Current Steel Structures Research

REIDAR BJORHOVDE

This is the second contribution in the *Engineering Journal's* new 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 collaboration between researchers in different countries is a unique and interesting feature of several of the projects described in the paper. Certainly the ease of electronic communication has been a facilitating mechanism, but many of the studies also involve physical testing. Equipment, testing protocols, and procedures tend to vary significantly from one country to the next, which can make meaningful interpretation of the results a very difficult task. The problem is that testing procedures are rarely standardized or even generally accepted, except for basic experiments such as tension specimens, stub columns, and flexural performance of beams subjected to uniform moment. The fact that these truly international projects are being conducted at all reflects the importance of global interaction, but most of all, the ability of the researchers to focus on key subject matter and to share their knowledge in a creative and productive fashion.

Finally, in years past the language barrier was a critical impediment to international interaction and projects. English has *de facto* become the international language of communication for all manner of business. This is clearly benefiting the engineering community in all countries, as it represents one of the most "portable" of the professions, although familiarity with other languages and the cultures they reflect continues to be a major facilitator of successful interaction between individuals and their institutions.

Reidar Bjorhovde is the research editor of the AISC *Engineering Journal*.

STRUCTURAL MEMBERS

Analysis and Behavior of Beams Curved in Plan: Mark Bradford at the University of New South Wales in Sydney, Australia has directed this project.

The study reflects the importance of horizontally curved beams and girders, which are used extensively for structures such as monorail girders and steel and composite bridge girders. Practical design information is limited and complex, primarily because of the nonlinear interaction between bending and torsional displacements. This is further complicated for the ultimate strength by the yielding that will occur due to bending as well as torsion. The researchers note that it is logical to expect any design criteria to converge to traditional lateral beam buckling treatment when the curvature is very small, but many recommendations do not recognize this and are therefore not correct.

A new line-type finite element was developed to incorporate all of the relevant nonlinearities. Following an evaluation of the response of a range of curved beams, a set of accurate design equations has been developed that are in agreement with the design specifications of a number of countries. In addition, a series of physical tests were conducted to assess the accuracy of the model and the recommended criteria. The latter are formulated as bending-torsion interaction equations, a physical representation of which is shown in Figure 1. The horizontal axis represents non-dimensional

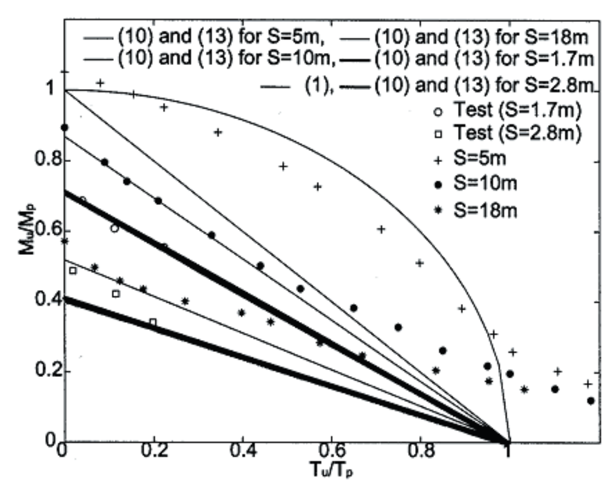

Fig. 1. Comparison of bending and torsional strength from interaction equations with analytical and experimental results.

torsional strength, T_u / T_p, where T_u is the ultimate torsional moment and T_p is the torsional plastic moment. The vertical axis gives the non-dimensional bending moment values, M_u/M_p, similar to what is used in American design equations. S is the horizontal span of the curved beam, with values ranging from approximately 6 ft (1.7 m) to 9 ft (2.8 m) for the test specimens, and spans from 17 ft (5 m) to 60 ft (18 m) for the beams that were analyzed by the finite element model. The "open" points represent test results; the other symbols give the analytical data. The solid lines represent the tentative proposed interaction equations and offer a comparison with the experimental and analytical findings; the parenthetical numbers refer to certain equations. The correlation to tests and theory appears to be good.

Shear Resistance of Longitudinally Stiffened Panels: Darko Beg of the University of Ljubljana in Slovenia and Ulrike Kuhlmann of the University of Stuttgart in Germany are the co-directors of this international cooperative project.

The project aims to quantify the influence of the following parameters on the shear resistance of longitudinally stiffened panels, using physical testing and numerical simulation:

- Shape and amplitude of initial geometric imperfections
- Position of stiffeners
- Number of stiffeners (limited to one or two)
- Stiffener stiffness
- Shape of stiffeners (open or closed)

Four full-scale tests of short plate girders were conducted, with the webs loaded in shear. The webs used closed trapezoidal stiffeners: one version had the stiffeners placed at mid-height, another one used the stiffeners at two-thirds of the web height. Different stiffener stiffnesses were aimed at promoting overall web buckling in one case; in another, the stiffness was selected such that local buckling would take place. Material properties, as well as the magnitudes of the initial web imperfections were measured before the tests.

The tentative findings indicate that the normal panel stresses are more affected by the geometric imperfections than the shear stresses. Further, relatively low stiffener stiffness facilitates local buckling of the panels. Finally, it continues to be difficult to separate completely the individual influences of shear and bending.

Understanding the Behavior of U-section Steel Sheet Piles: Mike Byfield of the University of Southampton in England is the director of this research effort.

Over the years, Z-shaped piles have largely replaced U-shaped piles. This change was primarily prompted by the slip that was found by several studies to take place between individual U-piles, despite the fact that U-piles had performed very well for many years. The slip caused a significant loss of pile wall bending strength. This effect is recognized in the United States, and was the primary reason for adopting Z-piles in lieu of U-piles. However, construction projects in many other countries have continued to use the U-piles, primarily because they are easier to install.

The project undertook several ⅛ scale pile tests, with accurate representation of the loading the sheet pile walls will be subjected to in service. It was found that the interlock friction between individual piles actually prevents inter-pile movement (in other words, slip) in most permanent sheet pile walls. This appears to reaffirm the use of U-piles as an important element in construction projects.

FRAMES AND FRAMING SYSTEMS

Integrated Blast and Fire Analysis of Steel-Framed Structures: This is another project featuring international collaboration. Richard Liew of the National University of Singapore directs the effort, in cooperation with Jorgen Amdahl of the Norwegian University of Science and Technology in Trondheim, Norway.

The main objective of this study is to establish design guidelines for structures subjected to the extreme loads associated with fire and blast. Computational fluid dynamics and advanced nonlinear analysis programs are used to analyze representative structures. Among other considerations, a design approach has been developed that takes into account the catenary action of floor beams in post-flashover fire conditions.

The study also incorporates the effects of a fire that has been caused by blast. Specifically, the pressure wave generated by the explosion may lead to permanent deformations in some of the structural members and also influence their fire resistance. Figure 2a gives a graphical illustration of a frame that was first subjected to blast located approximately 20 ft from the center column in the external frame, showing the buckled column. Figure 2b shows the appearance of the structure following the blast-induced fire, and the results demonstrated that the structure would be able to survive these conditions without collapse. The guidelines that are being developed include criteria for the evaluation of the fire resistance of deformed systems.

Finally, it has been found that compact shapes under these conditions tend to behave as more slender members, as a result of the high strain rate associated with the blast load and the high temperature induced by the post-flashover fire. This is attributed to the changes that take place for the material properties as a result of the high temperature, as well as the high strain rate. The researchers therefore aim to develop modified criteria for local buckling classification, considering the effect of these extreme loads.

Validation of English Portal Frame Practice for Use in Continental Europe: Mike Byfield of the University of Southampton in England is the director of this research effort.

The market for portal frames is very large in Europe and especially in England, where more than 500,000 tons of hot-rolled shapes are used for such structures each year. The United Kingdom design is based on tried-and-true plastic analysis, which has not seen much use in other areas of Europe for many years (or in the United States, for that matter). The project aims at developing a fully analytical approach to the analysis and design of portal frames, using a minimal number of assumptions. It is very different from the traditional plastic method, since it uses a direct solution of the beam equations as well as a non-linear moment-curvature relationship that explicitly incorporates strain hardening and residual stress. Since the procedure does not utilize the empirical assumptions of the plastic analysis, it appears to be attractive to designers who are not very familiar with plastic design, which includes most of the rest of Europe.

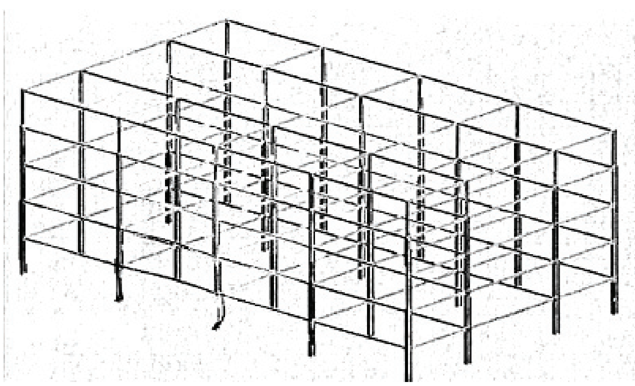

Fig. 2a. Frame appearance immediately after blast (see center column in front).

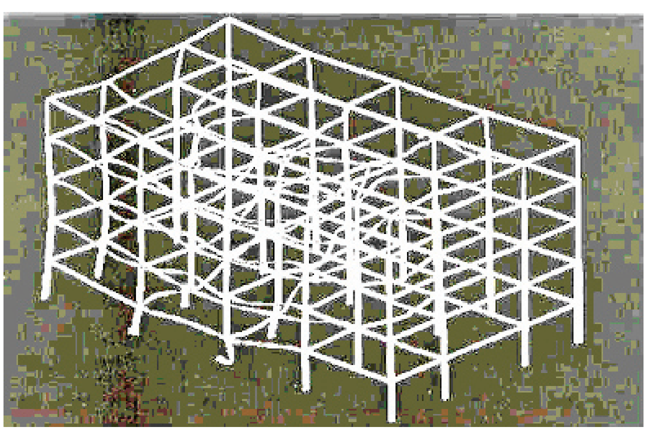

Fig. 2b. Frame appearance after blast-induced fire.

CONNECTIONS

Rotation Capacity of Moment Connections: Darko Beg of the University of Ljubljana in Slovenia and Ioannis Vayas of the National Technical University in Athens, Greece, are the directors of this internationally cooperative project.

Focusing on the fact that although many mechanical models detail the strength and stiffness of connections through the so-called component method, the data and methods of assessing the rotation characteristics of the connections are less than adequate. Using the component method as the basis for the development, detailed finite element models have been developed for a range of typical connections, and some physical tests were conducted to verify the numerical results. Following a Monte Carlo approach with a large number of calculations for each connection type, good correlation was found for the rotation model, the physical tests and the design criteria. Among other results, it was determined that the rotation capacity is heavily dependent on the mechanical properties of the materials. This has also been found by other research studies, and is especially important in view of the values of actual versus nominal material properties.

Design of Simple Beam Connections in Steel Buildings: Jean-Pierre Jaspart directs this study at the University of Liège in Belgium.

Recognizing that current design rules provide detailed requirements for the performance of the elements of simple beam connections (bolts, welds, plates, etc.), the project aims at developing criteria for the response of the complete connection in terms of shear strength, rotation capacity and ductility. A design handbook has now been assembled for the European Convention of Constructional Steelworks (ECCS), covering shear tab, double angle and shear end plate connections.

Bolted Links for Eccentrically Braced Steel Frames: Dan Dubina of the Polytechnic University of Timisoara in Romania leads this research effort.

Eccentrically braced frames have seen extensive use in high-seismic areas, due to their energy absorption capacity. The links have traditionally been fully welded, which sometimes have prompted difficult and expensive repair efforts following an earthquake. The project proposes to develop criteria for bolted links, as illustrated in Figure 3, using flush end plates and high strength bolts.

Physical tests were conducted to examine the cyclic performance of the bolted links, using link length, stiffener spacing and bolt preloading as the test parameters. The results to date show that shorter links are preferable, primarily because they are easier to replace following damage. Further, longer links and closer stiffener spacing imposed higher demands on the connection. Finally, full bolt preload provides higher initial connection stiffness, a more stable hysteretic response and larger deformation capacity; this is recommended for use with short links. The findings also provide criteria for limiting the link length, in order to prevent excessive damage.

Static and Cyclic Behavior of Connections in Steel and Composite Structures: This is a joint project of three Portuguese universities: University of Coimbra (Luis da Silva), Technical University of Lisbon (Luis Calado), and the University of Minho (Paulo Cruz).

The study is focusing on the development of guidelines for the design of semi-rigid (PR) frames, with emphasis on the influence of the column base connections and the beam-to-column connections. Using analysis and physical tests, the project addresses three distinct levels of activity, as follows: (i) connection components, (ii) overall connection behavior, and (iii) frame behavior. Pseudo-dynamic tests are performed to examine the static and cyclic behavior of structures that utilize steel and composite columns and beams, with extended end-plate connections, top and seat angle connections with web angles, and fully welded connections.

The project is comprehensive, including the recently completed and validated development of a methodology to simulate the performance of the pseudo-dynamic connection tests. Such a methodology is currently being developed for the response of the column base connections.

Numerical, Experimental, and Analytical Study of Minor Axis and 3D Bolted Connections: Miklos Ivanyi of the Budapest University of Technology and Economics in Budapest, Hungary, directs this research program.

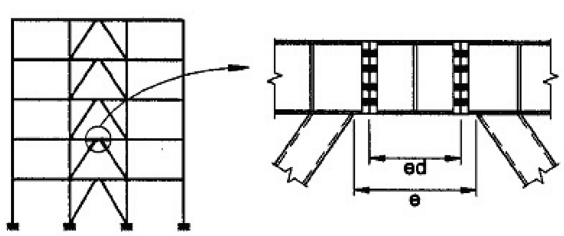

Fig. 3. Use of bolted links for eccentrically-braced frames.

The research work focuses on the response characteristics of minor axis connections as well as three-dimensional connections, observing that the data base for such connections is very limited.. The aim is to develop component-type models for these elements, in line with current approaches for connections in general. The testing has been completed; the analytical model has been prepared and is now undergoing validation testing.

Connection Design for Steel Buildings at Risk from Terror Attack: Mike Byfield of the University of Southampton in England directs this research effort.

The test of an 80-ft long sub-frame from a current multistory building demonstrated that bolt fracture can occur when the beams experience very large deflections, of the type that is likely to occur when the structure has been subjected to blast or impact loading. This form of non-ductile failure may be compounded by overstrength beams, which sometimes can absorb twice their ultimate (limit state) design loads when undergoing large deformations. This is because normal limit state design is based on lower-bound estimates of the strength. The problem is that this mode of behavior may force the failure to take place in the connections, rather than through the ductile, energy-absorbing flexural mode.

The project aims at developing a design approach that incorporates upper-bound criteria for the beam strength, and then sizing the components accordingly. The methodology appears to be particularly relevant for buildings or areas within the buildings that may be vulnerable to blast or similar attack.

COMPOSITE CONSTRUCTION

Behavior and Strength of Composite Columns Subjected to Fire: Jean-Marie Aribert of INSA (Institut National des Sciences Appliquées) in Rennes, France, is directing this project.

Using numerical simulation, the project aims at developing improved and simplified column buckling criteria for concrete-filled tubes in a structure subjected to fire conditions. The current Eurocode rules are complex and not as accurate as needed.

Load-Carrying Capacity of Anchor Plates with Welded Studs: Ulrike Kuhlmann at the University of Stuttgart in Germany heads this research project.

Load transfer from a steel structure to a supporting concrete structure is often accomplished by anchor plates with headed studs. Current design criteria tend to underestimate the capacity of these connections. A large series of tests was conducted, using anchored connections subjected to shear and normal forces. The strength model that has been developed incorporates all relevant parameters, including type of stud, concrete reinforcement, and load direction and eccentricity. Additional tests have shown good correlation between the tests and the predicted capacities.

FABRICATION AND MATERIALS

Improvement of Fatigue Life of Welded Structural Components: This project has been led by Henning Agerskov of the Technical University of Denmark in Lyngby, near Copenhagen, Denmark.

The original study was based on the need to improve the fatigue resistance of the welded components of a large diesel engine. The crankshaft housing of the engine had been designed for constant amplitude loading and infinite life at the full design load. The critical detail was a complete penetration butt weld for thick plates, welded from one side only with no access to the root side. A series of studies were undertaken to determine the fatigue life of the detail, including approaches for how to improve it. It was found that grinding of the weld toe led to very significant increases in the fatigue life, with improvement factors ranging from 2.8 to infinity. Finally, in most of the tests the grinding caused the location of the crack initiation point to move from the weld toe to the non-ground surface between the weld toes.

Effective Use of High Strength Steels in Welded Structures Subjected to Fatigue Loading: This is a joint project between two German universities: (i) University of Stuttgart (Kuhlmann) and (ii) Bauhaus University Weimar (Bergmann).

The use of high strength steels in dynamically loaded structures continues to be somewhat limited since the fatigue strength of as-welded assemblies is virtually independent of the material strength. Through a parametric study the project aims at verifying the fatigue strength of such steels in composite road bridges. An experimental program is underway to study the effectiveness of the post-weld treatment methods, TIG-dressing and UIT (ultrasonic impact treatment), for the welded details of transverse stiffeners. The program includes 50, 65 and 100 ksi steels, and the results so far show that the treatments are very promising. The most efficient method appears to be UIT, increasing the fatigue strength for 50 and 65 ksi steels at 2 million cycles by more than 100 percent. For the 100 ksi steel the improvement was so large that the eventual fatigue failure shifted from the weld toe region to the base metal.

STEEL AND COMPOSITE BRIDGE STRUCTURES

Design of a New Type of Orthotropic Plate: Miklos Ivanyi Jr. directs this study for the company Uvaterv in Budapest, Hungary with the cooperation of Professor Miklos Ivanyi of the Budapest University of Technology and Economics.

In traditional orthotropic plates the trapezoidal longitudinal stiffener is welded to the transverse girder web and to the bottom flange of the main girder, as shown in Figure 4a. In a recently developed orthotropic plate the stiffeners and the transverse girder web are not connected, as illustrated in Figure 4b. This approach provides for a significant reduction in the amount of flame cutting and welding, but more importantly there is no longer a need to assess the fatigue condition of the weld between the stiffener and the web. On the other hand, the potential for local buckling of the free edge of the web near the trapezoidal stiffener must be considered. Finite element analyses of the new and traditional plates have been conducted, and a design guide is under development.

Design of Composite Bridges with Twin Steel Girders: Jean-Marie Aribert of INSA in Rennes, France, leads this research effort.

This is a major undertaking, with three main components:

- Development of a simplified approach to take into account the longitudinal stiffening effect of the steel girders subjected to the transverse load that is applied during launching of the girders. Span lengths up to 400 ft (120 m) and web depths up to 17 ft (5 m) are being considered, using 50 and 65 ksi steel.
- Evaluation of the percentage of moment redistribution that takes place in continuous bridge girders, comparing the actual negative moments at internal supports with those calculated using linear ("uncracked") analysis. Slender cross sections (Class 3 and 4 by Eurocode definitions) are used, with constant and variable web depth.
- Development of an improved classification of composite cross sections at internal bridge supports, where the web is very slender (Class 4) and the flange is compact (Class 1 or 2).

Optimization of a Symmetric Welded I-Section: This study is being conducted by Kaj Avellan of the Finnish consulting firm Avestment OY.

The optimum ratio between the web and flange areas of homogeneous sections is approximately two. However, it

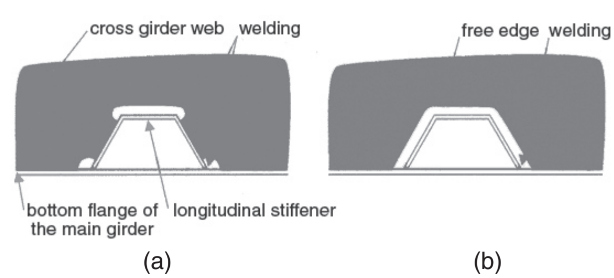

Fig. 4. Traditional and new orthotropic deck details.

is not known how this works out for hybrid shapes with the flange made from higher strength steel at a higher price than that of the web. A closed-form solution has been developed that may be used by bridge and other structural designers, with the optimum ratio of web to flange area found as follows:

$$\text{Area Ratio} = \beta = (\text{Web Area})/(\text{Flange Area}) = A_w/A_f$$

$$\textbf{Optimum Area Ratio} = \beta_0 = \mathbf{1/(}r - K\mathbf{/2)} = \mathbf{1/\{}r - \mathbf{[(3}\alpha - \alpha^3\mathbf{)/4]\}}$$

where the following terms are used:

r = unit price ratio = (unit price of web steel)/(unit price of flange steel) = p_w/p_f

α = strength ratio = F_{yw}/F_{yf}

K = hybrid factor = $1/[2(3\alpha - \alpha^3)]$

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