Current Steel Structures Research

REIDAR BJORHOVDE

This is the fourth of 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. Topics 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 how they apply to American practice are provided as much as feasible, and the locations of the researchers and their institutions are identified whenever such data have been given.

Among the subjects presented in this paper are several that focus on novel developments towards high- and super-high-strength steels, as well as further studies addressing characteristics of weathering steels for bridges. Similarly, a number of projects address the properties of cast steel, with notable applications in structures that have been designed with joints and other elements in cast steel. In an interesting development toward using methods that originally were based on the characteristics of light-gage cold-formed steel members, work is now under way in Australia in parallel with American studies, aiming at incorporating improved criteria for slender elements in hot-rolled structures through the use of the so-called Direct Strength Method that was developed in the United States. Extensive work in many locations continues to address seismic response characteristics and performance-based design approaches.

Significant cooperation between researchers and design and industry professionals is a major factor for several promising developments, especially as far as structural systems and construction techniques are concerned. In a unique case of collaboration, a special case of bridge loading has been studied simultaneously in France and Germany, although different aspects of the subject matter were addressed by the two institutions.

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

Buckling-restrained braces, steel plate shear walls and shear panel damping devices have been examined in several investigations; they are also used in a number of construction projects. Some studies are examining the seismic response of staggered truss systems and other unique framing systems.

MATERIALS ISSUES

Improved Weathering Steels for Bridge Applications: This is a project being conducted at the Research Institute of Industrial Science and Technology (RIST) in Seoul, Korea, with additional contributions from the steel company POSCO. Dr. Tae-Yang Yoon of RIST is the project director.

It is known that traditional weathering steel will oxidize much faster under certain atmospheric conditions, and the "permanent" corrosion protection therefore may not be as effective as originally conceived. This has been known in the United States for some time insofar as the influence of salt-borne standing water for bridge applications is concerned. In coastal climates the corrosion process is accelerated significantly. This was the basis for the RIST project and a new weathering steel that has been developed by POSCO. A nonmetallic alloying element (Ca) has been used for the steel, which, together with the new rolling process, SIDT (strain-induced dynamic transformation), has resulted in a fine-grained microstructure material with four times the corrosion resistance of the usual weathering steel. The steel has a tensile strength of 500 MPa [approximately 73 ksi] and excellent fracture toughness.

The use of the material for bridge structures is now being examined through various physical tests at RIST.

Extra High Strength Steel Plasticity and Modeling: This project is conducted at the Luleå University of Technology in Luleå, Sweden, under the direction of Professor A. Olsson.

The study aims at determining structural design parameters for steels with yield stresses as high as 1,100 MPa (160 ksi). Using a unique biaxial test specimen, the plastic deformation properties have been obtained and evaluated in comparison with uniaxial test data that are commonly used to obtain material properties. Whereas the three material grades that were examined display some amount of plastic deformability, further work is now under way to examine structural performance criteria in particular. One of the issues with such high-strength materials is that the modulus of elasticity, E, in some cases is a function of the rolling direction of the material. The value of E is generally close to that of "normal" steel with yield stress levels of 36 to 100 ksi, for which E is assumed to be a constant.

In a related project at the Luleå University of Technology, Drs. Clarin and Lagerqvist have examined residual stresses in square hollow structural section (HSS) elements in the same three grades of steel. The data indicate general agreement with such data for milder grades of steel, and, as would be expected, the residual stress-to-yield stress ratio is significantly lower for the higher strength grades. This was also found in past studies of the residual stresses in materials with yield stress as high as 100 ksi.

The practical uses for civil engineering structures of the extremely high-strength materials are still some time off. For the usual buildings and bridges, where serviceability is often the governing criterion, it is difficult at this time to estimate the potential usage of these steels. Ductility and fracture toughness demands will certainly limit the applicability of the materials, but unique requirements may prove that it is possible to derive actual structural benefits. This may especially be the case for tension-type structures and elements.

STRUCTURAL MEMBERS AND JOINTS

Shallow Composite Beams with Web Openings as Connectors: This shallow composite beam is a new system that has been developed in a project at Korea University in Seoul, Korea, with Dr. Sang-Dae Kim as the director.

The aim of the project was to develop a floor assembly that would reduce the floor-to-floor height in multi-story buildings. The end product is the so-called Innovative, Technical, Economic and Convenient Hybrid (iTECH) system, which is an asymmetric steel assembly with web openings where a plate is welded on top of inverted structural tees that have been cut in honeycomb style. The assembly is completed in a fabrication shop, and concrete is placed within the honeycomb system in situ. Shear connectors are not used, since the longitudinal shear strength is developed through the bond at the interface of the concrete and steel and through the bearing strength of the opened web area. A series of analytical and physical tests were conducted as part of the development process, with very satisfactory performance results.

It has been found that this composite floor facilitates easy and rapid erection of the structure. The economics of buildings using the iTECH system is now being investigated on a larger scale, for application to a range of building projects.

Cast Steel Joints: Researchers at Tongji University in Shanghai, China, have conducted numerous projects related to the strength, performance and design of various types of cast steel joints for planar and space trusses, including a study of the very complex cast steel elements that were to be used in the new South Railroad Station in Shanghai. The latter project included a full-scale test as well as 3D finite element analyses. Figure 1 illustrates the test setup, noting that the dimension L_2 is approximately 0.8 m (2 ft 8 in.), the dimensions, L_1, are approximately 0.5 m (1 ft 8 in.), and the net distance between the top ("balance") beam and the rigid support beam is about 2.4 m (8 ft).

The tested mechanical properties of the cast steel were a yield stress of 339 MPa (49 ksi), a tensile strength of 569 MPa (83 ksi), a modulus of elasticity of 214 GPa (31,000 ksi) and an elongation at fracture of 28.6 percent. These are comparable to the typical properties of ASTM A572 steel, for example.

Socket-Type Footings for Composite Columns: Innovative research work on improved column footings has been conducted at University of Sannio, Benevento, Italy under the direction of Dr. L. Di Sarno.

In particular, aiming to improve the response characteristics of column base connections under static as well as cyclic loads and recognizing that the typical simple connection (see Figure 2a), in general, offers limited advantages, the researchers have developed a socket-type footing (see Figure 2b) that provides much larger energy absorption capacity and improved structural response, including enhanced inelastic redistribution properties of the column bases as well as the columns. Figure 2 illustrates the two types of column bases.

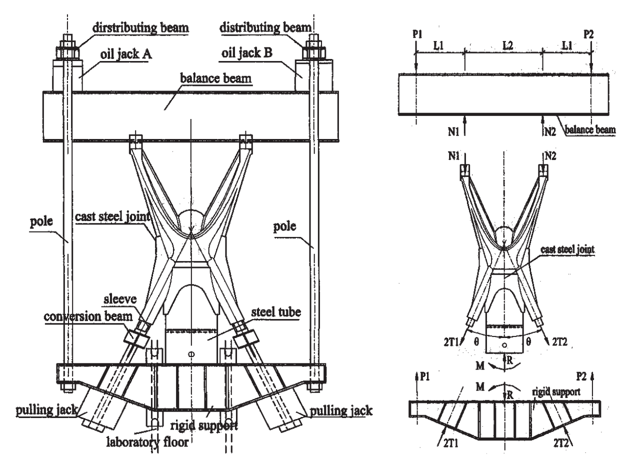


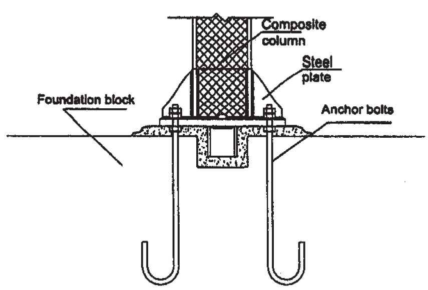
Fig. 1. Test setup for cast steel joint of the south railroad station of Shanghai.

SPECIAL STRUCTURES AND SYSTEMS

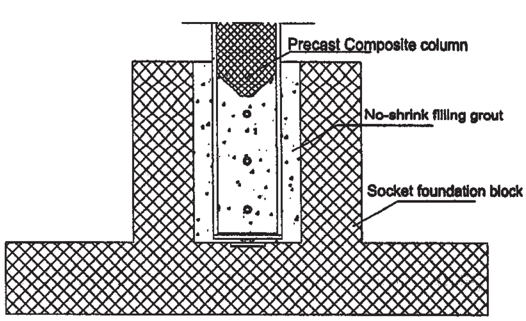
Improved Modeling and Assessment of Lattice Towers: This effort represents a long-term and very successful development, starting at the University of Queensland in Brisbane, Australia, and over the past several years at the City University of Hong Kong, under the continued leadership of Professor S. Kitipornchai.

One of the major issues in the assessment of the strength and performance capacity of lattice towers for the electrical utility industry is that for many years it has been required that full-scale tower tests be conducted to determine the load-carrying capacity and stability. This is still the case in the United States and several other countries. At the same time it is recognized that such tests are not only very complicated to conduct and can only be done at very few facilities, but the tests are also very expensive.

A part of the difficulties associated with tower analysis and design is the fact that these structures are assumed to be trusses, and the influence of secondary braces is neglected.



(a)



(b)

Fig. 2. Traditional and socket-type column footings.

The modeling approach of the researchers takes into account realistic end conditions for main members and braces, connection eccentricities, load application points and member buckling conditions. In particular, it is demonstrated that the stiffness of the bracing connections is a major contributor to tower strength and performance. Although the braces generally have very low axial forces, they have significant effects on the strength of the tower.

The modeling approach that has been developed provides results that are in very good agreement with the tests that have been conducted. It offers significant advantages over the traditional physical testing procedure.

Behavior and Strength of Scaffolding Systems: This project reflects an ongoing research and standards development effort on the design, behavior and strength of scaffolds in steel and other materials, as conducted at the Hong Kong Polytechnic University under the leadership of Professors S.-L. Chan and K.-F. Chung.

Recognizing the importance of scaffolds for the entire construction industry, it is known that the design efforts for these types of structures tend to be very limited. The studies of the researchers have included full-scale test with good correlation to the analytical evaluations. The research work has resulted in refined and very practically oriented approaches to assess the stability and strength of steel scaffolds, including second order effects. Realistic connection characteristics as well as structural imperfections are also taken into account.

SEISMIC EFFECTS ON MEMBERS AND FRAMES

Strengthening Reinforced Concrete Columns by Encased Steel Shapes: This project is a joint effort of the University of Liège in Belgium and the University of Trento in Italy, with Professor A. Plumier from Liège as the director.

The primary aim of this project is to mitigate the "soft story" failure mechanism in reinforced concrete frames by strengthening the reinforced concrete (RC) columns in the key stories by fully encased steel shapes. The concept focuses on the use of the encased steel shapes as "fusible links" or members that are able to dissipate the earthquake energy. The intent is to rehabilitate the buildings, without having to strengthen all of the RC members.

The research effort has involved analytical evaluations as well as a very large number of full-scale tests with cruciform column-and-beam elements and infill walls. The column is subjected to a constant axial load; the assembly is then loaded by a cyclical lateral load applied at the level of the top of the column. The number of test parameters is large: three different ductility demand levels in accordance with the current (European) design requirements, two types of reinforcing steel anchorage details, steel shape panel zones with and without continuity plates, and strong and weak axis orientations of the encased shapes. Of the 38 tests, 19 focus on the response of the composite column itself; 19 focus on the steel-concrete panel zone.

Design criteria are in the process of being developed, taking into account all of the representative parameters that have been tested. The criteria will be calibrated to the current design codes.

Buckling-Restrained Braced Frames with Backup Moment Frames: This study has been conducted at Tongji University in Shanghai, China, with Dr. Qiang Xie as the director.

The aim of the project was to develop a system that would mitigate the large post-yielding story drifts that sometimes occur in some of the stories of frames with buckling-restrained braces (BRB). Using moment frames as the backup assembly, the evaluation focused on the stiffness levels that would be necessary for the moment frames in order to reduce the overall drift to acceptable levels. With 4-story and 12-story moment frames as the basic structures, the key parameters were various ground motions at two seismic input levels. The results show that no more that 10 percent of the moment frame stiffness is needed to achieve uniformity of story drifts for the BRB frame.

Performance of Steel Plate Shear Wall Frames with Low-Yield Steel: This study is part of an extensive testing program to determine the strength, stiffness and behavior of various steel frame structural systems under seismic loads. It is being conducted at the National Center for Research in Earthquake Engineering in Taipei, Taiwan, with Professor K.-C. Tsai as the director.

The frames that were used for this part of the research program utilized 345 MPa (50 ksi) steel beams and columns, with the shear wall in so-called *low-yield* steel. The low-yield material had an initial yield stress of 131 MPa (19 ksi); it is not an ASTM-approved grade. The columns and beams were the rough equivalent of W18 shapes; the shear wall had a thickness of 3 mm (⅛ in.). Reduced beam section connections were used for the beams, to force all of the beam inelastic action into these regions. Figure 3 shows the test assembly that was used (dimensions in mm).

The researchers have designated this type of assembly as a buckling-delayed shear wall. Specifically, the lower yield stress and the small plate thickness facilitate earlier onset of energy dissipation than what is found in more typical (in other words, thicker plate) shear walls. The improved performance was also aided by the lateral (out-of-plane) restrainers that were used for the beams; these elements were HSS members that are also shown in Figure 3.

Further research with this system is being undertaken to verify the applicability to a larger range of structures. But the initial results are very promising.

Hysteretic Performance of Shear Panel Dampers: This study has been conducted at the University of Nagoya in Nagoya, Japan, under the direction of Professor Tsutomu Usami.

Recognizing the significant energy dissipation capacity of shear members and elements, as is the case for steel plate shear walls, transversely and longitudinally stiffened girders and other members can withstand large deformations prior to buckling. This was the basis for the University of Nagoya project, where the shear panels have been identified as *passive energy dissipating dampers* (PEDD). The study incorporated extensive finite element evaluations of the potential performance of the dampers, using a range of panel thicknesses, web slenderness values, and stiffener placements.

The results demonstrated that all of the panel assemblies exhibited stable hysteresis loops without any pinching, with large energy absorption capacity. For example, the webs yielded completely prior to buckling. The researchers have also proposed suitable design criteria for the shear panels.

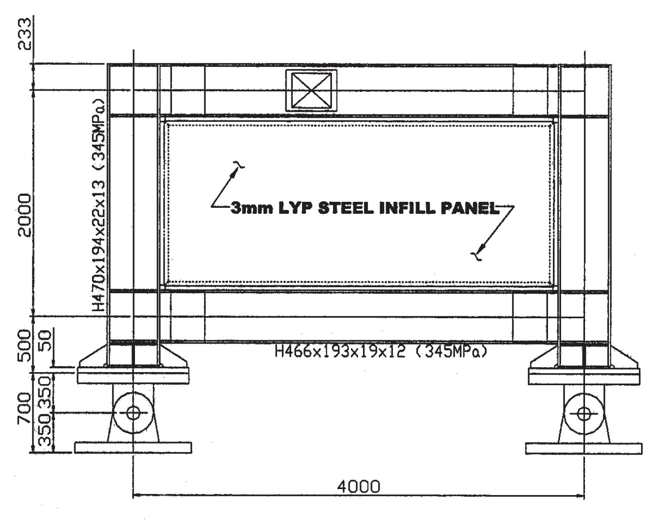


Fig. 3. Steel plate shear wall test specimen with low-yield steel.

BRIDGE STRUCTURES AND BRIDGE CONSTRUCTION TECHNIQUES

Patch Load Resistance of Longitudinally Stiffened Girder Webs: Patch loading (partial edge loading) has been the subject of two major European projects. One of these was conducted at the bridge design organization SETRA, located in Bagneux, near Paris, in collaboration with the university INSA–Rennes, in Rennes, France. The work was conducted by Professor Jean-Marie Aribert and structural engineer Laurence Davaine. The other patch loading project was located at the University of Stuttgart in Stuttgart, Germany, with Professor Ulrike Kuhlmann as the director.

In France and Germany, as in many other countries, bridge erection is now often done by incremental launching, whereby the girders are slid or rolled into position. Figure 4 shows an example. Since it is now possible to produce high-strength steel plates in thicknesses up to 150 mm (6 in.) and more, longer bridge spans have become the norm. It is not uncommon to launch bridges with spans as long as 120 m (360 ft), and such girders will typically have webs as deep as 4 to 5 m (13 to 17 ft).

Bridge girders using this construction method are particularly sensitive to web buckling under patch or partial edge loading. The researchers in France devised a theoretical treatment of the problem, using a finite element solution which subsequently was compared to the design criteria of the Eurocode.

The Stuttgart project utilized physical tests of seven bridge girder sections, with the number of longitudinal stiffeners, the position of the stiffeners, and the interaction between bending and shear as the primary test parameters. Figure 5 shows the general layout of the test specimen that was used. Among other results, it was found that closed section stiffeners enhanced the girder strength very significantly.

As was found in the French and the German studies, the results showed that the current European design criteria are conservative, in particular because they have been based on short patch loading lengths and open section stiffeners.

Fatigue Tests for Welded Joints with Ultra-Thick Plates: This study has been conducted by the Korean research organization RIST as a joint effort with the steel company POSCO.

Data on the fatigue performance of welded joints with very thick plates are limited, but they are much needed because of the use of such plates in many bridge structures. In the current RIST-POSCO project steel plates with thicknesses up to 100 mm (4 in.) in material with tensile strengths of 500 to 600 MPa (73 to 87 ksi) were used. The steel for the plates was produced through (1) a conventional rolling process and (2) a thermo-mechanically controlled process. The fatigue tests are currently under way, but tentative results indicate that the plate thickness is not a major factor.

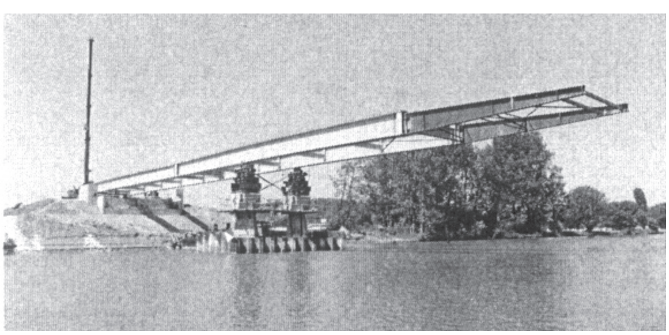


Fig. 4. Incremental launching of a bridge.

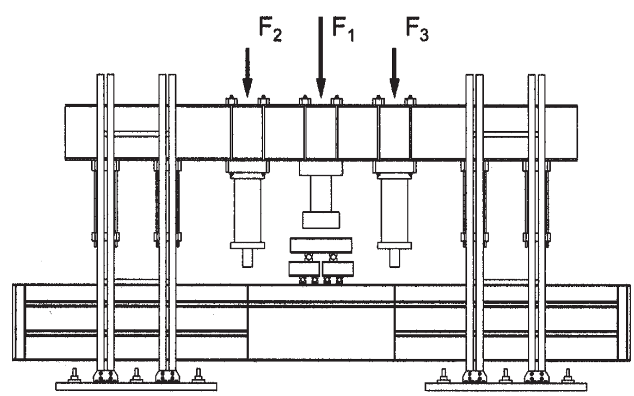


Fig. 5. Test specimen and assembly for bridge girder patch loading capacity.

ACKNOWLEDGMENTS

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

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

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

Jostein Hellesland, University of Oslo, Oslo, Norway

Sang-Dae Kim, Korea University, Seoul, Korea

Ulrike Kuhlmann, University of Stuttgart, Stuttgart, Germany

Guo-Qiang Li, Tongji University, Shanghai, China

René Maquoi, University of Liège, Liège, Belgium

K.-C. Tsai, National Center for Research in Earthquake Engineering, Taipei, Taiwan

Riccardo Zandonini, University of Trento, Trento, Italy

Additional contributions have been provided by Kit Kitipornchai of the City University of Hong Kong and Tsutomi Usami of the University of Nagoya in Nagoya, Japan.