolled W-shapes continue to be the best product for most structures, but there are a number of cases for which custom-made cross sections are needed. In times past, the shapes would be welded together from universal mill (UM) or flame-cut (oxygen cut) plates, and some very heavy built-up shapes were used for high-rise structures in particular. Residual stress and column strength data for such welded shapes were incorporated into the database that was used to develop the Structural Stability Research Council (SSRC) column curves, and these curves in turn are the basis for the column equations in the AISC Specification and a number of other design standards in the world.

Welded built-up columns with universal mill plates exhibit high compressive residual stresses at the rolled edges and correspondingly low column strength, and these types of shapes have not been used for many years. Several codes (Canada's S16, for example) specifically prohibit the use of UM plates for such applications. Flame-cut (FC) plates, on the other hand, have tensile residual stress at the edges and therefore provide higher column strength. Columns made from FC plates have been used for many projects.

Recognizing that fabrication methods have changed significantly over the years, techniques such as plasma and laser cutting, for example, are now commonly used in shops. The heat input and cooling period associated with such processes are different from those of flame-cutting, for example. It might therefore be expected that residual stresses and consequently column strengths of shapes built-up from such plates will be different.

This was the rationale for the project carried out at McMaster University. A variety of column sizes and slenderness ratios in 50 ksi steel with plasma cut (PC) plates as well as flame-cut plates (for comparison) were physically tested for weak axis flexural buckling, and residual stresses and initial out-of-straightness values were measured. It was found that the column strengths of the PC and the FC columns were similar, although the FC columns were slightly stronger for low slenderness ratios (38 < L/r < 76) and the PC columns exhibited somewhat higher strength for higher slenderness ratios (L/r > 76). This is consistent with the higher tensile residual stresses in FC plates. However, the differences were not significant. Overall, the new data fit within the existing database for columns, and no changes are needed for the design criteria, including the values of the resistance factors.

PERFORMANCE OF STRUCTURES UNDER FIRE AND OTHER EXTREME LOADING CONDITIONS

Design of Steel and Composite Cellular Beams Subjected to Fire

This is a collaborative project between the University of Liege, Belgium and steel producer Arcelor from Luxembourg. Jean-Marc Franssen from the University of Liège is the director of the study.

The cellular beams are also known as SmartBeams™ in the United States; they have been used in various construction projects in Europe and now also in the U.S. An example of a severely deflected beam is shown in Figure 1, reflecting the kind of deformation demands that are associated with fire conditions. The study aims at determining the response characteristics of these members, with special emphasis on the local temperatures and strain demands in the regions surrounding the circular openings. Further, the local stability of the web areas between the holes (the "web posts") is important for the Vierendeel modeling that is commonly used for the cellular beams. Finally, the shear connection between the floor slab and the beam is also being modeled.

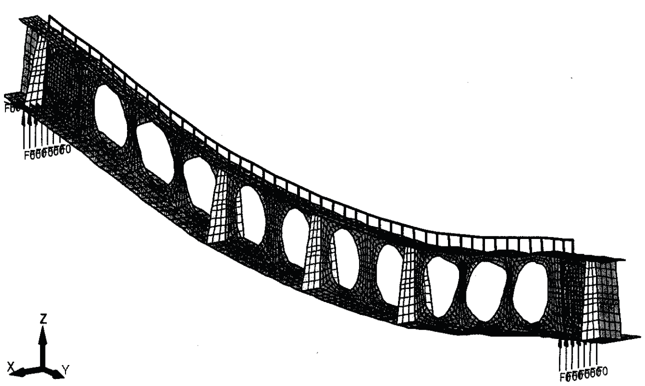

Fig. 1. Cellular beam under severe deflection conditions.

Failure of Floor Slabs under Extreme Loading

This project is conducted at Imperial College in London, England, under the direction of Bassam Izzuddin and Ahmed Elghazouli.

The primary objective of the study is to arrive at computational models for composite floor slabs under fire conditions. Restraint conditions are incorporated in the models, and eventually the theoretical models will be evaluated through physical tests of composite beams as well as two-way floor slabs. The project offers the potential for significant improvements in the assessment of structural stability and robustness of structures subjected to fires.

Behavior and Design of Steel Structures under Fire

This is a joint project between the Harbin Institute of Technology (HIT) in Harbin, China, and the Hong Kong Polytechnic University (HKPU) in Hong Kong. Drs. C.-K. Iu and X.-X. Zha from HIT and Professor S. L. Chan from HKPU are the directors of the effort.

Starting from the behavior and strength of individual steel members under elevated temperatures and proceeding to complete framing systems, at this stage of the work the emphasis is placed on the development of numerical techniques. In a related study the HIT research group is also examining the post-fire conditions of structures and their elements. One of the primary issues in this part of the project are the post-fire cooling conditions and the fact that localized member failures due to large contraction deformations have been observed in some building fires. It is anticipated that full-scale fire tests will eventually be conducted.

Reinforcing of Steel Blastwalls Using Energy Absorbing Impact Barriers

This is a collaborative project, conducted at Imperial College in London, England (Dr. L.A. Louca) and at the National University of Singapore (Professor Y.S. Choo).

Blast resistant walls (often referred to as blastwalls) are integral elements in offshore structures, aiming at protecting personnel and critical equipment and structural elements in cases of fires or explosions. Past experiences have shown that low-pressure conditions are not adequate as design considerations for these types of protective walls, and the current effort aims to develop significantly hardened wall systems that at the same time can offer energy absorption capacity. In certain ways this is similar to what is being done for connections and structures that will be subjected to major seismic events.

At this time the research work focuses on numerical modeling and correlation with the few test results that are available. Due to structural scales and magnitudes of loads most physical testing will be prohibitively expensive. On the other hand, it is expected that local failure modes (such as the failure of individual welds and other types of connection details) will point to the primary limit states that need to be incorporated in any design criteria. Practical design considerations will eventually be completed.

It is not anticipated that the blastwalls will become practical protection elements for land-based structures such as high-rise buildings or industrial installations. The concept may be feasible for power plant structures and similar components of the national infrastructure.

PERFORMANCE-BASED LIMIT STATES AND DESIGN CONSIDERATIONS

Progressive Collapse of Tall Buildings

This project is conducted at Imperial College in London, England; the directors are Drs. Bassam Izzuddin and Ahmed Elghazouli and Professor David Nethercot. It is a collaborative effort with the London offices of the design firm Ove Arup and Partners.

On the background of one of the first and well-known cases of progressive collapse, the Ronan Point precast concrete structure in England and the criteria that were promulgated after that failure, the project aims at developing improved, practice-oriented guidance for engineers to assess structural robustness of multi-story buildings. The study focuses on two areas of response, both of which have been observed in actual collapses:

- The impact of a failed floor on lower floors in the structure
- Dynamic column removal

For the case of a failed floor falling onto a lower one, the ductility and rotation demands for the connections of the lower floor are critical, since these characteristics play a major role in the evolution of the collapse. In addition, catenary action of beams, girders and other elements of the floor as well as spans and floor heights, service loads and connection types have to be considered. These parameters have been incorporated into the software that is utilized, although the current state of the solution is too complex for practical applications. The next phase of this part of the project aims at providing a simplified but realistic and practical design tool.

The dynamic column removal process has built upon the model that is incorporated in the American GSA guidelines, for which a dynamic amplification factor of 2 is used. However, the researchers observe that the GSA solution does not take into account the energy dissipation associated with plastic deformations, nor does it provide a practical means of estimating connection ductility demands. The current status of the nonlinear solution reflects the damage in the immediate vicinity of a removed column as well as the accumulation of damage in other areas of the structure. Excellent agreement has been found between the simplified and the full nonlinear analysis results. Additional numerical evaluations are underway.

Seismic Performance of Steel Frames by Using Simplified Methods

This study is being conducted at the Technical University Federico Santa Maria in Valparaíso, Chile under the leadership of Professor Carlos Aguirre.

Considering that Chile occupies some of the most seismically active regions of the world, earthquake response characteristics are primary factors for all structural engineering research and design developments. Further, in addition to having an active building and bridge construction industry, numerous installations for mining and other industries have unique demands for strength, stiffness and ductility, not the least because of unusual mass distributions in the structures.

The project focuses on assessments of performance-based criteria for a range of steel-framed multistory buildings (4, 8, 12 and 16 stories). Using ground motion records for several earthquakes that occurred over the past 20 years, the Spectrum Capacity Method and the N-2 (nonlinear analysis) Method are used to analyze the frame responses. The initial results are promising, indicating that either of the two methods may be suitable for simpler and still realistic evaluations of the building performances.

It is also recognized that significant educational work must be undertaken to ensure that the concepts of performance-based design are understood and will be used by code writers and eventually by practitioners. This is not unique to Chile: performance based design is being aggressively studied in many areas, but professional recognition is most likely still some time away from uniform acceptance.

NOVEL MATERIALS AND APPLICATIONS

Glued Connections and Members for Structural Steel Applications

This is a large-scale research and development effort at the Technical University of Brandenburg—Cottbus, in Cottbus, Germany. The project director is Professor Hartmut Pasternak.

Glued joints have been used extensively in wood construction and now also in applications involving fiber-composite materials and the like for retrofitting reinforced concrete and masonry structures. Many years ago there were also developments towards the use of glued joints for steel bridges, but the studies did not progress very far, mostly because of issues related to the long-term stability against UV and other environmental effects for the glues that were used at the time.

The Cottbus project is currently examining applications for multistory frames and trusses as well as cladding. A range of epoxy-type adhesives is considered, some of which cure at room temperature and others at elevated temperatures. In addition to studying the basic strength and deformation characteristics of glued joints (tension, compression, shear, static versus dynamic loads), structural applications for joints and members are explored in detail because of the unique load-carrying mechanisms of the joints. Current results indicate that the elements perform well under compression and shear, under static as well as dynamic loads. Improved framing details are being developed, to ensure adequate shear transfer capacity and to reduce local bending effects.

It appears that the greatest promise for glued construction may be found in cladding applications and similar steel framing systems. This includes truss systems with members of various cross sections, and also certain light beam-to-column connections.

STEEL AND COMPOSITE BRIDGE STRUCTURES

Effects of a Midspan Diaphragm on the Dynamic Behavior of a Composite Railroad Bridge

This is a case study project carried out at the university INSA-Lyon in Lyon, France, in collaboration with the French national railroad administration, SNCF. The director is Professor Jean-François Jullien.

The bridge in question is a multi-girder bridge for the TGV high-speed trains of France. The concrete bridge deck is the primary contributor of transverse stiffness, and the effect of any transverse beams is not known. The transverse elements tend to be expensive additions to the structures. The project focuses on the use of diaphragms to improve transverse stiffness, including the modeling that is needed to assess the effectiveness of a diaphragm. Three-dimensional models have been developed for a nonlinear analysis procedure, including the dynamic train loads and the response of the bridge deck. A number of train speeds are also taken into consideration.

At this time the static and dynamic solutions show that the diaphragm does not contribute significantly to the transverse stiffness, and it may only be needed for accidental lateral loads on the bridge. Further analyses will determine whether the diaphragms may be omitted.

ACKNOWLEDGMENTS

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

Carlos Aguirre, Technical University Federico Santa Maria, Valparaíso, Chile

S.-L. Chan, Hong Kong Polytechnic University, Hong Kong, China

André Colson, National Association of General Contractors, Paris, France

Mike Gilmor, Canadian Institute of Steel Construction, Willowdale (Toronto), Canada

René Maquoi, University of Liège, Liège, Belgium

David Moore, British Constructional Steel Association, London, England

Additional appreciation is due Professor Hartmut Pasternak of the Technical University of Brandenburg—Cottbus, in Cottbus, Germany.