Current Steel Structures Research

No. 31

REIDAR BJORHOVDE

INTRODUCTION

This issue of "Current Steel Structures Research" focuses on a selection of research projects at one university in Europe and one in Hong Kong. The descriptions will not include all of the current projects at the schools. Instead, selected studies provide a representative picture of research under way and demonstrate the importance of these 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 Technical University of Lisbon in Lisbon, Portugal, and the University of Hong Kong in Hong Kong, China. The studies presented reflect elements of the projects as well as other major, long-time activities. All of the projects are multiyear 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 the case for important studies in the United States, the outcomes of the projects focus on industry needs and implementation in design standards.

The lead researchers have been active for many years, as evidenced by their leading roles in research and development of their respective countries. They have also been frequent participants in the work in 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.

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.

Reidar Bjorhovde, Dr.-Ing., Ph.D., P.E., Research Editor of the *Engineering Journal.* Tucson, AZ. E-mail: rbj@bjorhovde.com

SOME CURRENT RESEARCH WORK AT THE TECHNICAL UNIVERSITY OF LISBON IN LISBON, PORTUGAL

Established by the university in 1995, the Institute of Structural Engineering, Territory and Construction (ISETC) is a broad-based research unit that aims to develop novel concepts in scientific and technological research and to transfer those findings to society through education, standards and practical utilization by designers. The institute is housed in the Department of Civil Engineering, Architecture and Geosciences and is financed partly by the Portuguese National Research Council (through noncompetitive funding), partly by competitive funds allocated to specific projects by various governmental agencies and partly by funds coming from consulting work performed by institute staff. The institute is entirely autonomous for administrative and financial services, and it incorporates a library and five laboratories. For structural engineering, the most important units are those focusing on computational mechanics, structures and strength of materials, and construction. The staff of the institute currently numbers 101 faculty members and post-doctoral fellows, with 83 doctoral and master degree students.

Research on steel structures is carried out almost exclusively within two groups: (1) Mechanics, Modeling and Analysis of Structures and (2) Structural Design and Geotechnical Engineering. The directors of these groups are Professor Dinar Camotim and Professor Luis Calado, respectively. A number of the current projects are presented in the following.

Analysis of Thin-Walled Steel Structures Using Generalized Beam Theory (GBT): Professor Dinar Camotim is the project director and chief researcher, and Drs. Nuno Silvestre, Rodrigo Gonçalves, Cilmar Basaglia and Rui Bebiano are the researchers. The project is sponsored by the Portuguese National Research Council.

Generalized beam theory (GBT) is a one-dimensional beam modeling approach that incorporates folded-plate concepts. Developed by Professor Camotim, it is an alternative and very promising approach to shell finite element theory and finite strip analysis. It has proven to be particularly suitable for members and structures incorporating the complex shapes and systems typically associated with cold-formed construction (Camotim et al., 2010a, 2010b). Due to the unique modal features, GBT-based analyses exhibit high computational efficiency along with accurate and elegant solutions for structural behavior and performance.

The objectives of the current project are:

1. Complete the development, numerical implementation and application of GBT formulations currently in progress.

2. Develop, implement, validate and apply novel GBT formulations to solve structural problems not yet tackled by this approach.

3. Develop design applications based on GBT results.

4. Promote and disseminate the use of GBT in the technical community, including practical use in design offices.

Recent achievements of the research team are the development and numerical implementation of GBT solutions for the following subject areas:

1. Performing local, distortional and global buckling and post-buckling analyses of thin-walled steel frames.

2. Accounting for load application effects (distance from the shear centre) in thin-walled members, including localized buckling.

3. Analyzing the buckling behavior associated with the occurrence of web crippling (or patch loading) for various loading configurations.

At this time, it is also important to mention the development of Version 1.0 of the user-friendly GBT-based software GBTUL (an acronym for Generalized Beam Theory at the Technical University of Lisbon), which can perform buckling and vibration analyses of open-section thin-walled steel members. The software is available for free and can be downloaded from www.civil.ist.utl.pt/gbt.

Figure 1 is an example of what has been done using the GBT approach in comparison with results obtained with the well-known software ANSYS. The figure shows the results for a two-span I-beam under top and bottom loading. Figure 1a shows the ANSYS and GBT pre-buckling transverse normal stress distributions, Figure 1b shows the buckling mode given by ANSYS and Figure 1c gives the results of the GBT analyses. The correlations are clearly very good, especially in view of the complexity of the subject.

Distortional Mode Interaction in Cold-Formed Steel Columns: This project is a joint effort among the Technical University of Lisbon; the Federal University of Rio de Janeiro, Brazil; and the University of Hong Kong, China. Professor Dinar Camotim is the project director, with researchers Pedro Dinis and Nuno Silvestre from the Technical University of Lisbon; Eduardo Batista, Federal University of Rio de Janeiro; and Ben Young from the University of Hong Kong. The project is sponsored by the Portuguese National Research Council.

Cold-formed steel columns are often highly susceptible to local (L), distortional (D) and global (G) buckling and exhibit similar L, D and/or G buckling stresses for some commonly used geometries. This implies that their post-buckling behavior, ultimate strength and failure modes are influenced by effects that involve some or all of these buckling modes. The objectives of the project are the following:

1. Provide in-depth understanding of the mechanics of the interaction phenomena.

2. Through physical tests, determine the individual failure modes and assess their effect on the column response.

3. Use numerical and experimental ultimate strength data to develop and validate design approaches that are based on the direct strength method (DSM) (Silvestre et al., 2012).

Recent results have provided in-depth understanding of the response of simply supported and fixed-lipped channel columns affected by L-D, D-G and L-D-G buckling (Dinis and Camotim, 2011). There is clear experimental evidence regarding the occurrence of L-D and L-D-G interaction and of the subsequent reduction of the ultimate strength. Further, efficient DSM design approaches are now being developed for lipped-channel columns affected by L-D-G and D-G interaction (Silvestre et al., 2009; Silvestre et al., 2012). Figure 2 illustrates the interaction between local and distortional buckling, as demonstrated by tests at the University of Hong Kong.

Energy-Absorbing Fuses for Seismic-Resistant Steel Frames: This project is a joint effort among the Technical University of Lisbon; the Polytechnic University of Milano, Italy; the Technical University (RWTH) of Aachen, Germany; the National Technical University of Athens, Greece; and the steel company Sidenor SA from Greece. Professor Luis Calado, Lisbon, is the project director, with researchers Carlo Castiglioni from Milano, Ioannis Vayas from Athens, Bruno Hoffmeister from Aachen and D. Kalteziotis from Sidenor. The project is sponsored by the Research Fund for Coal and Steel of the European Union.

The project focuses on the development of structural systems that are simple to repair. Two innovative systems of seismic-resistant steel frames with energy-absorbing (dissipative) fuses were developed, as follows:

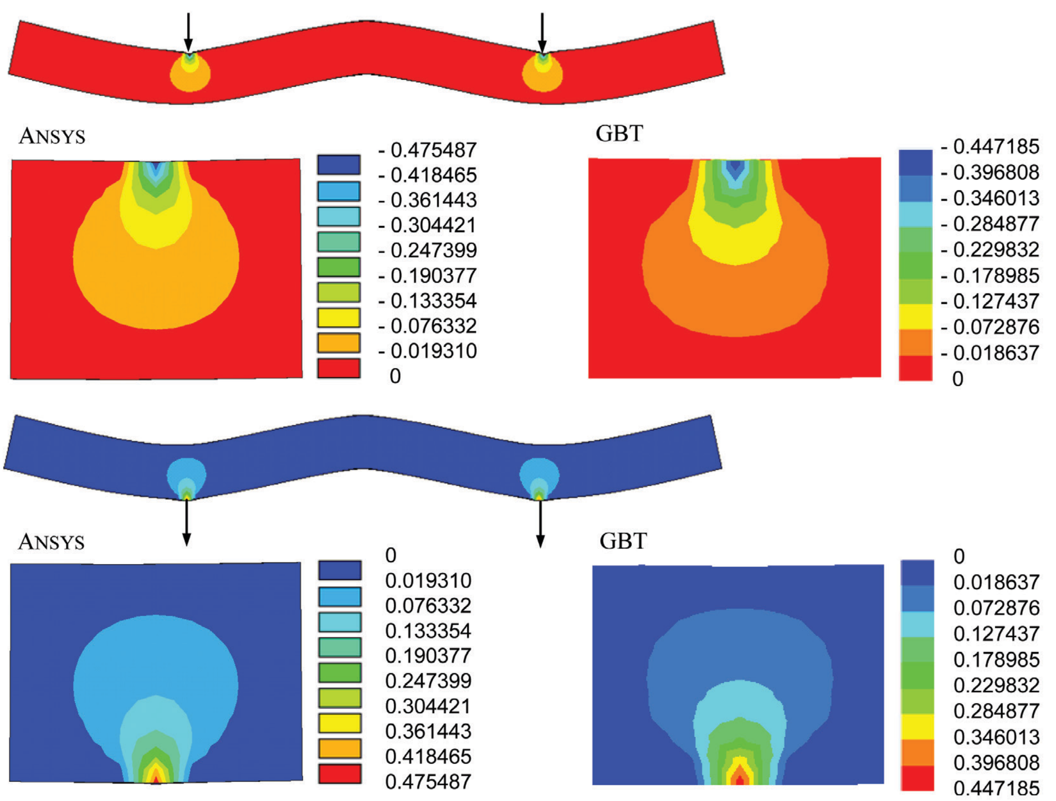
1. The FUSEIS1 type consists of two closely spaced strong columns, rigidly connected to multiple beams, with the beams connecting columns. Alternatively, the beams are interrupted and connected by short pins. An example is shown by the test setup in Figure 3, where the frame was

tested at the Polytechnic University of Milano (Castiglioni et al., 2011).

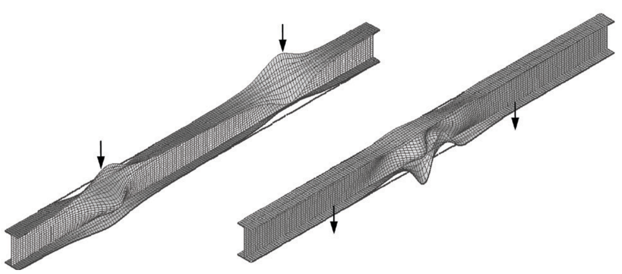
2. The FUSEIS2 type consists of seismic fuses for steel and composite moment resisting frames. The fuse is developed by plates bolted or welded to the web and the flanges of the beam. A sample application is shown in Figure 4, where the frame and its fuse elements were tested at the National University of Athens (Castiglioni et al., 2012).

One of the advantages of these systems is that any damage will only take place within the fuses, and these are easily replaced following a strong earthquake. Specifically, the FUSEIS2 systems dissipate energy through inelastic deformations and combine ductility and architectural transparency with structural stiffness. The project has also provided a design guide for practical applications of the systems, including design examples.

Steel-Concrete Composite Truss Bridges: The project is a joint effort between the Technical University of Lisbon



(a)



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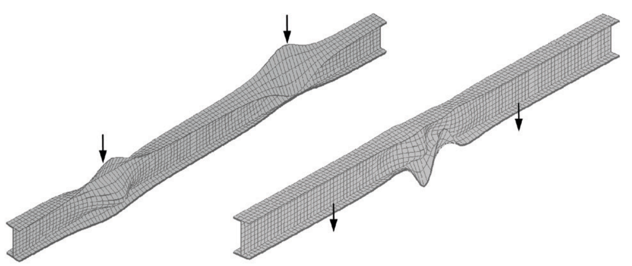


(c)

Fig. 1. Two-span I-beam under top and bottom loading: (a) ANSYS and GBT pre-buckling transverse normal stresses; the failure modes according to the results of (b) ANSYS and (c) GBT (Drawings courtesy of Professor Dinar Camotim).

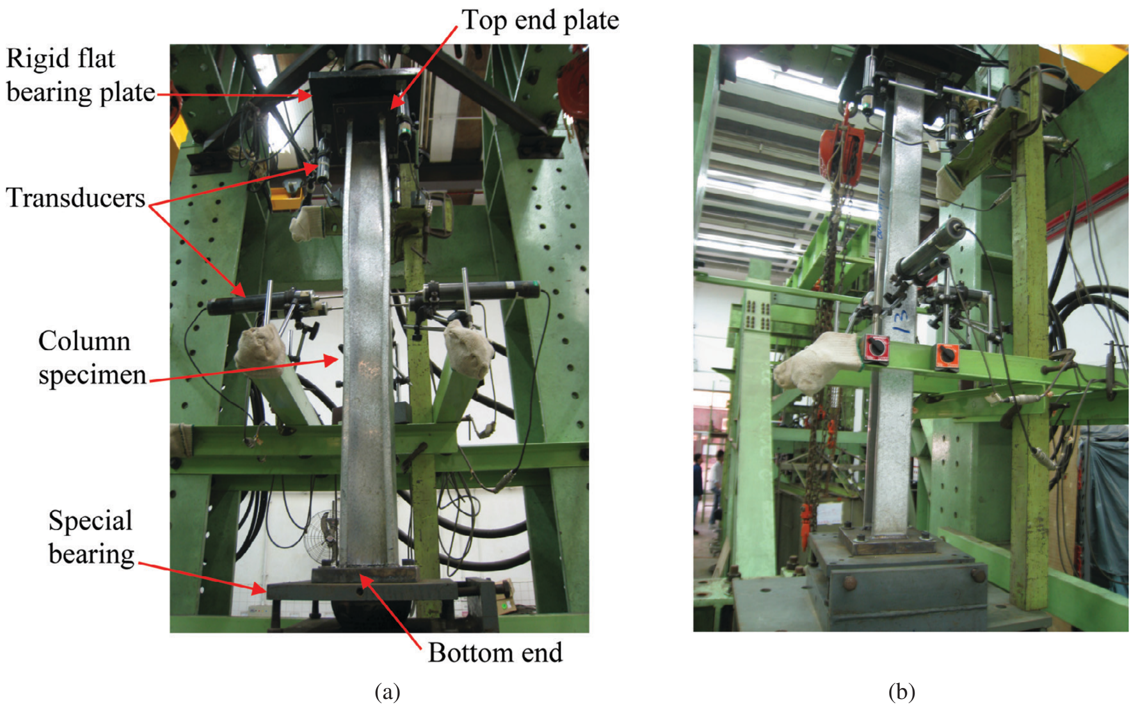


Fig. 2. Tests of lipped channel columns showing local and distortional buckling interaction (a) front view of test setup; (b) side view of test setup (photos courtesy of Professor Ben Young).

Fig. 3. Full-scale test frame with FUSEIS1 devices and failure mode (photo courtesy of Professor Carlo Castiglioni).

and the GRID Consulting Engineers Company in Lisbon. The project researchers are Professors António Reis (director) and José Oliveira Pedro. The project has been supported by grants from the Portuguese National Research Council and from the research partner, the GRID company.

The aim of this project is to examine the behavior and structural performance of three types of composite truss bridge decks—namely, wide decks supporting overhangs in curved bridges, three-dimensional triangular decks, and semi-through decks as are now commonly used in railroad bridges. In the curved bridge decks, main and secondary Warren-type trusses are combined to form an equivalent box section. Horizontal tubular bracing is placed between the lower chords, thus achieving box-type behavior while being subjected to torsion. The chords and diagonals are made of welded rectangular hollow sections (RHS) and the lateral trusses are built with circular hollow sections (CHS). To avoid intermediate internal diaphragms—for the sake of construction simplicity and aesthetics—a key issue is the differential displacement between the main trusses under eccentric loading. The secondary bending moments at the transverse cross beams, connecting the upper and lower chords, were evaluated by means of shell finite element analysis. Figure 5 shows a typical curved bridge deck with main and secondary Warren-type trusses forming an equivalent box cross-section.

Composite truss bridge decks with triangular cross-sections constitute one of the most interesting developments over the past several years (Reis, 2008). Examples are shown in Figure 6. Several major issues have been addressed:

1. The shear failure of the lower chord in the vicinity of the internal supports, where high girder shear forces must be balanced by diagonal axial forces.

2. The negative bending moment redistribution near the supports at the ultimate limit state.

3. The torsional stiffness of the bridge deck under eccentric traffic loading.

Two tests were carried out on $\frac{1}{5}$-scale bridge models subjected to two-point loading. The tests aimed at simulating the bending moment between the support section and the mid span cross-sections.

So-called semi-through trusses are currently adopted for railroad bridges, where vertical clearances are often the main deck constraint. An example of such a bridge is shown in Figure 7. Low slenderness values are currently required for the chord to reduce its size as well as to satisfy the serviceability limit states for deformability and vibration in these bridges. This is particularly important for very high speed railroads, where the deck maximum vertical accelerations are restricted, to ensure reasonable comfort levels (Reis and Pedro, 2011).

Steel-Concrete Composite Cable-Stayed Bridges: This project is being conducted at the Technical University of Lisbon. It has been funded by the Portuguese National Research Council. The researchers are Professors José Oliveira Pedro (director) and António Reis.

Cable-stayed structures provide elegant and efficient

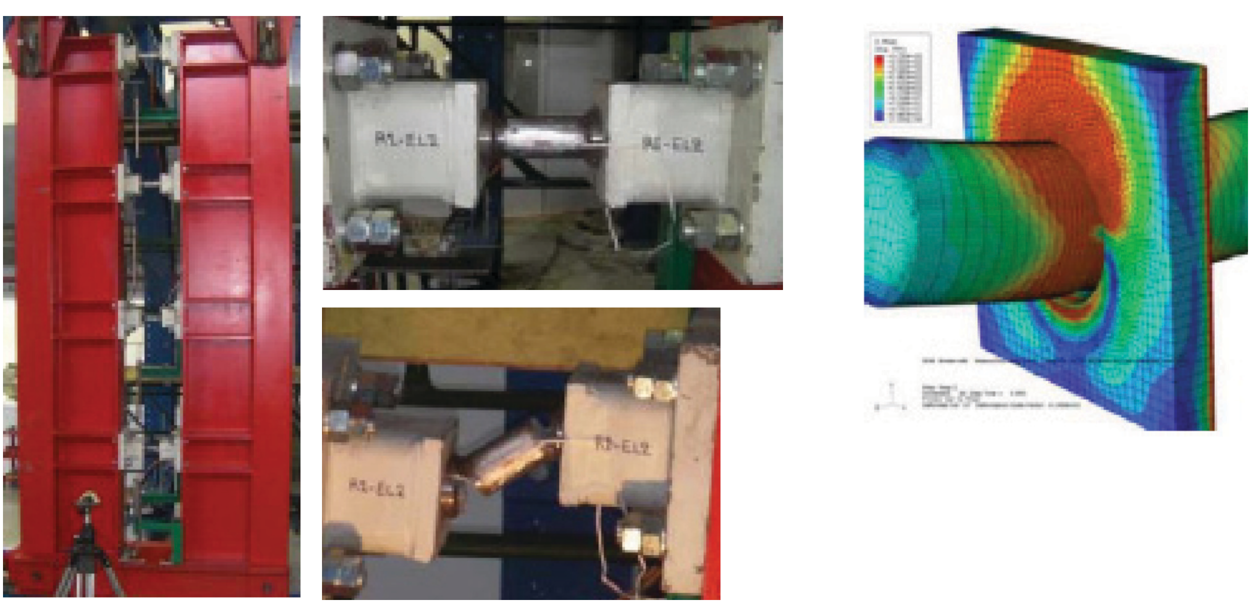


Fig. 4. Test setup details for a composite frame using the FUSEIS2 device (photos courtesy of Professor Ioannis Vayas).

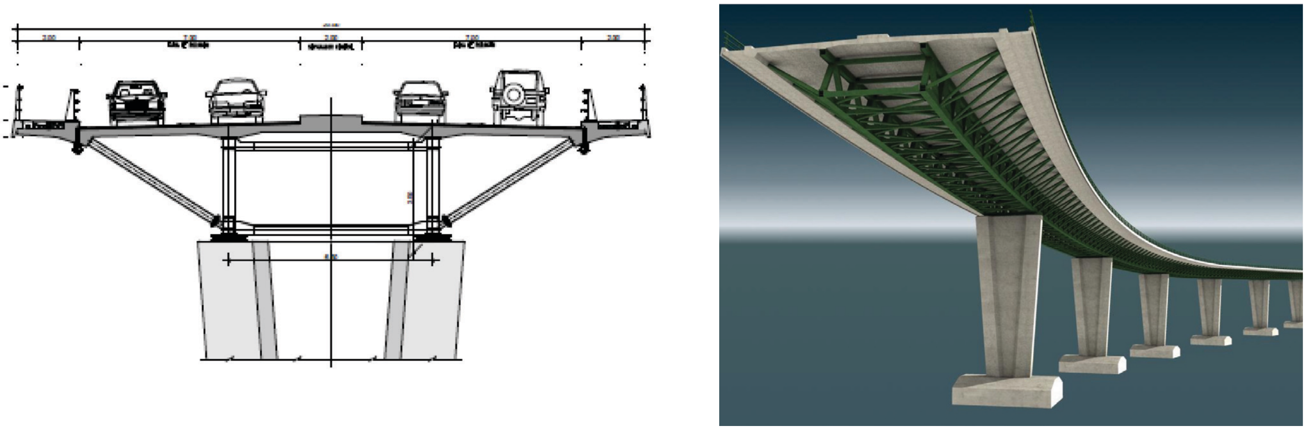
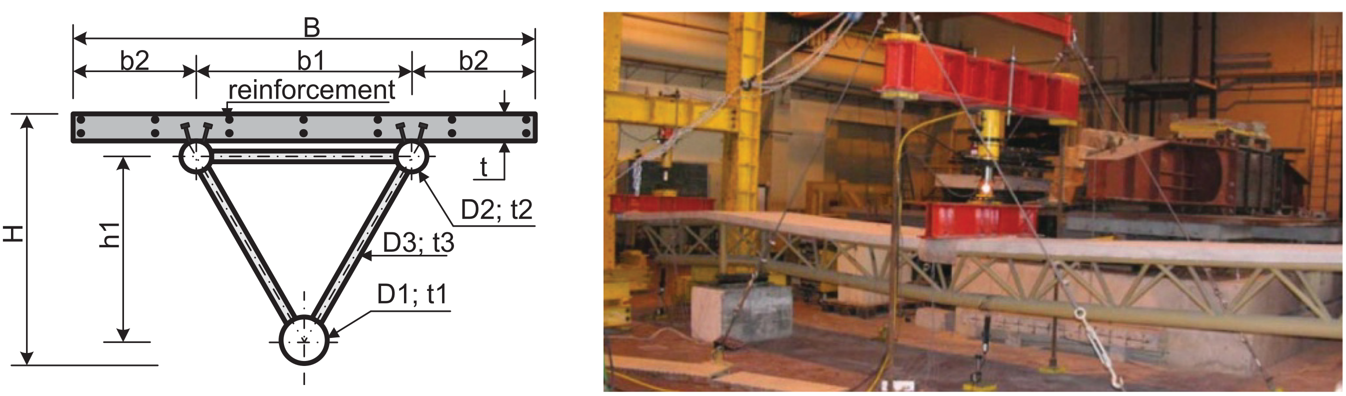


Fig. 5. Curved composite bridge deck cross-section and bridge (images courtesy of Professor António Reis).



(a) (b)

Fig. 6. Triangular bridge deck model tests at the Technical University of Lisbon: (a) bridge deck cross-section; (b) testing of ⅕-scale bridge model (drawing and photo courtesy of Professor António Reis).

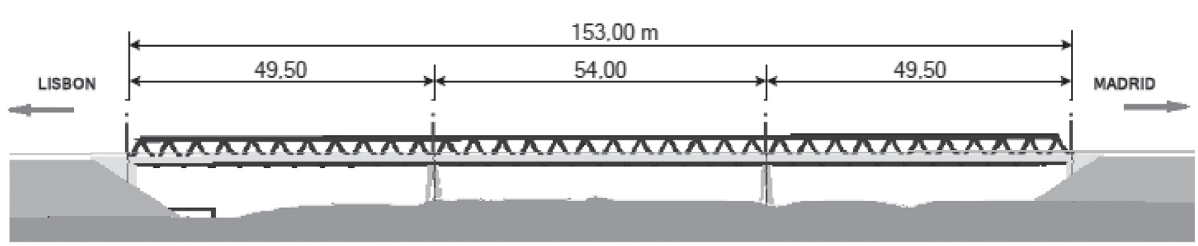


Fig. 7. Semi-through truss bridge for the railroad line between Lisbon and Madrid (drawing courtesy of Professor António Reis).

solutions for long-span bridges. For spans up to 2,000 to 2,500 feet, steel-concrete composite girder decks are the most economical and competitive solutions, as confirmed by a variety of bridges built in the past 20 years. Contemporary designs typically use very thin and light decks; such solutions are adopted to reduce the areas exposed to wind and to provide significant savings for the construction of the deck, the cables, the piers and the foundations. Very flexible decks can only be used by continuous-stay cable systems with multiple stays. As a result, deck slenderness of long-span, cable-stayed bridges has been increasing steadily, with slenderness ratios now ranging from about 100 to approximately 300 (Pedro and Reis, 2008).

Bridge safety may be evaluated by identifying the critical cross-sections of the deck and determining the ultimate load and the collapse mechanism. Failure occurs when the ultimate strain is attained at one or more deck elements. A nonlinear analysis modeling the construction stages is required to ensure the correct distribution of dead loads. Service live loads with different patterns are then applied, and increasing load scenarios are evaluated until failure is reached (Pedro and Reis, 2010). Further, the structural response of the bridge during its lifespan is assessed by taking into account the concrete time-dependent effects (shrinkage and creep). Finally, the global and local stability of the composite deck under the high compressive forces that are induced by the staying scheme may also be relevant (Pedro and Reis, 2011).

The aim of this project is to investigate specific issues related to the service and ultimate response of composite cable-stayed bridge decks, with particular emphasis on the global stability of the deck under high applied load levels. It is anticipated that major developments and proposals will be provided toward state-of-the-art criteria for bridge analysis and design in accordance with Eurocodes 3 and 4 (ECS, 2004, 2005).

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF HONG KONG

Bolted and Screwed Connections under Ambient and Elevated Temperatures: The project has been funded by STALA Tube Company, Finland; BlueScope Lysaght (Singapore) Pte., Ltd.; and the University of Hong Kong. Professor Ben Young is the director of this project; the staff researchers have been Shu Yan and S. M. Zahurul Islam.

A very large number of single-shear-bolted, double-shear-bolted and single-shear-screwed connections of thin sheet steels at ambient and elevated temperatures have been tested. The experiments were performed by steady-state and transient-state testing methods, as illustrated by the test setup in Figure 8.

For the analysis of the connections, finite element models were developed and verified by the test results, and

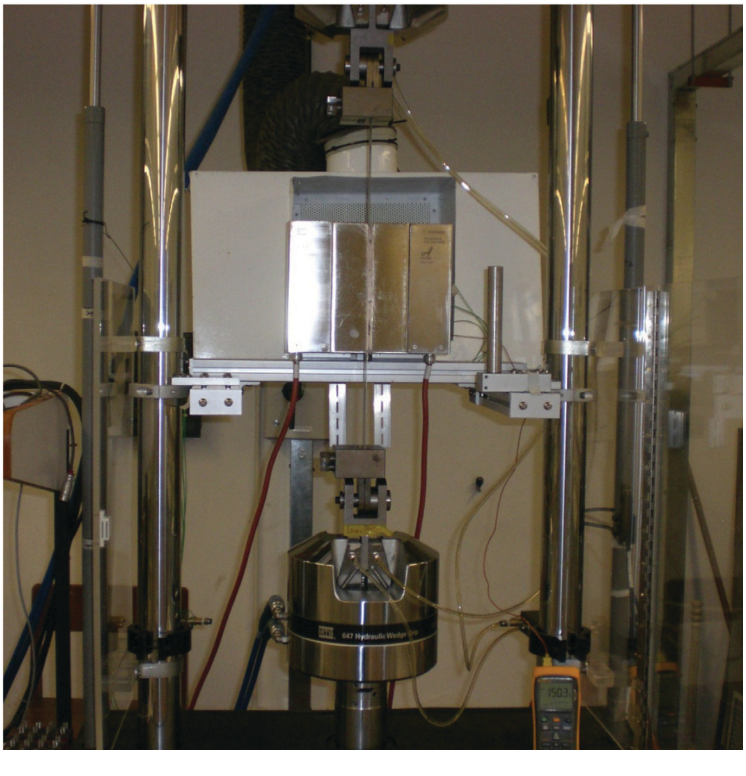


Fig. 8. Test setup for bolted and screwed connections (photo courtesy of Professor Ben Young).

parametric evaluations were performed using the verified finite element models. Bearing factors were determined for the limit states of the connections, including the limit states of tilting and bearing for the screwed connections (Yan and Young, 2011a, 2011b). Considering the effects of elevated temperatures, design equations have been proposed on the basis of the data. The predicted bearing strengths of bolted and screwed connections at elevated temperatures using the proposed equations have been found to be more accurate than those based on the current design rules (Yan and Young, 2012).

Additional testing has been performed for cold-formed stainless steel tubular shapes subjected to web crippling. The findings will be reported in forthcoming publications.

ACKNOWLEDGMENTS

Significant assistance has been provided by ISSRA member Professor Dinar Camotim of the Technical University of Lisbon, and his colleagues Professors Luis Calado, António Reis and José Pedro. Professor Ben Young of the University of Hong Kong provided input from the University of Hong Kong. Their efforts are sincerely appreciated.

REFERENCES

Camotim, D., Basaglia, C. and Silvestre, N. (2010a), "GBT Buckling Analysis of Thin-Walled Steel Frames: A State-of-the-Art Report," *Thin-Walled Structures*, Vol. 48, No. 10–11, pp. 726–743.

Camotim, D., Basaglia, C., Bebiano, R., Gonçalves, R. and Silvestre, N. (2010b), "Latest Developments in the GBT Analysis of Thin-Walled Steel Structures," *Proc. International Colloquium on Stability and Ductility of Steel Structures*, Rio de Janeiro, Brazil, E. Batista, P. Vellasco, L. Lima (eds.), Vol. 1, pp. 33–58.

Castiglioni, C.A., Kanyilmaz, A., Drei, A., Calado, L., Vayas, I., Rauert, T. and Gonçalves, R.M. (2011), "Dissipative Devices for Seismic Resistant Steel Frames," *Proc. 6th European Conference on Steel and Composite Structures*, EUROSTEEL 2011, Budapest, Hungary, Vol. B, pp. 993–998.

Castiglioni, C.A., Kanyilmaz, A., Drei, A., Calado, L., Espinha, M., Gonçalves, R.M., Rauert, T. and Vayas, I. (2012), "Seismic Resistant Composite Steel Frames with Dissipative Devices," *Proc. International Conference on Behaviour of Steel Structures in Seismic Areas,* STESSA 2012, Santiago, Chile, pp. 785–789.

Dinis, P.B. and Camotim, D. (2011), "Post-Buckling Behaviour and Strength of Cold-Formed Steel Lipped Channel Columns Experiencing Distortional/Global Interaction," *Computers & Structures*, Vol. 89, No. 3–4, pp. 422–434.

ECS (2004), *Eurocode 4: Design of Composite Steel and Concrete Structures—Part 1-1: General Rules and Rules for Buildings,* Standard No. EN 1994-1-1, European Committee for Standardization, Brussels, Belgium.

ECS (2005), *Eurocode 3: Design of Steel Structures—Part 1-1: General Rules and Rules for Buildings,* Standard No. EN 1993-1-1, European Committee for Standardization, Brussels, Belgium.

Pedro, J.O. and Reis, A.J. (2008), "Structural Analysis of Composite Cable-Stayed Bridges from Construction to Failure," *Proc. 5th European Conference on Steel and Composite Structures*, EUROSTEEL 2008, Graz, Austria, Vol. A, pp. 171–176.

Pedro, J.O. and Reis, A.J. (2010), "Nonlinear Analysis of Composite Steel-Concrete Cable-Stayed Bridges," *Engineering Structures*, Vol. 32, No. 9, pp. 2702–2716.

Pedro, J.O. and Reis, A.J. (2011), "Stability of Composite Cable-Stayed Bridges," *Proc. 6th European Conference on Steel and Composite Structures*, EUROSTEEL 2011, Budapest, Hungary, Vol B, pp. 1263–1268.

Reis. A.J. (2008), "Steel Concrete Composite Bridges: Options and Design Issues," *Proc. 7th International Conference on Steel Bridges*, Guimarães, Portugal, P. Cruz, L.S. Silva and F. Schröter (Eds.).

Reis, A.J. and Pedro, J.O. (2011), "Composite Truss Bridges: New Trends, Design and Research," *Steel Construction—Design and Research*, Vol. 4, No. 3, pp. 176–182.

Silvestre, N., Camotim, D. and Dinis, P.B. (2009), "Direct Strength Prediction of Lipped Channel Columns Experiencing Local-Plate/Distortional Interaction," *Advanced Steel Construction*, Vol. 5, No. 1, pp. 49–67.

Silvestre, N., Camotim, D. and Dinis, P.B. (2012), "Post-Buckling Behaviour and Direct Strength Design of Lipped Channel Columns Experiencing Local/Distortional Interaction," *Journal of Constructional Steel Research*, Vol. 73, pp. 12–30.

Yan, S. and Young, B. (2011a), "Tests of Single Shear Bolted Connections of Thin Sheet Steels at Elevated Temperatures—Part I: Steady State Tests," *Thin-walled Structures*, Vol. 49, No. 10, pp. 1320–1333.

Yan, S. and Young, B. (2011b), "Tests of Single Shear Bolted Connections of Thin Sheet Steels at Elevated Temperatures—Part II: Transient State Tests," *Thin-walled Structures*, Vol. 49, No. 10, pp. 1334–1340.

Yan, S. and Young, B. (2012), "Bearing Factors for Single Shear Bolted Connections of Thin Sheet Steels at Elevated Temperatures," *Thin-walled Structures*, Vol. 52, No. 3, pp. 126–142.