Current Steel Structures Research

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INTRODUCTION

This issue of "Current Steel Structures Research" for the *Engineering Journal* focuses on a selection of research projects at universities in Europe and South America. The descriptions will not discuss all of the current projects at the schools. Instead, selected studies provide a representative picture of the research work and demonstrate the importance of the schools to the home countries and, indeed, to the efforts of industry and the profession worldwide.

The universities and many of their researchers are very well known in the world of steel construction: the "Rheinisch-Westphälische Technische Hochschule Aachen" (now commonly referred to as RWTH Aachen), located in the city of Aachen, Germany; the Federal University of Rio de Janeiro in Brazil; and the University of Chile in Santiago, Chile. The studies that are presented reflect elements of the projects as well as other major, long-time activities. All of the projects are multi-year efforts, emphasizing the need for careful planning and implementation of research needs and applications, including the education of graduate students and advanced researchers. As is also always the case in the United States, the outcomes of the studies focus on design standards and industry needs.

The lead researchers have been active for many years, as evidenced by their leading roles in the design standards development of their countries, but they have also been frequent participants in the work of other countries and regions. Large numbers of English-language technical papers and conference presentations have been published, contributing to a collection of studies that continue to offer solutions to complex problems for designers as well as fabricators and erectors. Many of the projects also complement current work in the United States and elsewhere. The broad sharing of knowledge that is taking place promises significant results, not the least because of issues of finances and the sheer cost of research: synergism is a critical feature of multi-institutional, indeed multinational activities.

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.

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SOME CURRENT RESEARCH WORK AT RWTH AACHEN IN AACHEN, GERMANY

Established in 1870, RWTH Aachen has been one of the leading engineering academic institutions in Germany and Europe for many years. Steel structures research is performed under the auspices of the Institute of Steel Construction (ISC). For many years, the projects focused exclusively on steel and composite buildings and bridges, but in the 1980s, building aerodynamics and lightweight metal structures were added. In the 1990s, a number of projects with glass and steel and composite materials were also undertaken. Recognizing the importance of standards for all areas of construction, the institute has been heavily involved in the European design code development for more than 30 years. Most projects, therefore, aim at providing design criteria for structures and structural elements.

Under the leadership of Professor Markus Feldmann and, previously, Professor Emeritus Gerhard Sedlacek, the total annual research expenditures of the institute have typically amounted to €2.8 million (approximately $3.7 million in current funds). More than two-thirds of these funds are provided by external agencies—such as various ministries and commissions of the European Union—as well as by industry. RWTH Aachen is also a partner in many of the multi-university, multinational research projects that are under way in Europe at any one time; these efforts are strongly supported by the European Union, as well as the individual countries.

The current projects of the institute address major topics of steel and composite structures:

- All aspects of the stability of members and frames, as well as plate buckling.
- Performance considerations for steel, including brittle fracture and fatigue, as well as the unique demands of welded construction.
- Bridge engineering in general, including integrated abutments and bridge dynamics.
- Strength and behavior of new composite shear connections.

- Strength, ductility and stiffness of new types of connections using adhesive bonding.

- Wind towers for energy production, including new connection types and foundations.

- All aspects of sustainability.

- Static and dynamic response of buildings and bridges under wind loads.

- Glass engineering, including structural uses of glass, the strength and stability of columns, shear panels and beams of toughened and laminated panels or steel-glass composites.

Flexural and Lateral-Torsional Buckling of Steel Frames by a General Second-Order Approach: Professor Markus Feldmann is the project director, and the primary researchers from Aachen are Matthias Wieschollek, Nicole Schillo and Johannes Naumes. The project is sponsored by the German council of steel construction, along with the Federal Ministry of Economics.

Hot-rolled wide-flange shapes and similar welded sections have high in-plane strength about the strong axis. For efficient member performance, this should be exploited by preventing lateral-torsional buckling. The current rules of Eurocode 3 (ECS, 2005) provide for out-of-plane stability checks that can be performed according to one of the following methods: (1) a method using second-order analysis for which equivalent geometric imperfections are defined and (2) a method with member checks using flexural or lateral torsional buckling curves.

The research work treats out-of-plane stability checks using second-order analysis with equivalent geometric imperfections that have been defined in Eurocode 3 in agreement with elastic buckling modes. The use of out-of-plane modal bending moments makes the assessments clear and simple. The project aims at defining the appropriate range of the procedure, as verified by tests and finite element analyses, as well as developing design aids and worked examples (Bijlaard et al., 2010). Figure 1 shows one of the LTB test setups.

Fig. 1. Lateral buckling test. (Photo courtesy of Professor Markus Feldmann)

The ultimate objective is to propose improved LTB rules in Eurocode 3.

Assessment of Structures with Welding Discontinuities: Professor Markus Feldmann is the director of this project and the primary researcher is Björn Eichler. The project is sponsored by the German council of steel construction, along with the Federal Ministry of Economics.

Design specifications and structural welding codes require full penetration welds for complete butt joints. This will sometimes lead to time-consuming and expensive repair work for the steel fabricator whenever the welds are produced with root gaps, as illustrated in Figure 2. A classification method for the assessment of such partial penetration details is still missing. Recently, a fitness-for-purpose strategy has been developed, primarily based on an accurate detection of the root gaps by nondestructive testing methods and then by a fracture mechanics solution in order to provide for the structural reliability of a welded steel member or joint (Feldmann et al., 2009).

Using this approach, a weld can be assessed in terms of its actual safety rather than having it be rejected due to insufficient penetration according to the conventional codes. The method uses a fracture mechanics safety assessment for a particular accidental scenario that includes extremely low temperatures, the presence of a root gap that is interpreted as a crack-like flaw, the presence of nominal stresses, and material properties as given in the governing material standards.

The results provide for sufficient bearing capacities for monotonic as well as cyclic loading. This can be verified for partial penetration in cross- and T-joints and also for butt joints for full penetration.

Toughness Requirements for Plastic Design with Structural Steel: Professor Markus Feldmann is the director for this project. The principal researchers are Dirk Schäfer and Björn Eichler. The project has been sponsored by the Commission of the European Union through the Research Fund for Coal and Steel (EU-RFCS).

The design criteria in Eurocode 3 (ECS, 2005), like those of all other structural steel design specifications in the world, are based on ductile material behavior. However, no mechanics-based criterion for the choice of a steel grade with sufficient toughness on the upper shelf of the toughness-temperature-diagram is available. This is particularly important for plastic design of structures with low-temperature service conditions.

Specifically, for the case of a cleavage fracture, the lower shelf of the toughness-temperature-diagram is relevant. A fracture mechanics assessment method has been developed and implemented to facilitate the choice of steel. However, considering the pure upper-shelf behavior, the method is not sufficient for practical purposes.

The European research project PLASTOTOUGH aims at developing an upper-shelf criterion for the choice of steel material for plastic design at low temperatures. Two approaches have been used: (1) a fracture mechanics solution is validated for monotonic loading, and (2) an approach based on damage mechanics has been developed for cyclic loading situations (Bleck et al., 2009). The damage mechanics solution is based on an extended von Mises yield criterion. This considers the formation, growth and coalescence of voids at the hot spot of plastic strain in the state of ductile fracture, with relation to damage curves that indicate crack initiation. Physical testing has demonstrated that the local ductility demands can be determined. Further, the results show that the strain requirements of global plastic rotations as well as of local strain demands can be verified, using both the fracture mechanics and the damage mechanics models.

As is well known by seismic researchers, in the case of seismic events a structure must provide appropriate deformation capacity. It can be shown that the cracking associated with ultra-low-cycle fatigue is not relevant for buildings, as long as the behavior is determined using reasonable limits

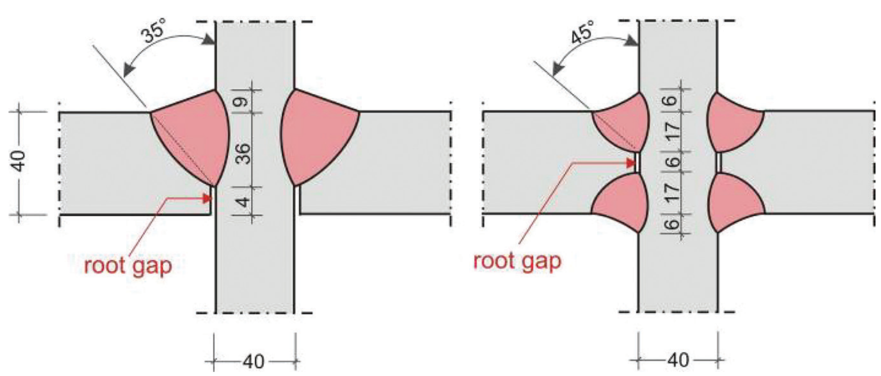


Fig. 2. Butt welds with root gaps (dimensions in mm).
(Figure courtesy of Professor Markus Feldmann)

for inter-story drift. For seismic issues these material performance investigations demonstrate that an elevated level of toughness is an appropriate solution (Feldmann et al., 2011a).

Composite Bridges with Integral Abutments: Professor Markus Feldmann is the director for this project. The principal researchers are Daniel Pak and Johannes Naumes. The project has been sponsored by the Commission of the European Union through the Research Fund for Coal and Steel (EU-RFCS).

The Institute of Steel Construction at Aachen has led the European project INTAB that aims at developing and promoting the integral abutments in composite bridge construction. It is one of the multi-institution, multicountry projects of the European Union, through the joint efforts of the Luleå University of Technology (Sweden), the University of Coimbra (Portugal), the University of Liège (Belgium) and the steel companies Arcelor (Luxembourg) and SSF (Germany).

Bridges with integral abutments are characterized by two unique features. First, the superstructure is fully fixed to the abutment structure, such that end moments are created that counteract the moments in the span, creating a bridge with relatively shallow members. Second, expensive expansion joints can be avoided.

As illustrated in Figure 3, the abutments are rigidly connected to the superstructure of integral bridges. The piles are not only loaded by vertical forces, but also by shear forces and moments as well as by forced displacements and rotations. The magnitude of these forces depends on a number of parameters, such as the stiffness of the soil, the stiffness of the superstructure, the stiffness of the piles and the length of the superstructure.

The interaction among the pile, the abutment and the girder is particularly important for the design of the piles. Rigid connections transfer all forces and displacements into the piles. Although these types of connections are generally preferred, the rigidity of the abutment and pile configuration, along with the soil interaction, is often unclear. Different approaches have been developed for considering the moment and force distributions in the abutment and the girder span, along with the effects of the continuous support of the soil behind the steel sheet pile and the low cycle resistance and response of the superstructure (Feldmann et al., 2011b).

Development of Innovative Steel-Glass Structures for Architectural and Structural Applications: This project was reported in the *Current Steel Structures Research* paper published in the first quarter 2012 issue of *Engineering Journal*. It is part of a larger-scale development of steel and glass structures. The lead research institution is RWTH Aachen; the research work presented in the earlier *Engineering Journal* issue was conducted at the Czech Technical University in Prague, the Czech Republic.

SOME CURRENT RESEARCH WORK AT THE FEDERAL UNIVERSITY OF RIO DE JANEIRO IN BRAZIL

The Federal University of Rio de Janeiro (FURJ) is the leading university in Brazil and a premier international university, with a broad program in all areas of civil engineering. The department of civil engineering has a large student population and a number of research activities, of which one of the most important areas is steel construction in all forms. Professor Eduardo Batista is the head of the

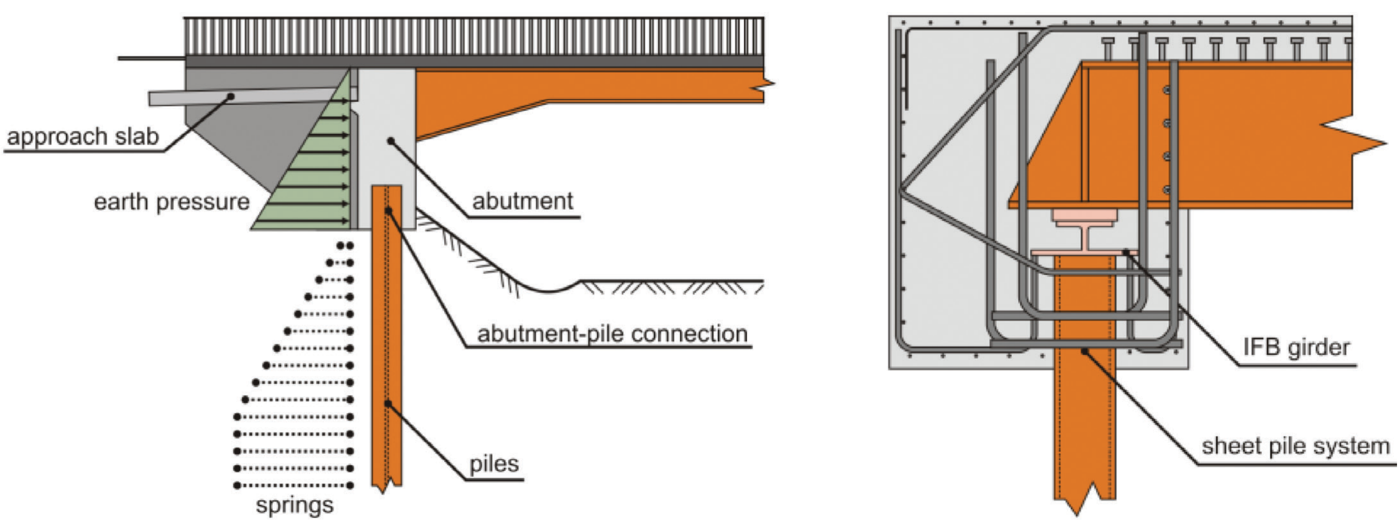


Fig. 3. Typical details of the integral abutment for a bridge.
(Figure courtesy of Professor Markus Feldmann)

structural steel group; he and his colleagues are primary members of the Brazilian steel design code development work. They have published a number of significant papers in international journals and participate actively in workshops and conferences. Because of the robust Brazilian economy, the research and educational focus of the university is highly likely to make it an increasingly important institution in South America.

While a number of research projects are being conducted at FURJ, the following discussions will touch upon key efforts in three of the most active areas.

Cold-Formed Steel Construction: Cold-formed steel members in Brazil are primarily used for simple and small structural applications, such as in residential construction. Such elements are also used extensively for roofing and rack systems. The major benefits of cold-formed construction are derived from custom-made structural systems, as has typically been the case in North America and Europe. For emerging markets like those of many countries in South America, significant benefits are realized, especially for residential and small industrial applications.

As is recognized in design code applications, the complex structural behavior of thin-walled open sections is primarily dependent on torsional behavior and related stability phenomena. In particular, the interaction among the various buckling modes gives rise to limit states that are not found in hot-rolled steel members. The research activities at FURJ, therefore, aim to develop solutions for the following cold-formed member response characteristics:

1. Buckling behavior and nonlinear post buckling and buckling mode interaction.

2. Member strength, including for beams, columns, beam columns and trussed systems.

Fig. 4. Cold-formed trussed beam under full-scale load test (beam span 20 m = 67 ft). (Photo courtesy of Professor Eduardo Batista)

3. Design rules and procedures for practical design (Batista, 2009, 2010).

4. Development of suitable criteria for national design codes.

The FURJ researchers and the university interact aggressively with industry to address practical needs and applications. For example, rack systems and lightweight solutions for large-span roofing systems have been studied extensively. A project example is shown in Figure 4, where a trussed beam from a family of standard cold-formed structures was evaluated by numerical analyses and full-scale tests in order to assess its behavior under service loads and to identify the collapse mechanism and the eccentricity effects in the connections.

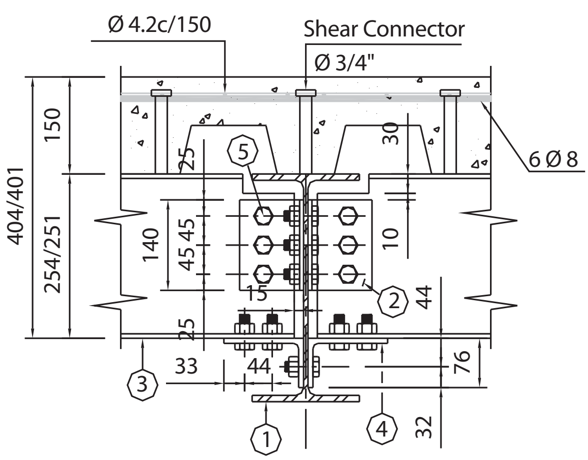
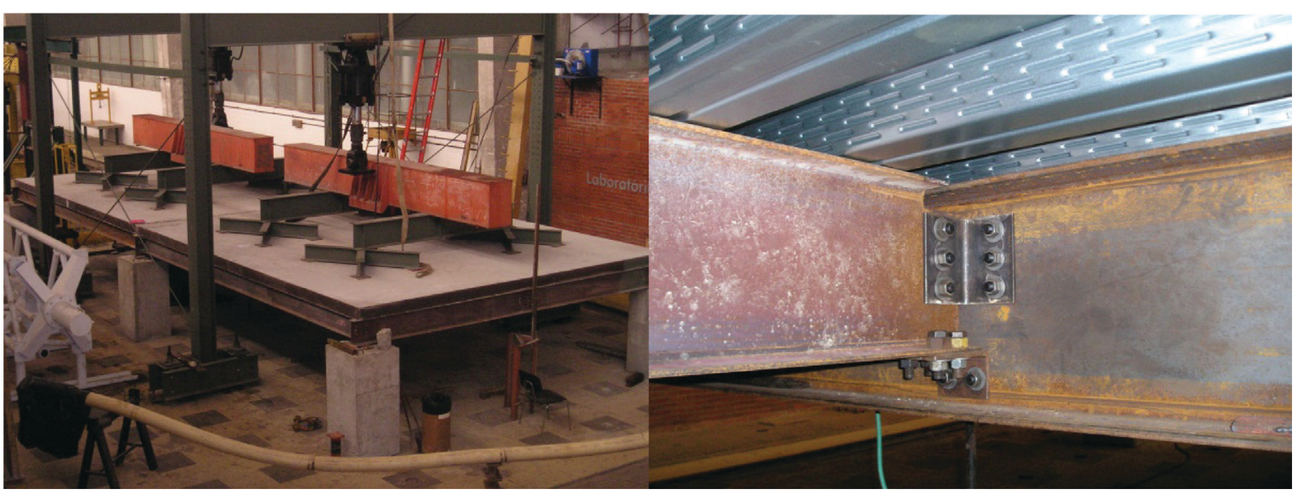


Fig. 5. Details of the semi-rigid beam-to-girder connection (dimensions in mm).
(Drawing courtesy of Professor Eduardo Batista)

Performance of Steel-Concrete Composite Structures: Composite construction is now used extensively in Brazil, particularly for shopping malls and similar long-span systems, multi-story parking structures, and commercial high-rise buildings. Design and fabrication of suitable connections effectively determine the success of each project. The composite construction research at FURJ has therefore focused on beam-to-column connections, including the semi-rigid response characteristics (Oliveira and Batista, 2009). The projects have focused on the composite semi-rigid connections because such details offer potential cost savings and improved structural performance. With this background, it was decided to emphasize the semi-continuous floor system concept.

The research work was conducted in two steps: (1) test the connection itself through a series of individual full-scale tests and (2) test the beam-to-girder connection in a composite floor system. Figure 5 shows the details of the composite connection. The results were used to develop a proposed design method in a case study for an existing parking structure, concluding that it would provide significant economies for the project. Figure 6a shows the overall testing assembly, and Figure 6b provides a close-up view of the connection.

Behavior of Steel and Composite Structures under Fire Conditions: Professor Alexandre Landesmann is the director of this project. The focus is on thermo-mechanical performance of structures under high temperatures and fire conditions. Analyses are performed on the basis of a transient



(a) *(b)*

Fig. 6. Full-scale testing of a semi-continuous floor system and one of the connections.
(Photo courtesy of Professor Eduardo Batista)

heat-transfer model, which takes into account the properties of heated materials and simulates the inelastic behavior of steel and composite structures subjected to fire. The method of analysis also allows for different steel (insulated or not) and composite configurations (Landesmann, 2012).

The studies have now been expanded to include finite element analysis of the distortional post-buckling behavior, the ultimate strength and the design of cold-formed steel-lipped channel and rack-section columns subjected to various (uniform) temperature distributions. Figure 7 gives results for the von Mises stress distributions at the distortional collapse of 65-ksi yield stress steel columns and subjected to four different temperatures.

The failure load data gathered from the numerical analysis are used to carry out preliminary assessments of the applicability of the direct strength method (DSM) to estimate the load-carrying capacity of columns failing in distortional buckling under fire conditions (Landesmann and Camotim, 2010).

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF CHILE IN SANTIAGO, CHILE

The University of Chile is one of the premier institutions in that country, with excellent contributions to the state of the art of steel structures, in particular as related to the seismic performance of industrial structures. The Chilean code for the seismic design of such structures is excellent and one of the very few in the world that addresses their unique considerations and demands (INN, 2003).

Steel construction in Chile is significantly complicated by the fact that the country has no steel mills that produce hot-rolled wide-flange shapes; even much of the plate steel has to be imported. As a result, the engineering profession has to use welded built-up shapes. With a small number of steel fabricators, the engineering talent is very broad and solid, and the fabricating equipment (especially for welding) is first class. The quality of steel construction is therefore generally very good, but material supply problems and costs will vary a great deal in response to international market conditions. Design and fabrication of steel structures in Chile can offer real challenges.

Double Split Tee Moment Connections: The director of this project is Professor Ricardo Herrera Mardones. Following the investigation prompted by the failures of steel structures after the 1994 Northridge earthquake, several new connections and improved connection details were proposed, and many more have been developed in recent years. Among them, the double split tee (DST) connection has been prequalified for use in steel seismic resistant construction.

Significant research has been conducted on the behavior of the connection and the tee-stub, providing models and design procedures that have been incorporated by various design codes. However, most of the research has been carried out on tee-stubs cut from hot-rolled wide flange sections.

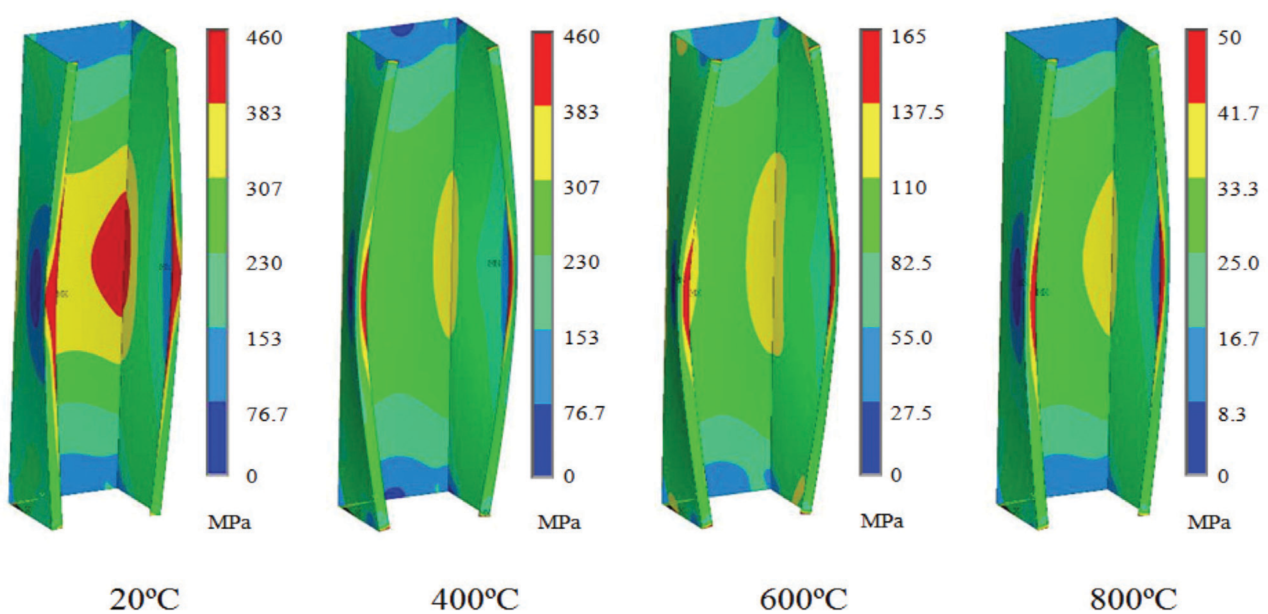


Fig. 7. Von Mises stress distributions for distortional buckling of columns at different temperatures. (Drawing courtesy of Professor Alexandre Landesmann)

Because welded tee-stubs have the advantage of improved material utilization and freedom of sizing, as compared to hot-rolled tee-stubs, and because Chile has no steel mills, the use of the welded DST was a natural consequence.

The proposed project will conduct analytical and experimental studies on the behavior of welded tee-stubs subjected to cyclic loading through the stem. The objectives of these studies include determining the limit states that control the behavior of welded tee-stubs, increasing the database of tests for these components, and evaluating the applicability of current design recommendations and models to welded tee-stub moment connections. To achieve these aims, finite element models of welded tee shapes will be calibrated and subjected to cyclic loading, and representative configurations will be tested under cyclic loading to simulate the conditions for a double welded tee moment connection. Simplified models and design recommendations will then be used for the design of double split tee connections.

It is expected that this project will provide designers with information to analyze and design structural systems with DWT connections and to generate data to prequalify the connections for use in seismic resistant design.

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