# Current Steel Structures Research

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Behavior, strength and design of all types of connections were addressed at the Sixth International Workshop on Connections in Steel Structures, which was held in Chicago, June 23–25, 2008. More than 60 international experts provided three days of paper presentations and extensive technical discussions of a variety of subjects. These workshops are a continuing and cooperative effort primarily between North America and Europe, with AISC and ECCS, the European Convention for Constructional Steelwork, serving as the hosts for the event. Some of the research efforts that are presented in this paper reflect studies of the workshop participants, and all of the papers are presented in a book that will be published by AISC later this year or early in 2009.

The research efforts discussed in this paper examine the behavior and strength of various forms of braced frames under seismic conditions, focusing on connection details for improved energy absorption as well as frame behavior. A novel connector in cast steel offers significant potential for braced frames using tubular members, and the development of a unique structural fuse system for bracing members is examined through an actual construction project. Further, block shear continues to be the subject of ongoing projects, and the most recent effort focuses on the limit states that govern connections with unusual failure paths. Punching shear failures in connections with high-strength bolts in tension is examined in a recent Hungarian study, and researchers in Chile are looking at improved response characteristics of certain types of shear lugs for column bases. Analytical models are critical for evaluation of frames with partially-restrained (PR) connections, and an American researcher has focused on a novel type of hybrid element. An unusual study of the performance of crane girders in actual structures offers novel and interesting findings regarding typical response accelerations of such girders. Finally, stainless steel continues to attract attention for several applications, and work in Hong Kong examines web crippling phenomena for thin-walled hollow structural sections

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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.

## STRUCTURAL BEHAVIOR AND STRENGTH UNDER SEISMIC LOADS

**Behavior and Strength of Link-to-Column Connections in Eccentrically Braced Frames:** This project has been conducted at the University of Texas in Austin, with Professor Michael D. Engelhardt as the director. Funded by the National Science Foundation and AISC, the study formed the basis for the doctoral dissertation of Taichiro Okazaki, who is now a professor at the University of Minnesota (Okazaki and Engelhardt, 2007; Okazaki, Engelhardt, Drolias, Schell, Hone and Uang, 2008).

Eccentrically braced frames have been used extensively as an efficient and stable seismic load-resisting structural system. The original usage focused on the shear links being used within the beams of a chevron-type frame, for example. However, the links certainly would appear to serve very well at the beam ends, connecting directly to the columns, and the performance of such elements was the focus of the University of Texas project. The work was in part prompted by the fact that the AISC seismic design specification (AISC, 2005b) contains detailed test performance criteria for link-to-column connections, and such test data were very scarce at the time the project was undertaken.

Using ASTM A992 steel and a range of different sizes of members and connection details, 24 full-scale tests were performed. It was initially found that the link-to-column connections tended to fail prematurely in the weld between the link and the column flange, unable to provide adequate inelastic rotation capacity. Figure 1 shows one such example. Modifying the welding details to have an all-around fillet weld between the link and the column flange proved successful, providing adequate inelastic rotation capacity. Another test used stiffeners parallel to the link web in the section of the link that was closest to the column; this was also found to supply adequate rotation capacity. Figure 2 shows this test specimen near the end of the loading regime. Additional work is now being done, focusing on the need for improved design criteria.

**Use of Cast Steel Connectors for Bracing Connections in Special Concentrically Braced Frames:** This project has been conducted at the University of Toronto, Ontario, Canada, with Professors Jeffrey Packer and Constantin Christopoulos as the directors. The study was undertaken specifically to examine the potential use of a cast element connecting the gusset plate and a circular hollow section (CHS) as the bracing member, to take advantage of the favorable buckling characteristics of the CHS. In addition to improved gusset plate geometries and overall connection performance criteria, it was felt that the fabrication of such framing systems would exhibit significant advantages. Figure 3 shows the details of a typical connection.

The initial part of the study used a single type of connector that was bolted to the gusset plate and shop welded to the ASTM A500 steel tubular member, using complete joint penetration welds (de Oliveira, Packer and Christopoulos, 2008). Subsequent developments provided additional sizes of connectors and tubular members, to arrive at more practical bracing member sizes that did not impose such large axial forces on the connection region. Figure 4 shows the range of connectors that were developed by the Cast ConneX Corporation.

Each of the connectors shown in Figure 4 were used together with the heaviest tubular shapes that fit the connector dimensions, and the connection assemblies were then tested cyclically in accordance with the criteria of the AISC *Seismic Provisions for Structural Steel Buildings* (AISC, 2005b). All of the tests satisfied the AISC criteria, and the failures of the

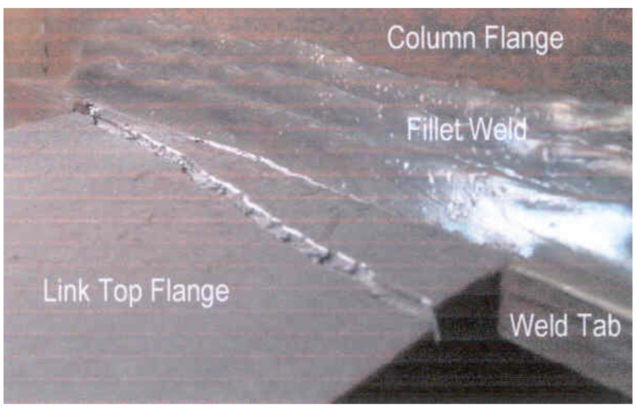



*Fig. 1. Fracture of link-to-column flange connection (courtesy of Professor T. Okazaki).*

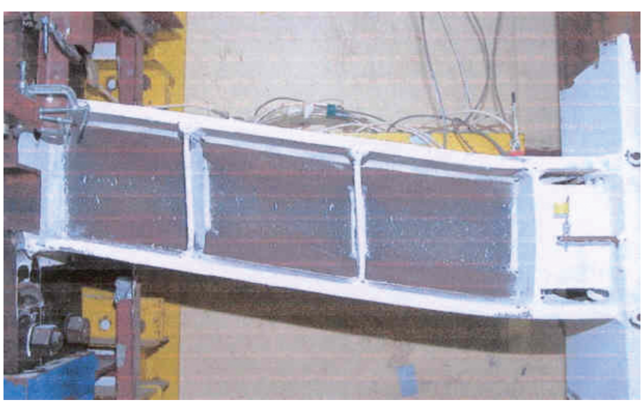


*Fig. 2. Satisfactory performance of connection with stiffened link next to column (courtesy of Professor T. Okazaki).*

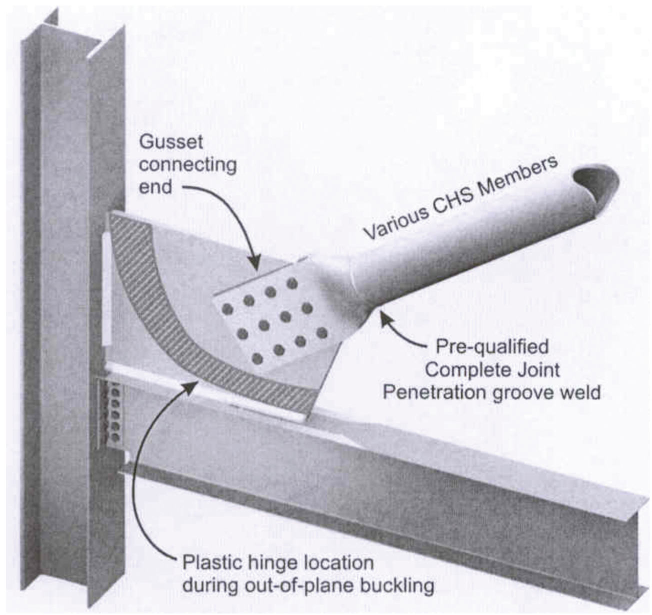



*Fig. 3. Bracing connection with cast steel connecting element between gusset plate and tubular bracing member (courtesy of Professor J.A. Packer).*

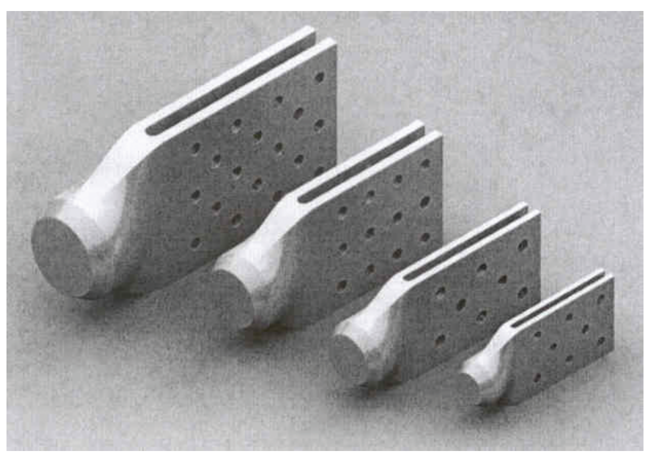


*Fig. 4. Range of sizes of cast steel connecting elements (courtesy of Cast ConneX Corporation).*

brace assembly occurred as flexural buckling of the tubular member with a plastic hinge forming at mid-length. Figure 5 shows one of the specimens after buckling. These tests were conducted at École Polytechnique in Montreal with Professor Robert Tremblay as the director, and further work will be done jointly by the two universities.

Full-scale tests of a complete connection region, as shown in Figure 3, with realistic member sizes, will subsequently be tested for inelastic cyclic performance assessment.

**Minimizing the Strength of Bracing Connections:** This is a study that was conducted by Canam Corporation in connection with the fabrication of structures for four major stadium projects in the New York City area. Richard Vincent, Vice President for Research and Development, was in charge of the study.

Recognizing that bracing member connections are designed to allow the member to yield in tension, and also that the size of such members may be governed by the compressive member capacity, the result is usually that the member size and its connections become large, complex and costly. This approach may also prompt increases in the column sizes for the structure, further increasing the project costs (Vincent, 2008).

The aim of this study was to arrive at members with smaller net areas for the tensile load demands, allowing the requisite yielding in tension and at the same time preventing local and overall buckling during the compressive load cycle. The size of the connection could therefore be reduced, while satisfying all performance requirements. The reduction of the net area of the member would effectively provide a structural fuse detail, with adequate inelastic deformation capacity in tension and satisfactory compression response. An example of a suitable fuse detail with a wide-flange bracing member is shown in Figure 6.

Additional evaluations will eventually be performed, including testing of the bracing members with the fuse detail, to establish ranges of member sizes and fuse details for various performance criteria.

## OTHER CONNECTION PERFORMANCE ISSUES

**Block Shear Evaluation for Members with Uncommon Failure Paths:** This project has been conducted at the University of Alberta in Edmonton, Alberta, Canada, with Professor Robert Driver as the director. The work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada, as well as the Steel Structures Education Foundation of Canada.

A number of research projects have addressed the many issues associated with block shear since the phenomenon was first identified (Birkemoe and Gilmor, 1978). Design standards in North America and elsewhere have undergone numerous revisions as additional findings were reported, although the subject now appears to have reached its final form and practical solution procedures (Driver, Grondin and Kulak, 2006; Cai and Driver, 2008).

In addition to analyzing all relevant tests that have been reported in research literature, an additional 12 tests were performed to assess limit states and failure paths of atypical connection geometries. Using wide-flange shape elements with ¾-in.-diameter ASTM A490 bolts, various gage sizes,

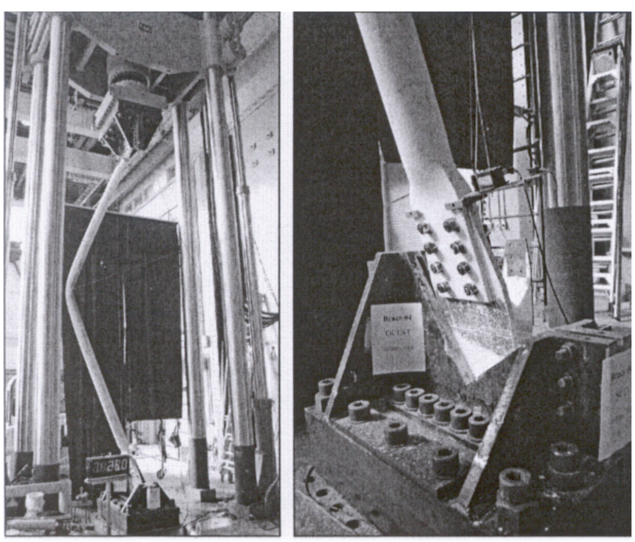


*Fig. 5. Testing of tubular brace with cast steel connectors (courtesy of Professor J.A. Packer).*

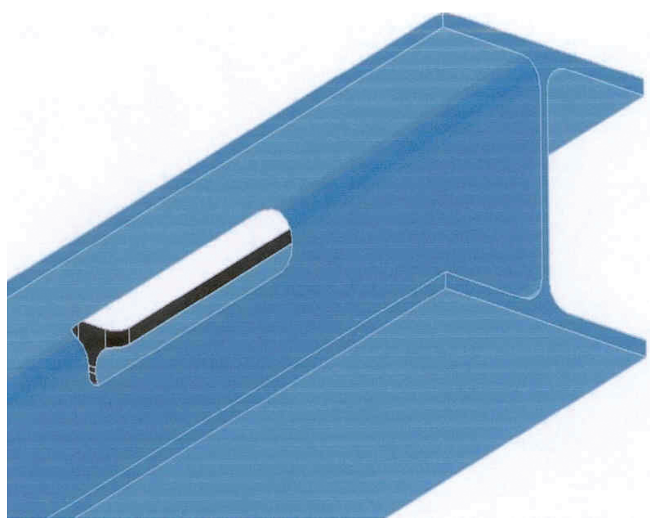


*Fig. 6. Wide-flange bracing member with material removed to create structural fuse (courtesy of Richard Vincent).*

and end distances, as well as the number of rows of bolts, the connections were made to the web of the shapes. The tests demonstrated failures through bolt tear-out along the shear planes on both sides of the bolt, as shown in Figure 7a. A splitting crack as shown in Figure 7b developed after the bolt tear-out limit state had reached is maximum load. Figure 7c shows the failure that developed in some cases, where fracture did not occur and the ductility of the steel allowed large hole deformations to take place. This is a phenomenon that also has been observed in other block shear tests.

Analyzing all of the previous and current test results, the researchers report excellent and consistent agreement with the so-called unified block shear equation. The requirements of the current AISC *Specification for Structural Steel Buildings* are found to be very conservative (AISC, 2005a). The authors note that the new equation has been adopted for the draft of the 2009 Canadian steel design standard, CSA-S16.

**Testing of Shear Lugs for Column Bases:** This is a recently started research project at the Technical University Federico Santa Maria in Valparaíso, Chile. Professor Carlos Aguirre is the director of the study.

Chile sometimes experiences very severe earthquakes, and for column base plates, shear lugs are therefore often used in combination with anchor rods. The study aims at determining the strength and deformation characteristics of different types of shear lugs, two examples of which are shown in Figure 8. The initial results show that the anchor rods yield prior to reaching the shear lug capacity, and the deformation capacity is substantial. Following a drop in load-carrying capacity, the anchor rods eventually fracture and the shear lug buckles locally along with weld fractures. The study will continue with additional tests; eventually the AISC-based design procedure will be reassessed and revised as necessary.

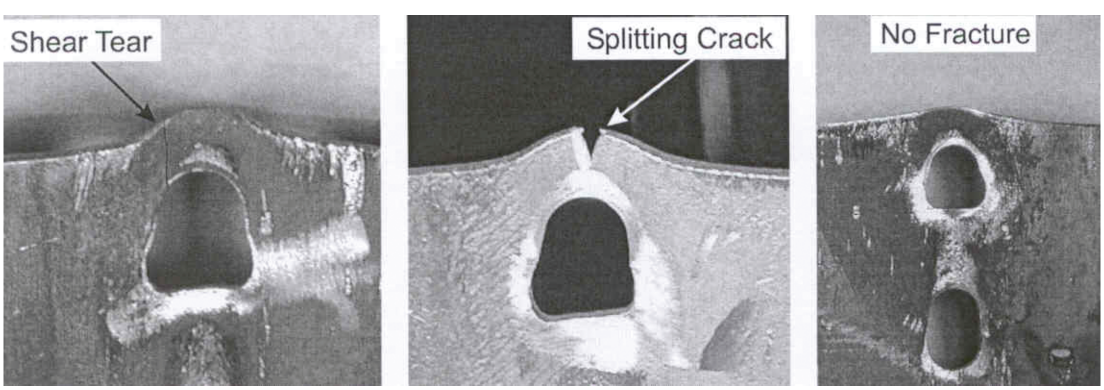
**Punching Shear Resistance of Tension Bolts:** This project is a joint effort between the University of Thessaloniki in Greece (Professor P. Baniotopoulos) and the University of Pécs in Hungary (Professor P. Ivanyi). The testing is done at the Budapest University of Technology and Economics in Hungary.

Individual bolts are loaded in tension perpendicularly to plates of thicknesses from 1 to 6 mm (0.04 to 0.25 in.); the bolts are used with and without washers. As an example of the results from this ongoing study, Figure 9 shows the punching shear failures with bolt pull-through of a 1-mm plate and a 5-mm-plate. In the case of the thinner plate (Figure 9a) the bolt and the nut simply pull directly through the plate, with fractures radiating from the corners of the nut. For the thicker plate (Figure 9b), the nut shears off a portion of the plate that reflects the shape of the nut. These and other punching shear failures will be modeled by finite element analyses, and additional static and dynamic tests will also be conducted.

## METHODS OF FRAME ANALYSIS

**Three-Dimensional Web-Based Semi-Rigid Steel Frame Analysis with Graphical Interface:** This is an NSF-funded research project at the University of Texas at Arlington, with Professor Ali Abolmaali as the director.

A novel type of hybrid element has been developed for the analysis, utilizing pseudo spring elements to represent the full inelastic behavior of the connections. Thus, the changing stiffness of the connections as well as the local yielding within the beam ends are reflected in the representative terms in the structural stiffness matrix. One of the advantages of the approach is that the number of degrees of freedom can be reduced, because individual connection elements do not need to be modeled. The hybrid element is illustrated in Figure 10.




(a) (b) (c)

*Fig. 7. Various failure modes in block shear tests (courtesy of Professor R.G. Driver).*

## INDUSTRIAL STRUCTURES

**Monitoring of Crane Girders in Actual Structures:** This is an ongoing project at the University of the Witwatersrand in Johannesburg, South Africa, with Professor A. Elvin as the director. The study is sponsored by the Southern African Institute of Steel Construction (SAISC).

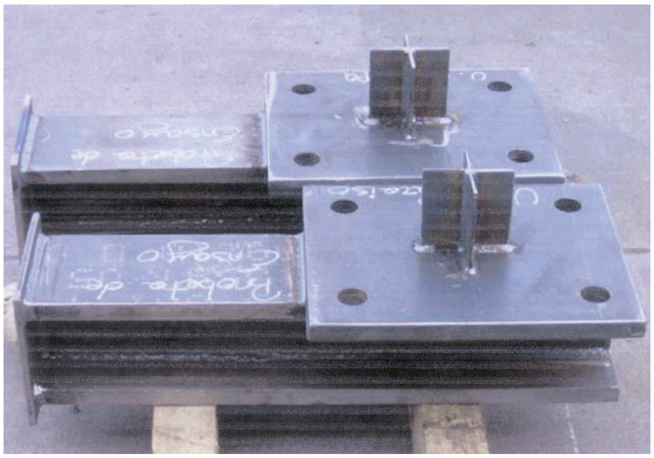
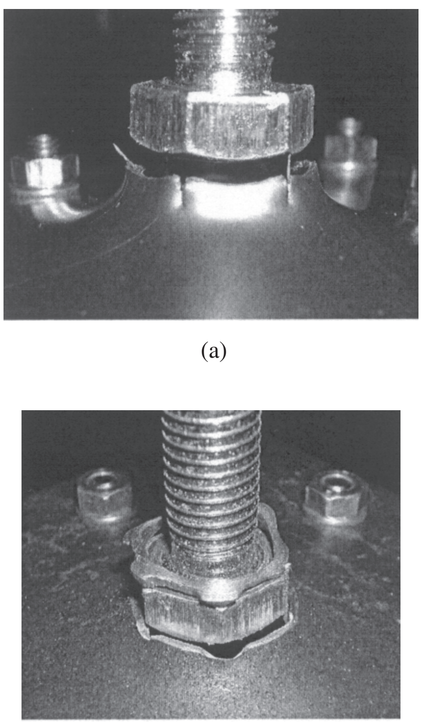


*Fig. 8. Test specimens for column base plates with cruciform shear lugs (courtesy of Professor Carlos Aguirre).*



(a)

(b)

*Fig. 9. Punching shear failures with bolts in 1-mm and 5-mm plates (courtesy of Professor Miklos Ivanyi).*

Although cranes and crane girders have been examined for individual response characteristics, *in situ* data on their behavior as well as the structures they serve are very limited. The project aims at establishing deflections and accelerations for 30 to 50 cranes of a variety of classes and load capacities. Wireless sensors with a three-dimensional accelerometer are installed on the crane girders as shown in Figure 11, and data logging monitors the performance of the girders.

Because the project is currently under way, the final results are not yet available. However, the researchers note that "surprising results" have been found. Specifically, vertical as well as longitudinal and transverse accelerations larger than 1.0 g have been measured. This may entail additional design considerations for certain types and uses of crane girders.

## STAINLESS STEEL APPLICATIONS

**Cold-Formed Stainless Steel Hollow Structural Sections:** This study has been conducted at the University of Hong Kong in China, with Professor Ben Young as the director.

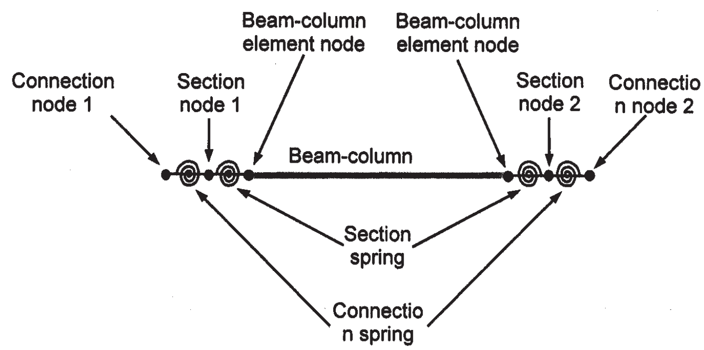



*Fig. 10. Hybrid element for incorporation of connection and beam response characteristics (courtesy of Professor Ali Abolmaali).*

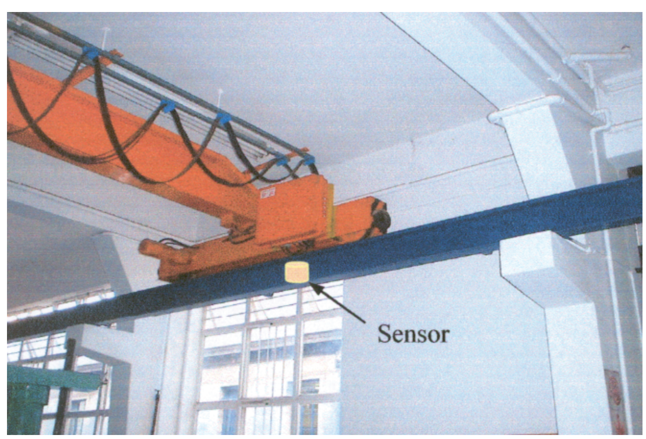



*Fig. 11. Monitoring the dynamic response characteristics of crane girders (courtesy of Professor A. Elvin).*

A very large program of physical testing was established for the project, using 155 pure web crippling tests, 15 pure bending tests, and 21 combined web crippling and bending tests. Figure 12 shows the test setup for a square hollow structural section (HSS) member. Finite element analyses were also performed, to assess current international design criteria, looking at American, Australian and European codes for stainless steel structures.

The results have shown that all current criteria for high strength stainless steel are either unconservative or very conservative. The researchers attribute this to the fact that the web crippling rules are generally based on tests alone and therefore empirical, and even more importantly that the tests have utilized cold-formed carbon steel instead of stainless steel. The project data have now been used to develop a unified web crippling equation for various types of stainless steel (Zhou and Young, 2007).

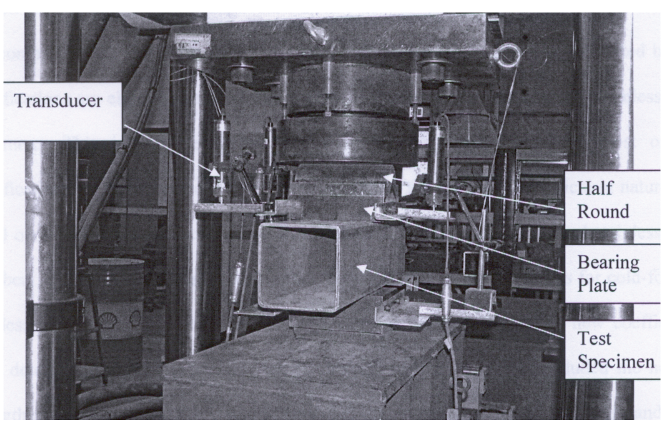



*Fig. 12. Web crippling test of a stainless steel HSS (courtesy of Professor Ben Young).*

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