Current Steel Structures Research

REIDAR BJORHOVDE

The new feature that was introduced for the steel structures research papers in the second quarter issue for 2010 of the *Engineering Journal* continues with ongoing work at three major European universities. While we will not be able to discuss all of the current projects at the schools, a selection of studies will provide a representative picture of the research efforts and demonstrate the schools' importance to the efforts of industry and the profession worldwide.

The universities are very well known in the world of steel construction: Imperial College in London, England; Delft University of Technology in Delft, the Netherlands; and the University of Liège in Liège, Belgium. Researchers at the three schools have been very active for many years, as evidenced by their participation and leading roles in the standards development committees of Europe and for the past number of years in the committees of the European Union (EU) and the European Convention for Constructional Steelwork (ECCS). Faculty and staff have authored large numbers of outstanding technical papers, reports and conference presentations.

Some of the findings have also been adopted by the design specifications of North America. For example, the equation for the equivalent moment factor C_b that is used in the 2005 AISC *Specification* was developed by Professor Nethercot, and many parts of the classical plastic analysis techniques were based on work by Professors Massonnet and Maquoi at the University of Liège.

References are provided throughout the paper, whenever such are available in the public domain. However, much of the work is still in progress, and in some cases reports or publications have not yet been prepared for public dissemination.

IMPERIAL COLLEGE—SELECTED PROJECTS

Progressive Collapse of Steel and Composite Building Structures: Professor David A. Nethercot has been the director of the project, with Professors B. A. Izzuddin and A. Y. Elghazouli also as members of the research team. The project was initiated six years ago and is now reaching the practical application stage with a design approach that addresses all of the key features of progressive collapse (Izzuddin et al., 2008; Nethercot et al., 2009).

The method is based on the alternative load path approach as well as the threat-independent column removal concept. The procedure is based on a simplified process that transforms the static response of the gravity loads into a dynamic response. Using a multilevel approach, the response at any level of structural modeling can be assembled from the known responses at lower levels. The modeling considers levels such as floor system, substructures and the complete structure.

In an interesting twist, a hand calculation procedure has been introduced that improves and clarifies the analysis approach (Nethercot et al, 2009). For example, the response of a connection to bending moment and axial load during column removal is represented by an explicit, simplified model (Stylianidis and Nethercot, 2010). This was then utilized to develop the hand calculation method that predicts the nonlinear response under gravity load. Figure 1 illustrates these stages as they evolve, following the removal of the column.

Apart from the practical uses of the procedure, this method also facilitates parametric evaluations that are critical to understanding the mechanics of the phenomenon. Indeed, recent studies have shown that the response characteristics of the beam-to-column connections are the most important feature of a progressive collapse scenario. Further, both the form of the response and the inherent resistance against progressive collapse depend on the interaction between the various elements of the structure. Primary among these are of course the moment-rotation response of the connections and their individual elements, including the ability to resist axial loads and deformations. This applies equally to steel and composite structures, for which strength (axial tension and compression), stiffness and ductility are paramount. The span-to-depth ratio of the beam appears to be significant, and this also depends on the position of the removed column within the frame and the axial restraint that is afforded by the connections (Nethercot et al., 2009).

Current project work aims at developing the relationships between causes and effects, by evaluating the interaction between the structural parameters and taking into account the dynamic nature of the response. This also includes the characteristics of the behavior of the floor system, for which a grillage model may prove useful.

Reidar Bjorhovde, Ph.D., Research Editor for *Engineering Journal,* Tucson, AZ. E-mail: rbj@bjorhovde.com

Behavior of Semi-Rigid (PR) Wide-Flange Beam-to-Tubular Column Connections: Professor A. Y. Elghazouli has been the director of the project. Sometimes referred to as "open beam-to-tubular column connections," questions have been raised about their strength, stiffness and ductility, in particular the ability of the wall of the tube to provide adequate deformation capacity. This applies especially when cyclic loading has to be considered.

Despite the relatively high cost of some connections involving HSS columns, they do offer certain architectural and structural advantages. The perceived complexity of connecting wide-flange shapes to HSS columns sometimes means that such connections do not get selected for a project. The project was therefore undertaken to develop suitable, practical and economical PR connections with appropriate performance characteristics. The chosen connections were (1) top and seat angle connections, (2) top, seat and web angle connections, and (3) combined channel-and-angle connections, where a channel is shop-welded with the legs against the wall of the HSS, using a typical bolted connection from the beam to the channel (this could be a top and seat angle connection, or a top and seat angle with a web angle connection). For the Type 1 connections blind bolts were used to connect to the HSS, with so-called Lindapter Hollo-bolts (Elghazouli et al., 2009).

The analytical and experimental results have shown that these connections provide more than adequate rotation capacities for "typical design scenarios" (which are not defined, but presumably compare to typical U.S. practice). The connections exhibited stable hysteresis loops in the cyclical tests that were conducted, with reasonable ductility and energy absorption. Further, it has been found that it is very important to ensure that there is a reliable mechanism for the transfer of compression forces to the column. Finally, the tests also showed that significant improvements in stiffness and strength were achieved when Grade 10.9 (same as ASTM A490) Hollo-bolts were used, as compared to the connections that used Grade 8.8 bolts (same as ASTM A325). Figure 2(a) shows a Type 1 connection after the test; Figure 2(b) shows a combined channel-angle connection.

For the analytical and design procedure developments, simplified mechanical models have been created for providing initial connection stiffness and moment capacity. More refined models are currently being examined, including procedures that can be used to design for various extreme loading conditions.

Finally, related projects at Imperial College include studies of connections between tubular columns and reinforced concrete flat slabs, as well as the seismic performance of concentrically braced frames and composite moment-resisting frames.

Structural Use of Stainless Steel: The project director has been Dr. Leroy Gardner. Recognizing that stainless steel offers certain behavior and performance advantages for structures, the availability of stainless steel rolled shapes is still very limited, and cost figures are not available.

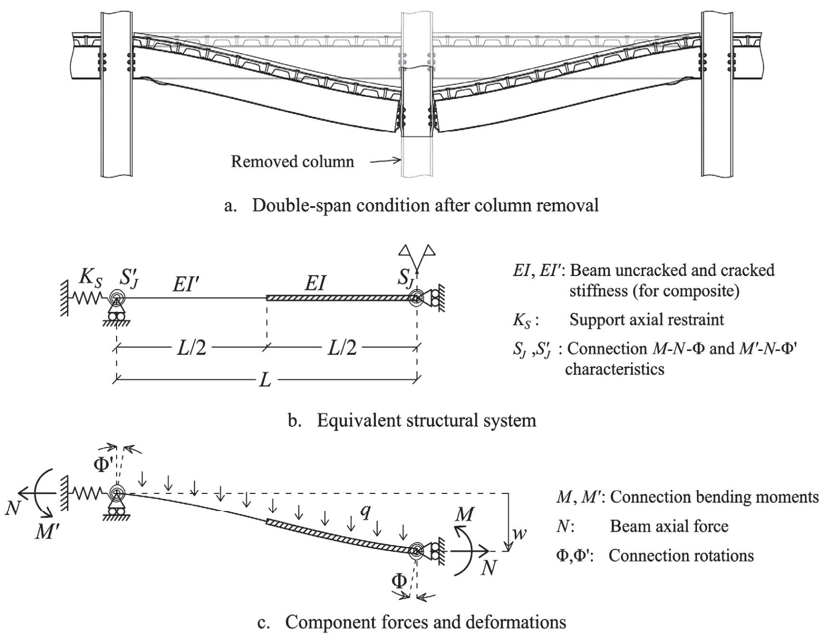


Fig. 1. Static load-deflection beam response following column removal (Figure courtesy of Professor D. A. Nethercot).

The primary stainless steel research efforts at Imperial College have focused on the following general subjects:

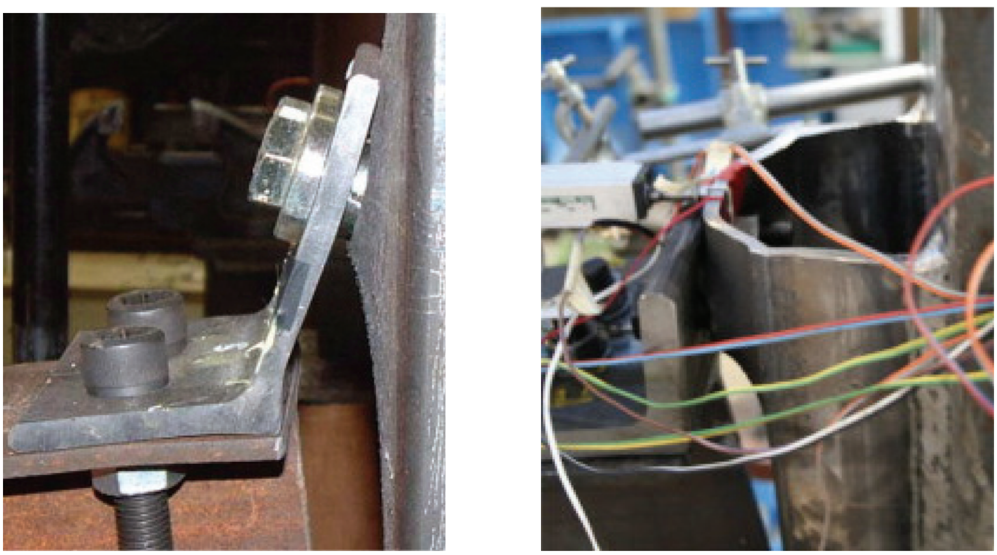
1. Improving the accuracy and efficiency of the design criteria, by taking into account the strength increases that are provided through the cold-forming process (Cruise and Gardner, 2008) and by considering the actual (rounded) stress-strain characteristic and strain hardening under load, using an innovative deformation-based design approach (Ashraf et al., 2008).
2. Examining the performance of stainless steel under fire and under seismic loading. For example, austenitic stainless steel performs better than carbon steel (no steel grade given) under elevated temperatures, but the larger thermal expansion of the stainless steel is problematic due to the increased axial restraint (Gardner and Baddoo, 2006). For seismic conditions, austenitic stainless steel offers improved energy dissipation than comparable carbon steel (no steel grade given), due to the delayed local buckling (Nip et al., 2010).
3. Studying the suitability of new grades of stainless steel for construction, especially the so-called "lean duplex" grades. On the European market, this steel is twice the strength of the more common austenitic stainless steel, and it costs less. Preliminary studies have verified the structural performance of the material, but further studies are needed (Theofanous and Gardner, 2010).

Structural Steel Elliptical Hollow Sections: Dr. Leroy Gardner has been the director for this project. These sections have found favor with a number of architectural firms, but they are still somewhat of a rarity. The studies at Imperial College have focused on physical tests and numerical analyses, with the aim of providing design criteria for international specifications. Column, beam bending and shear tests have been conducted (Chan and Gardner, 2008, 2009), and Figure 3 shows two examples of the tests.

The design criteria have aimed at developing an equivalent circular cross section (CHS) and that way to be able to take advantage of existing code provisions.

The Continuous Strength Method for Structural Steel Design: This is an ongoing research and development effort, headed by Dr. Leroy Gardner. Essentially, the work focuses on an improvement of the approach that is used in most current design specifications to account for nonlinear response characteristics. Traditional approaches represent the material behavior by simplified elastic-plastic or rigid-plastic models, and strain hardening is generally ignored, although the spread of plasticity throughout the cross sections and redistribution of moments in the frame are taken into account.

The study by Dr. Gardner focuses on what is now known as the continuous strength method (CSM). CSM uses a systematic procedure to account for strain hardening, and it is based on the deformation capacity of the cross section (Gardner, 2008). By incorporating the effects of strain hardening, the method allows for compressive strengths greater than the yield load and bending capacities higher than the plastic moment. The approach provides for a more accurate representation of the structural behavior. For compact (stocky) sections, for example, member strength increases of 15% can be achieved, when compared to current methods. Additional criteria are currently being developed.



(a) *(b)*

Fig. 2. Semi-rigid connection tests: (a) top and seat angles with blind bolts; (b) combined channel and angle connection (Photos courtesy of Professor A. Y. Elghazouli).

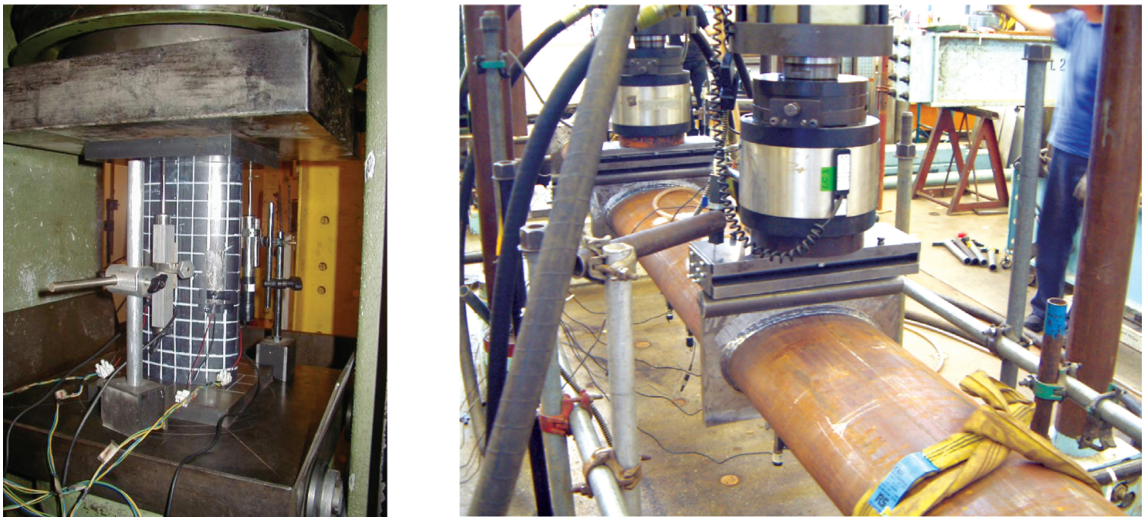
DELFT UNIVERSITY OF TECHNOLOGY—SELECTED PROJECTS

Application of Cast Nodes and Very High Strength Steel in the Offshore Industry: This project has been sponsored by Materials Innovation Institute (M2i) of the Netherlands and Bouwen met Staal, the Dutch steel construction society. Professor Frans Bijlaard is the project director.

The very high strength steels (VHSS) that are part of the project have been available in the European market for a number of years. Nominal yield stress values are up to 160 ksi (1,100 MPa), but such steels have not seen much use within the civil engineering and offshore construction industries. The primary reason is simply that design and fabrication methods and data are very scarce, and at this time design standards do not recognize these steel grades. Among potential advantages would be smaller size members and reduced fabrication costs. On the other hand, the fatigue performance of VHSS structures is likely to be problematic, because stress levels and stress ranges will be much higher than what is the case for structures in lower strength steels. Furthermore, VHSS welded connections require much higher fabrication quality, to avoid large stress concentrations in the connections and to use optimal configurations of the welded joints.

Fatigue Strength of Hybrid Truss Girders: This project is a part of the study of cast nodes and very high strength steel. Professor Frans Bijlaard is the project director.

Hybrid truss girders appear to be an effective application for very high strength steel. These girders are very stiff



(a) (b)

Fig. 3. Stub column test (a) and bending test (b) of eliptical hollow cross sections (Photos courtesy of Dr. Leroy Gardner).

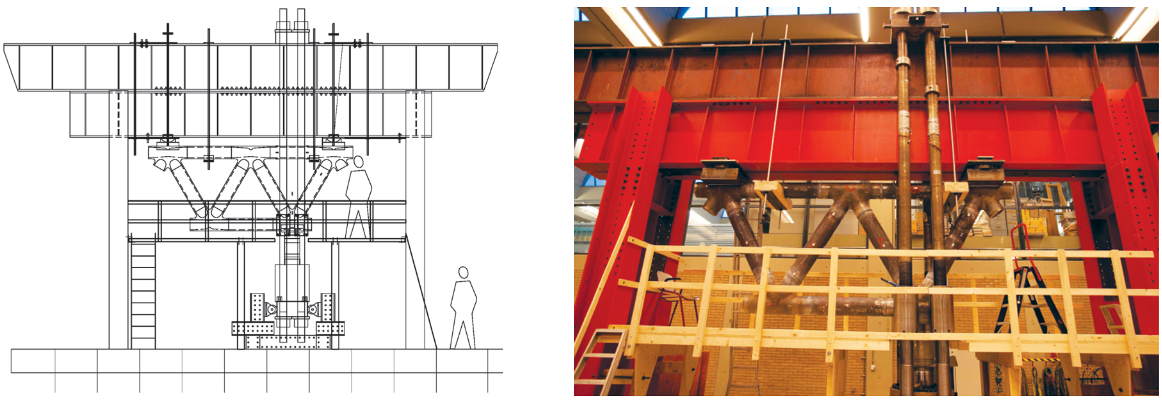


Fig. 4. Hybrid truss girder test specimen (Drawing and photo courtesy of Professor Frans Bijlaard).

and are typically produced with circular hollow sections (CHS). The use of cast steel nodes in combination with CHS elements would provide structures with highly fatigue-resistant connections. At this time, such solutions for bridges and offshore structures use steels with yield stress magnitudes up to 65 ksi (460 MPa). With this background, a program featuring fatigue tests of a truss girder was formulated, using welded CHS elements with K-joints in cast steel with yield stresses of 100 and 130 ksi (690 and 890 MPa). Figure 4 shows a schematic of the test assembly, along with a photograph of the installation in the Stevin Laboratory in Delft.

The large-scale tests were started in January 2010, and the initial results are now becoming available. It is anticipated that the test will be continued for some time. No evaluations of performance and the like are available at this time.

UNIVERSITY OF LIÈGE—SELECTED PROJECTS

Development of an Improved Design Method for Cold-Formed Stainless Steel Members: This is a very long-term research program, having been initiated in 2005. It is anticipated that the effort will be concluded in 2012. Professor Jean-Pierre Jaspart has been the project director.

The University of Liège has excellent testing laboratories, but the school also houses a major software development operation. This is particularly helpful to the researchers studying nonlinear materials, elements and connections.

As already observed in the discussion of some of the research projects being conducted at Imperial College, the actual use of stainless steel for structures has been fairly limited for many years. Part of the problem has been that the material properties of the steel have not been properly reflected in the code criteria, using formulations that were developed for carbon steel. Further, cold-formed elements, connections and structures require detailed attention to very small material thicknesses, local and distortional buckling, cross sections that are only partially effective (due to local buckling effects), and very complex connection details and fasteners.

The studies of stainless steel at Liège have involved extensive analyses and physical tests. In particular, the modeling of the elements has taken into account the nonlinear behavior of the material, biaxial loading, strain hardening, Bauschinger effects, and work-hardening stagnation under reversed deformations at large strain levels (Rossi, 2009).

In line with current advanced application of approaches such as the direct strength method (Schafer, 2006), the overall aim of the project was to arrive at advanced—but above all practical—design formulations. Conducting full-scale tests to confirm the theoretical evaluations, additional finite element models were developed and used to generate further results. The correlation between tests and theory were very good.

Figure 5 illustrates the finite element model that was developed in conjunction with the test program.

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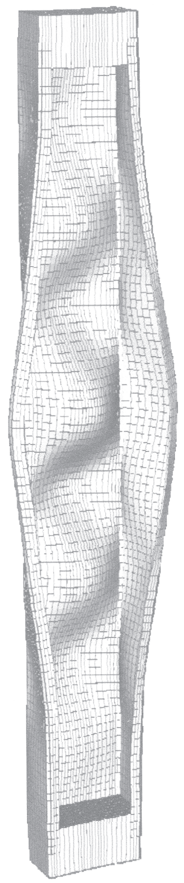

Fig. 5. Finite element model of locally buckled stainless steel cold-formed column (Figure courtesy of Dr. Barbara Rossi).

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