Current Steel Structures Research

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For a great many years worldwide research on the behavior and strength of steel structures was led by the work of numerous researchers in various American universities and research laboratories. Individuals such as Bruce Johnston, Lynn Beedle, Ted Galambos, John Fisher, Bill Munse, Ed Gaylord, Egor Popov, Bill McGuire and George Winter provided in-depth studies and novel theories and other developments that helped industry and practicing professionals form a construction culture that was unique in the world. The work of these giants fostered generations of advanced researchers and engineers whose efforts have cemented the leadership position of the United States in steel construction.

All of the above being said, international communication and collaboration is the order of the day, and researchers in other areas of the world have been playing increasingly important roles for several years. Extensive studies continue in Europe, China, Japan, Korea and Australia, and our neighbors to the north, in Canada, offer some of the finest new research directions. Indeed, everybody works together to improve the state-of-the-art of steel structures, and the final level of emphasis on design code development really points to the critical nature of cooperation.

The projects discussed in this paper again emphasize the success of studies where researchers work closely with industry partners and fellow researchers in other countries. This form of collaborative work was started in the United States, but the efforts within the European Union over the past several years have raised the approach to new levels of successful activity. As an example, the numerous projects at Luleå University of Technology in Sweden reflect extensive involvement of industry and researchers from all of Europe. Similar efforts are underway at many other European universities, offering advanced solutions and numerous business opportunities. Important and useful results are forthcoming on a regular basis.

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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

Analytical Studies of the Behavior of Welded T-Stub Moment Connections: This is a project being conducted at the University of Chile in Santiago, Chile, with Ricardo Herrera and Guillaume Desjouis as the directors.

T-stub connections have been used extensively for moment frame construction, for a number of practical reasons. They offer significant moment capacity and stiffness and are relatively easy to erect. In the United States the T-stubs normally consist of WT shapes, but this is often not an option in many parts of the world, where the availability of hot-rolled shapes is very limited. The project at the University of Chile focuses entirely on welded built-up T-stubs, and this has occasioned the need to examine limit states that are unique to the welded assemblies. Specifically, the stem-to-flange weld is a critical feature. The project aims at developing design criteria for these connections, considering deformation demands as well as practical details.

Finite element models of the connections were developed, taking into account the loading conditions of the T-stub in actual connections. In addition to examining the influence of the material properties of the steel and the welds and the geometry of the welding zone, other geometric parameters such as bolt placement and pattern as well as the relative thicknesses of the stem and the flange of the T-stub were also examined. As expected, the findings indicate that the flange-to-stem weld is the critical detail. Further, tees that are made from I-shapes may not be able to develop the stem yielding limit state, which is the preferred condition for these connections. The ductility of the connections is therefore somewhat limited, with the possibility that brittle fractures may occur during high-deformation demand conditions.

COMPOSITE CONSTRUCTION FOR BUILDINGS

Large Web Openings for Service Integration in Composite Floors: This project is funded through the Research Fund for Coal and Steel of the European Union as a collaborative effort between the Luleå University of Technology in Luleå, Sweden and the Technical University (RWTH) in Aachen, Germany. The French and British steel construction institutes are partners, as is the steel company ProfilARBED from Luxembourg. The project director is Professor Milan Veljkovic of Luleå University of Technology.

Due to the lack of European (Eurocode) design criteria for composite beams with large web openings (CEN, 2005), the researchers examined specific assemblies to allow their use in structures. Figure 1 shows the typical beams that have seen extensive use; they are known as "Smart Beams" in the United States.

The project examined a number of design, fabrication, and service issues related to such composite beams, as follows:

1. Structural behavior and strength under normal loading conditions, including moment and shear capacities, web buckling, beam stiffness and related deflection conditions due to the presence of the web openings, and composite action within the various regions of the beam flange.

2. Response characteristics under fire conditions, including any effects of fire protection methods and materials.

3. Fabrication processes for beams with web openings.

In addition, the researchers undertook a full examination of current design criteria for steel and composite beams with web openings. Full-scale tests have also been conducted, to verify the proposed design recommendations. Finally, design aids as well as software have been developed; the software addresses the design of beams with single web openings.

Welding of Shear Studs through Steel Deck with Various Forms of Coating: This project has been conducted at LeTourneau University in Longview, Texas, supported by a research grant from AISC. Professor Yoni Adonyi has been the project director for this study, which was completed in December 2006.

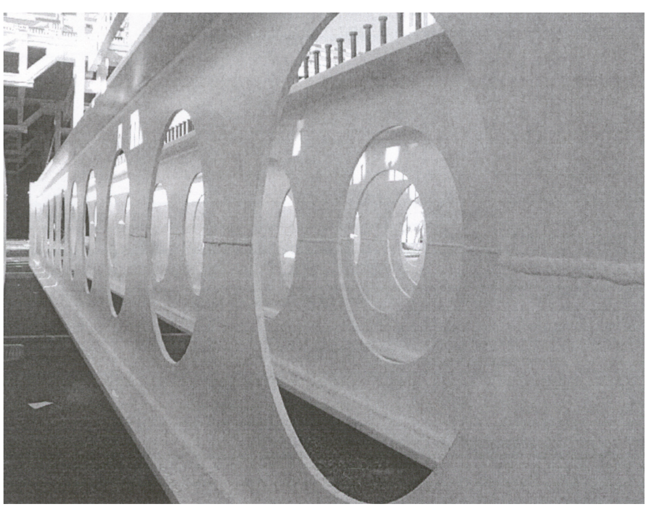

Fig. 1. Beam with large web openings (photo courtesy of Luleå University of Technology).

The study aimed at developing methods that will enhance the quality of direct, through-deck stud welds to steel beams with various forms of protective coating. It has been common construction practice for many years to use galvanized steel deck as part of composite floor systems (Fisher, 1970; Grant, Fisher, and Slutter, 1977), and the stud shear connectors have always been welded directly to bare steel beams, through up to two steel deck thicknesses. The fabrication and structural performance of the stud welds placed in this fashion have been well documented and tested in a variety of research projects and applications in structures.

However, quality and performance questions have been raised when the steel beam itself is coated in some fashion, whether it is to improve corrosion resistance or as part of the fire protection requirements. Without modifying current welding technology, the project examined the weld placement and quality in the presence of the following coating materials, and compared the results to those obtained for bare, uncoated steel:

1. Hot-dip galvanizing (HDG)

2. Zinc-based powder paints

3. Insulating alkyd-based coating

The findings demonstrate that although stud welding to bare steel is preferable, the results for insulating alkyd-based coating is generally consistent and comparable to bare steel. Zinc-based powder paints and especially hot-dip galvanizing can be problematic, although not impossible. The study also recommends changes to the power supply for the welding equipment, to obtain consistently high quality stud welds.

MODELING ELEMENTS FOR STEEL FRAMES

Elasto-Plastic Collapse Deflection Analysis of Three-Dimensional Steel Frames: This study has been conducted at Nagasaki University in Nagasaki, Japan, under the direction of Professors M. Shugyo and M. Shimazu. The aim of the project was to develop a new beam finite element, to improve frame analysis for large inelastic deformations of rigid, semi-rigid, and pin-connected steel frames. Using a plastic hinge formulation, a modified incremental stiffness method was developed that allowed for numerical integration about the end sections of the element. This permitted the element end sections to be discretized into small fiber areas, hence the name of the approach as the *fibered plastic hinge method.*

Tests and analyses of unequal-legged angle members were conducted, and it was determined that the modeling technique allows for an accurate representation of the member behavior. It is anticipated that the approach will be used in further studies of members with different boundary conditions in three-dimensional frames.

SEISMIC RESPONSE OF STEEL STRUCTURES

Experimental Evaluation of Steel and Composite Shear Walls: This project has been conducted at Tongji University in Shanghai, China, with Professor Guo-Qiang Li as the director. Focusing on the use of bare steel shear plate walls (SPSW) and composite steel plate shear walls (CPSW), the study aims at developing design and construction recommendations for these types of structural elements, while at the same time attempting to limit the potential negative influence of connecting boundary columns to the shear walls.

The research team developed three scaled models for each of two-sided composite steel plate shear walls (CSPSW) and two-sided restrained steel plate shear walls (SPSW), as shown in Figures 2 and 3.

The composite steel plate shear wall shown in Figure 2 omitted the connection to the boundary columns, in order to avoid the potentially adverse effect of the seismic response of these columns. The concrete plates were connected to the steel plate with bolts, providing out-of-plane buckling resistance of the steel plate. One specimen used a single, one-sided concrete plate; this was tested monotonically. The other two specimens used two-sided concrete plates; these were tested for cyclic loading. The concrete plates had different thickness and reinforcement.

The steel plate shear wall shown in Figure 3 used a two-sided steel plate with transverse hollow structural sections as out-of-plane restraining elements.

The test results demonstrated excellent seismic performance of the composite steel plate shear walls. The performance of the steel plate shear wall was rated as "adequate"—this may have been occasioned by the choice of plate thicknesses and even more by the restraining system. But both of the shear wall types were not connected to the boundary columns of the overall frame for the structure. Theoretical analyses have been performed; additional findings will be forthcoming.

High Strength Frames in Seismically Resistant Building Structures: This study has been conducted as part of the overall earthquake engineering program at the Polytechnic University of Timisoara in Timisoara, Romania. Professor Dan Dubina has been the project director. Specifically, the aim of this study was to examine the potential of using some of the high strength steel that is currently produced in Europe, as a means of providing seismic strength to the columns of structures while utilizing lower strength steel for the beams (Dubina, Dinu, Zaharia, Ungureanu, and Grecea, 2006).

As part of the project, eight and fifteen story frames were designed with S235 and S460 steel members [these grades correspond roughly to ASTM A36 and ASTM A573 (65) and ASTM A913 (65)]. Two lateral load resisting systems were examined, as follows; Figure 4 shows the frames that were used.

1. Systems with moment resisting frames and eccentric chevron bracing with a short shear link in the center span (EBF)

2. Dual systems with moment resisting frames and concentric chevrons in the center span (CBF)

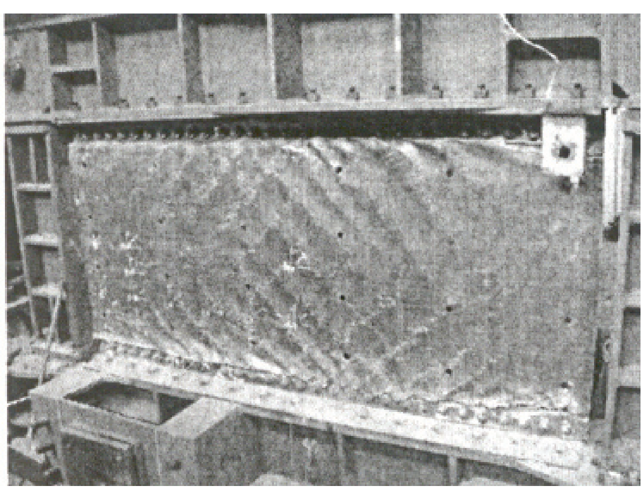

Fig. 2. Composite steel plate shear wall specimen (photo courtesy of Tongji University).

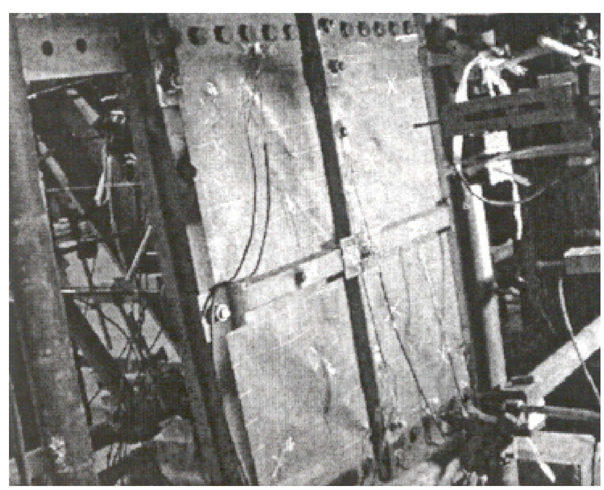

Fig. 3. Steel plate shear wall specimen (photo courtesy of Tongji University).

The heavily outlined members in Figure 4 used S460 steel, with additional details as follows:

1. S460 was used for the first two stories of the interior columns of the EBF eight-story frames.

2. S460 was also used for the first four stories of the 15-story EBF frame. Similar materials usage was specified for the eight- and 15-story CBF frames.

3. S460 steel was used for all beams that were connected to bracing members.

All other framing elements used the S235 steel.

The analyses showed that the use of the high strength steel in these chevron-braced systems was particularly advantageous because of the high demand occasioned by differences in bracing member capacity for tension and compression. However, buckling-restrained braces were not used. Finally, the energy dissipation in the lower-strength S235 members was significant, as would be expected.

FIRE RESISTANCE OF STEEL STRUCTURES

Behavior of Restrained Beams and Beam-to-Column Connections: This study has been conducted at Tongji University in Shanghai, China, under the direction of Professor Guo-Qiang Li. Specifically, the project aimed at investigating the behavior of the elements during the heating and cooling cycles of the fire test.

An analytical procedure was developed for the beam, taking into account large deflections and catenary response characteristics, and including local buckling effects. The procedure works very well for the members that were tested, an example of which is shown in Figure 5. The study is continuing, examining the broader implications for structural analysis and design. But it is very clear from the restrained beam tests as well as examinations of steel frame performance in general in other fire tests that these structures always respond as fully restrained systems.

Behavior of Composite Beams under Fire Conditions: This is another project from Tongji University under the direction of Professor Guo-Qiang Li. As part of an overall effort to arrive at improved analysis and design methods for steel structures under fire exposure, the Tongji University research group has analyzed and tested two full-scale restrained composite beams. Axial and rotation restraints were provided by a steel frame located outside the test furnace.

A simplified method of analysis to determine the temperatures and their distribution in the composite beam was developed, as was a procedure to assess the changes occurring in the axial force, the moments and the deflection of the beam. The methods take into account load ratio, restraint stiffness, steel beam to concrete slab cross-sectional area ratio, and the slab reinforcement steel ratio. Finally, the researchers have proposed a practical approach to the fire design of restrained composite beams.

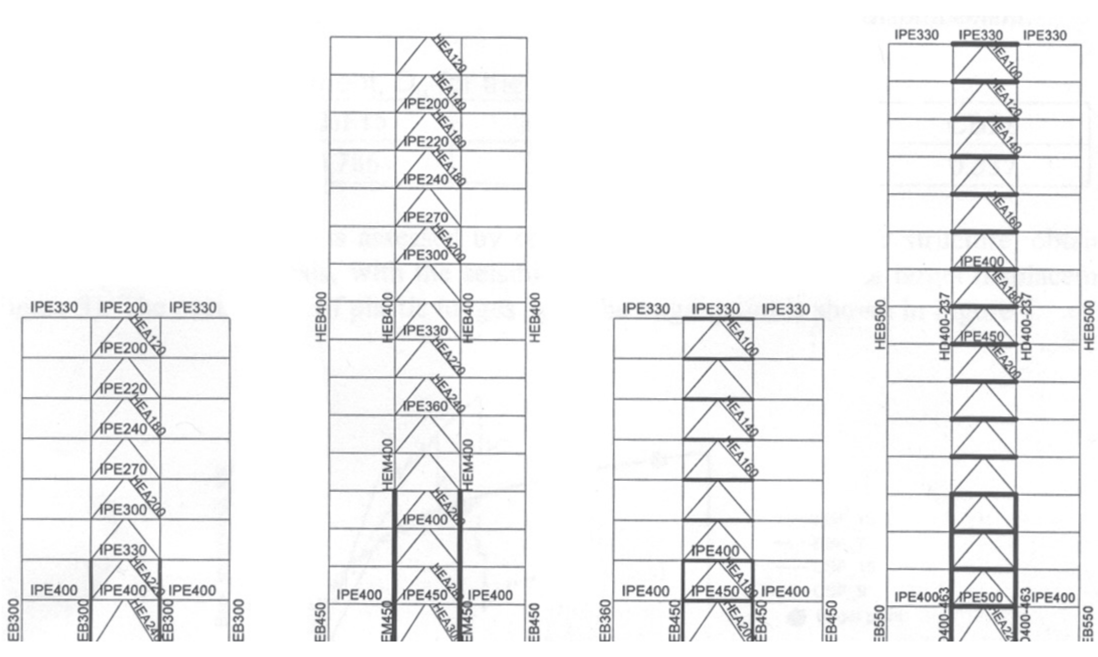

Fig. 4. Eight- and 15-story frames for system evaluation (photo courtesy of D. Dubina).

BRIDGE STRUCTURES

Economic and Durable Design of Composite Bridges with Integral Abutments: This is a cooperative project between the Technical University (RWTH) in Aachen, Germany, University of Liège in Liège, Belgium, and Luleå University of Technology in Luleå, Sweden. A Swedish consulting firm and the steel producer ProfilARBED are also part of the project team. The director is Professor Milan Veljkovic in Luleå.

The primary aim for the project is to determine the length limits that apply to bridges with integral abutments, and to develop the methodology for such. The researchers observe that experience with integral abutment bridges from Sweden and the United States has been very good, to mention two countries where the structures have been used extensively. Briefly, these structures outperform bridges with traditional joints because they are more economical to build as well as to maintain.

One of the issues in Europe is that broad design recommendations are not available. Among other issues, no inelastic behavior is permitted, even if the highest strain location within the bridge girder is at the top of a pile. The researchers speculate that these kinds of strains may only occur once or twice a year due to ambient temperature variations; it is also possible that this behavior may occasion low-cycle fatigue. This will be addressed in detail.

Finally, one of the other main issues with these types of bridges is that a clear understanding of soil-structure interaction is essential. To that effect, structural as well as geotechnical engineers are part of the research team.

Competitive Steel and Composite Bridges: This is another cooperative project between the Technical University (RWTH) in Aachen, Germany, University of Liège in Liège, Belgium, and Luleå University of Technology in Luleå, Sweden. A Swedish consulting firm and the steel producer ProfilARBED are also part of the project team. The director is Professor Milan Veljkovic in Luleå.

Involving extensive theoretical evaluations and physical testing, this project is heavily focused on the development of bridge girder cross sections that are optimized for efficient fabrication and erection procedures. Specifically, elimination of transverse and longitudinal stiffeners will lower fabrication cost, and efficient erection procedures such as incremental launching (see Figure 6) will enhance the competitive position of steel bridges.

From an American standpoint, it is interesting to observe that most of these issues have been addressed by DOT engineers, designers, steel fabricators and contractors for several years. It would appear that exchanges of concepts and procedures might be helpful.

OTHER STRUCTURES

High Strength Steel Tower for Wind Turbine: This is cooperative project between the Technical University (RWTH) in Aachen, Germany, the University of Coimbra in Coimbra, Portugal, the Aristotle University of Thessaloniki, Greece, and Luleå University of Technology in Luleå, Sweden. Industrial companies from Finland, Germany and Portugal are also project partners. The director is Professor Milan Veljkovic in Luleå.

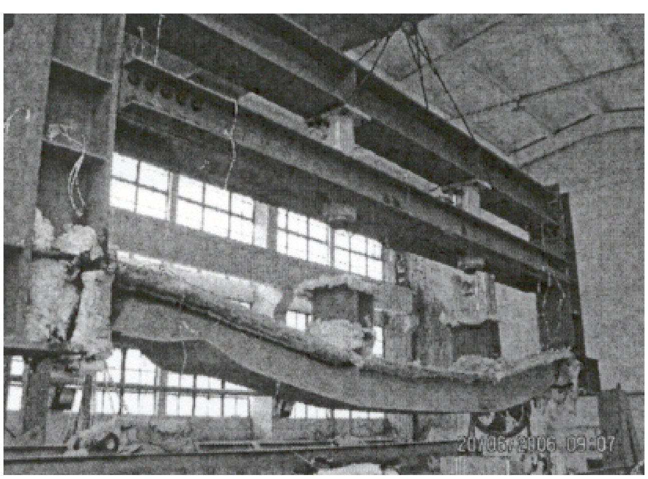

Fig. 5. Restrained beam fire test (photo courtesy of Tongji University).

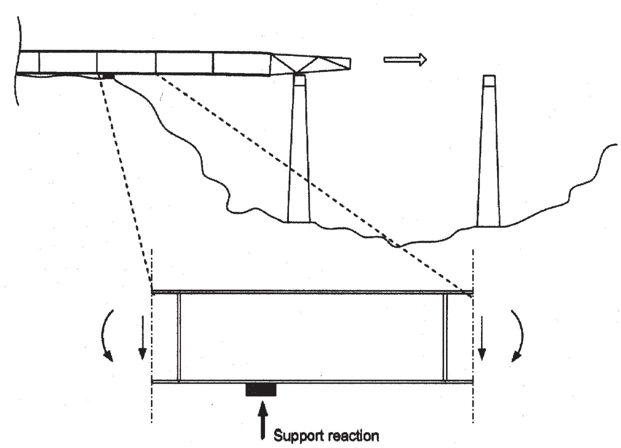

Fig. 6. Incremental launching of bridge girders (photo courtesy of Luleå University of Technology).

A somewhat esoteric subject for structural steel research, towers for wind turbines and the electricity that is generated in this fashion is certainly appropriate for today's issues of green construction and attention to energy needs. The project focuses on the optimization of tower fabrication and construction costs, through five phases:

1. Improved fatigue performance of the major tower joints (see Figure 7 for tower views and new joint detail)
2. Allow higher stress levels in the shell of the tower structure, preferably by making use of S460 steel (65 ksi yield stress).
3. Assess and improve local and overall stability criteria for the tubular shell of the tower.
4. Develop improved computational procedures through laboratory and in-situ testing
5. Develop a new set of provisions for the design of tower structures.

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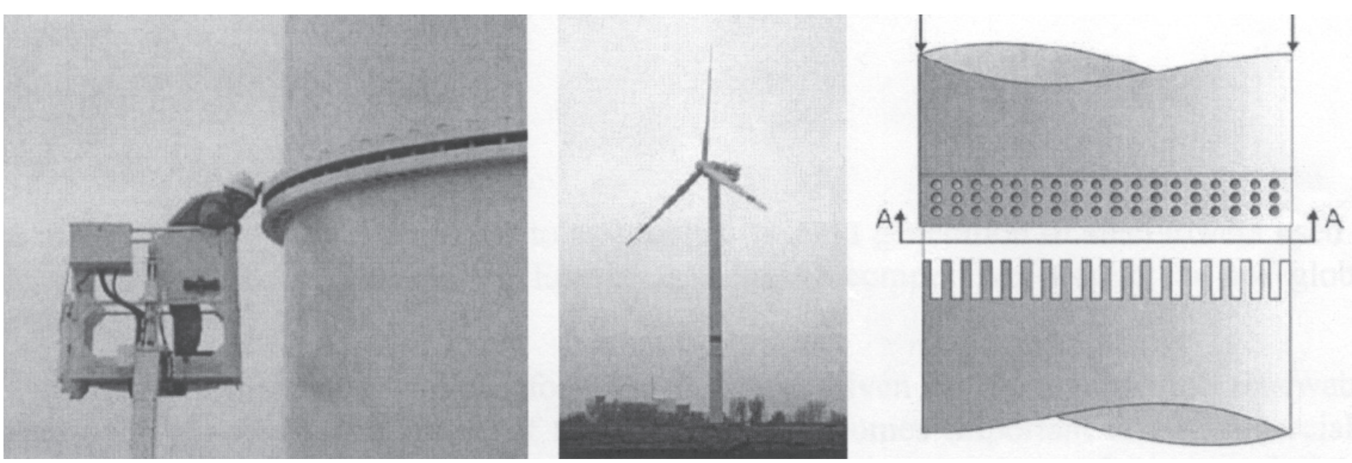

Fig. 7. Wind turbine tower and new joint detail (photo courtesy Luleå University of Technology).