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INTRODUCTION

This issue of "Current Steel Structures Research" for the *Engineering Journal* focuses on a selection of research projects at three of the leading universities in Australia and Southeast Asia. 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: University of Sydney in Sydney, Australia; National University of Singapore in Singapore; and Nanyang Technological University in Singapore. Components of various projects at some of these institutions have been discussed in previous research papers, but the studies that are presented in the following reflect additional elements of these projects as well as other, major, long-time efforts. 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 always the case in the United States as well, the outcomes of the studies focus on design standards and industry needs.

The Australian and Singaporean 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 THE UNIVERSITY OF SYDNEY IN SYDNEY, AUSTRALIA

For many years, the University of Sydney has been one of the leaders in international academia. The faculty has pursued an aggressive development of technical programs and research facilities. In spite of the somewhat remote geographical location, the researchers in Sydney have been very active contributors to design standards work in the United States and Europe. For example, individuals such as Nicholas Trahair, Gregory Hancock and Kim Rasmussen have worked actively with the technical staff of AISC and with the AISI cold-formed steel structures specification committee. There have been numerous significant contributors evaluating the performance of steel materials, steel and composite frames, frame stability, members and connections for steel structures, cold-formed steel structures, and rack structures. As one reflection thereof, Professor Trahair was the 2011 recipient of the prestigious Lynn S. Beedle Award of the Structural Stability Research Council (SSRC).

The Australian steel design specification continues to be among the most advanced in the world. The continuing, very active input to the North American (AISI) cold-formed steel structures specification by Professor Hancock and others has provided advanced solutions for frame stability, members in high-strength, low ductility steel and design criteria addressing distortional buckling.

Second Order Effects in Steel Frames with Locally Buckled Members: Professor Kim Rasmussen is the director of this project. Focusing on the increasing use of thin-walled members with slender cross sections for certain types of structures, it is recognized that frames may fail as a result of local or distortional buckling in certain members. The failure may occur before the frame ultimate limit state has been reached. As illustrated in Figure 1, local buckling reduces the bending as well as the warping torsional stiffnesses of the members, which in turn produces additional second order effects. The latter effect is illustrated by the frame in Figure 2.

The fundamental approach has focused on determining the reduction of the axial, bending and warping torsional stiffnesses as a function of the axial load as it exceeds the local and distortional buckling loads. This has now been achieved through the development of a suitable beam element for the OpenSees software package that incorporates warping effects (X. Zhang et al., 2011).

The project will now advance to full-scale tests of portal frames and rack structures, using members with 1-mm (0.04-in.) thick elements. Detailed evaluations of the physical tests as compared to the theoretical predictions will be provided, including the development of simplified methods of accounting for the stiffness reductions. It is anticipated that a novel approach to comprehensive frame stability analysis will be developed.

Direct Strength Method of Design of Simple and Complex Thin-Walled Shapes for Combined Actions: Professor Emeritus Gregory Hancock is the director of this project.

Following the development of the so-called Direct Strength Method (DSM) at Cornell University in the 1990s (Schafer, 1997, 2002, 2006), a great deal of research worldwide has been dedicated to provide extensions of the method and practical design solutions for a large range of engineering problems. Along with the continuing American work, the studies in Australia have been particularly broad and relevant. The project that is described in the following is a major study of certain structural engineering subjects.

A large number of cold-formed member and deck cross-sections are addressed in the study, including simple and complex C-, Z- and hat shapes and simple and complex deck sections. Some of the elements have lips and corrugations of various types. Recent studies have demonstrated that nonlinear finite element solutions will provide accurate results for the behavior of cold-formed C-shapes under shear and combined bending and shear (Pham and Hancock, 2010). As an illustration, Figure 3a shows the failure mode in shear of a C-shape, as observed in a physical test; Figure 3b provides the ABAQUS analysis result of the same shape. The correlation is very good.

Results and evaluations such as those just presented are not available for the large variety of member cross-sections that are used in structures today. Practical considerations such as bearing at support points and combined bending, shear and bearing need to be evaluated. The aim is to provide suitable DSM design procedures for all types of cross-sections.

Drive-in Racks Subject to Impact Loads: Professor Kim Rasmussen is the director of this project. It is one of several ongoing studies at the University of Sydney that focus on the strength and behavior of rack structures. Racks represent a very important industry for several areas of business, with unique members, connections and loading systems and features. The dead-to-live load ratio of racks tends to be

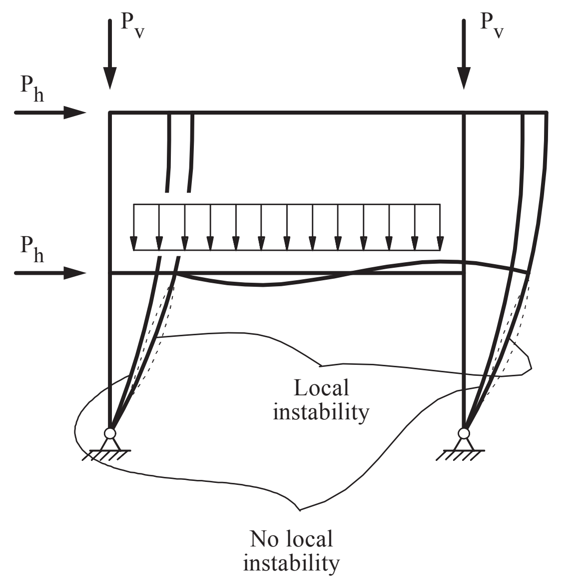


Fig. 2. Frame displacements with and without local buckling. (Figure courtesy of Professor Kim Rasmussen)

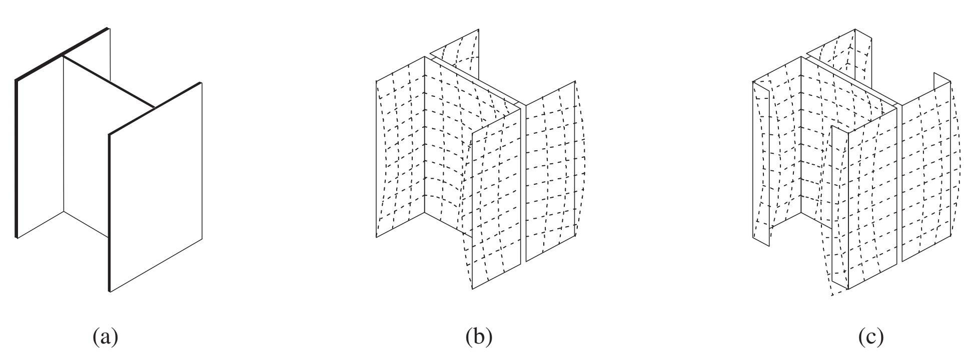


Fig. 1. Cross-sectional responses of compact and slender shapes: (a) compact cross-section without local buckling; (b) slender section failing by local buckling; (c) slender section failing by distortional buckling. (Figure courtesy of Professor Kim Rasmussen)

relatively low; the live loads tend to vary significantly and rapidly, due to the manner in which the loads are applied to the structures. Specifically, forklifts are used to place pallets on the rack, which for that reason may be subjected to forklift collisions and, subsequently, local bay collapses in the rack. Figure 4 illustrates a collapse caused by a forklift collision with a column or "upright," as the member is sometimes called. Such failures may even be transmitted to adjacent bays, with the potential for overall rack collapse, in part because of the types of connections that are used to carry the pallets and transmit the loads to the uprights.

A key issue of the rack response characteristic is the magnitude of the impact load caused by the forklift collision. Full-scale static and dynamic tests have been conducted with racks, as shown in Figure 5. Such tests are critical to determine the stiffness and three-dimensional behavior of the rack and also to assess the stiffness, damping characteristics and dynamic response to the impact of the horizontal (collision) loads that are applied to the upright. Component tests have also been performed, in particular to determine the behavior and strength of the connections and the uprights (Gilbert and Rasmussen, 2011). These connections are essentially temporary, effective only when pallets have been placed.

Parametric studies have recently been completed for a wide range of frames, including evaluations of the structural reliability. A forthcoming report will provide the design equations for the impact loads and the load factors that should be used for the racks (H. Zhang et al., 2011).

Long-Term Behavior of Composite Steel-Concrete Members and Its Effect on Their Ultimate Response: This is a 4-year project that is sponsored by the Australian Research Council (ARC) under the Discovery Project program. The project director is Professor Gianluca Ranzi.

The project was initiated because there is very little factual information available on numerical models that can be used to assess and benchmark long-term behavior and response of composite members. A number of static tests have been conducted at the University of Sydney over the past 4 years, as illustrated by long-term sustained load tests shown in Figure 6 (Al-Deen et al., 2011a, b).

Additional tests have been run to determine ultimate capacities, using solid slabs as well as slabs with steel deck. Pushout tests were also conducted.

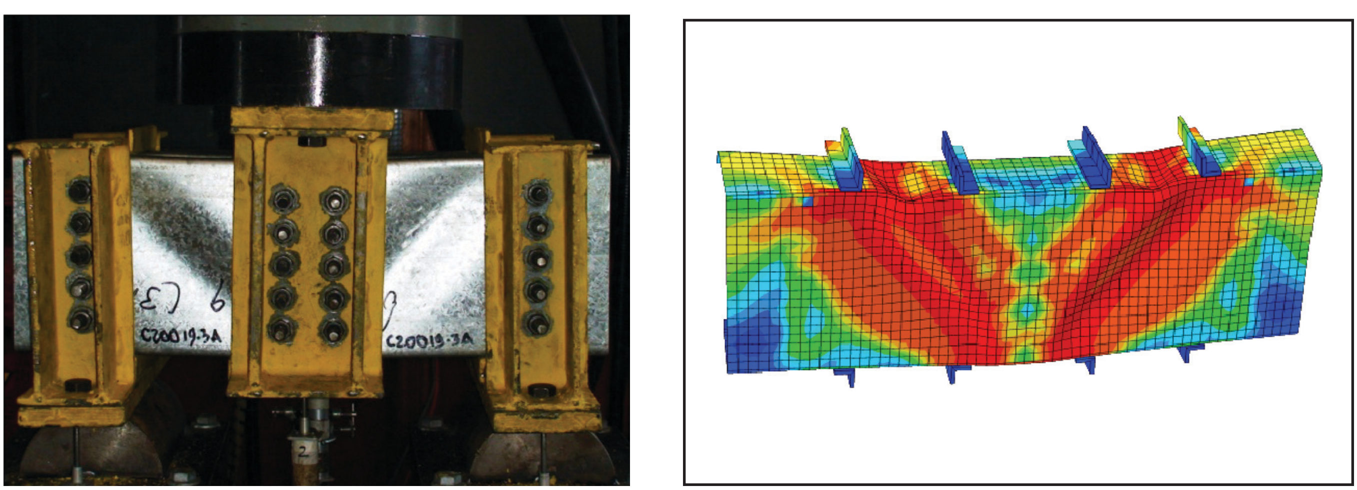
The following major observations have been made at this time:

1. For the geometries and material properties used for the specimens, the long-term effects did not influence the ultimate strengths.

2. The ultimate strengths were not influenced for solid slab beams as well as for beams with steel deck.

3. The ultimate strengths of composite beams with partial shear connections were not affected.

4. Some of the specimens were constructed as shored beams to ensure that the slab in the unloaded condition would only be experiencing shrinkage. This made it possible to determine shrinkage and creep deformations separately. It was found that shrinkage might affect the beam stiffness; additional work is now being done to model and quantify this phenomenon.



(a) (b)

Fig. 3. Failure mode shapes for physical test and analytical evaluation: (a) physical test of C-shape; (b) ABAQUS model of physical test. (Figures courtesy of Professor Gregory Hancock)

5. The shrinkage in a composite beam with steel deck differs significantly from that of a solid slab case. Additional research to address this subject is now being conducted under a separate ARC grant.

6. A study is now addressing the long-term response of composite columns as a joint effort between the University of Sydney and Harbin Institute of Technology in China (Wang et al., 2011).

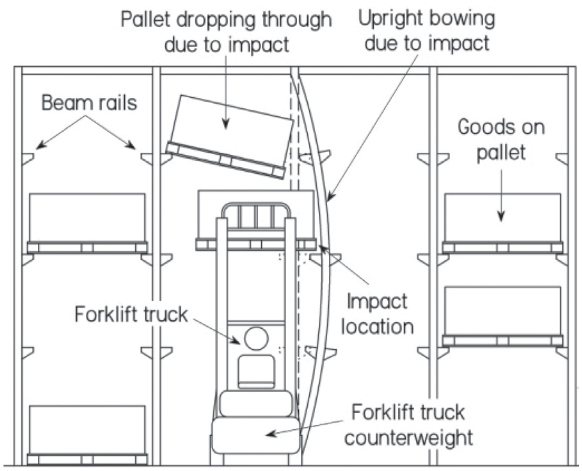


Fig. 4. Rack collapse as prompted by forklift collision with an upright. (Figure courtesy of Professor Kim Rasmussen)

SOME CURRENT RESEARCH WORK AT THE NATIONAL UNIVERSITY OF SINGAPORE

The National University of Singapore (NUS) is one of the leading universities in Asia, with a very broad program in all areas. In fact, some of the major international university surveys usually place NUS within the top 10 in the world. The School of Engineering is excellent, with top-rated computation and experimental facilities, and the support of the government as well as the collaboration with industry emphasizes the high priority Singapore as a country assigns to education and academia.

Ultra-High Strength Concrete-Filled Columns for High-Rise Construction: With the support of the A*STAR Science and Engineering Research Council, this project has been under way since 2009. Professor Richard Liew is the project director.

Some of these research activities were presented in the second quarter 2009 "Current Steel Structures Research" (Bjorhovde, 2009). Square and round, single and double tubular columns as illustrated in Figure 7 were originally tested for ambient temperature conditions. This work has now been extended to tests for elevated (fire) temperatures, as

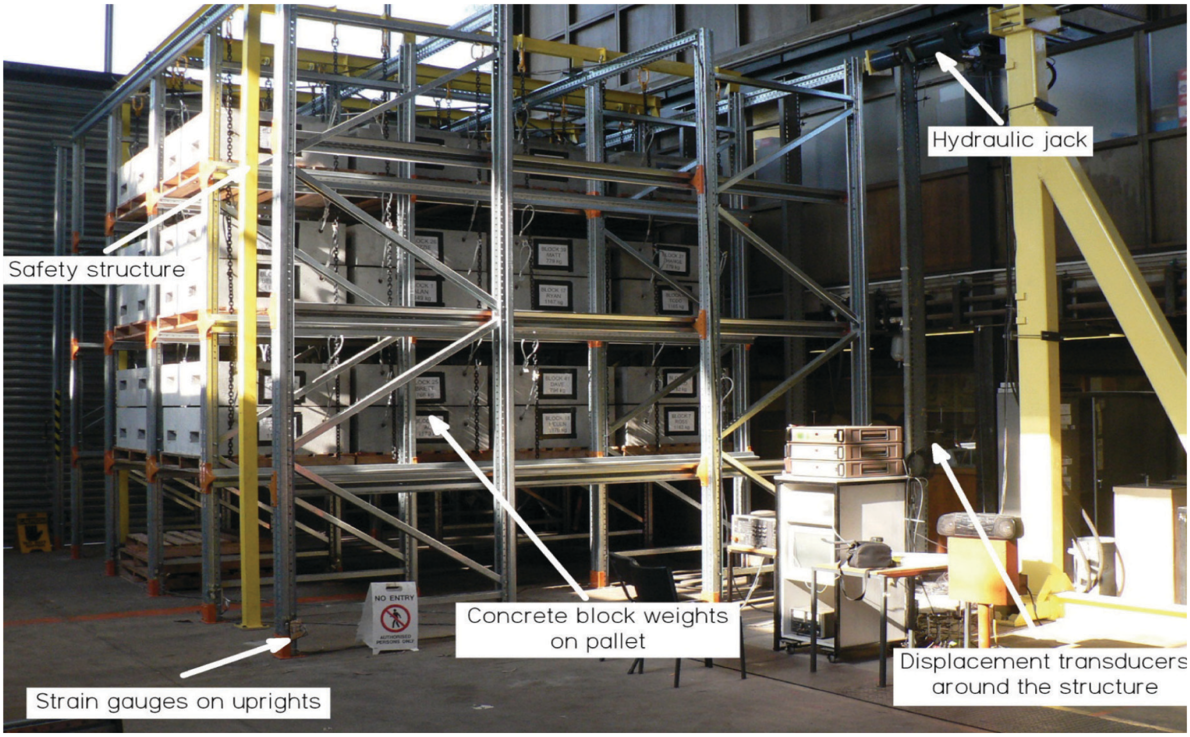


Fig. 5. Full-scale rack test. (Figure courtesy of Professor Kim Rasmussen)

shown in Figure 8. The steel strength for the members is as high as 700 MPa (100 ksi); the ultra-high-strength concrete (UHSC) strength is up to 200 MPa (29 ksi).

The advantage of using the very high strength materials is, of course, that the significant axial load capacity lends itself to smaller footprint cross-sections. For a location like Singapore, this is a very important consideration. On the other hand, the brittle characteristics of the UHSC material may prompt premature failures. If the concrete is also used for encasing the steel, the spalling at high temperatures will lower the compressive capacity and, in fact, also impose limitations on any kind of fire-fighting efforts. These are major drawbacks that must be addressed before the system can be adopted for construction (Liew and Xiong, 2011).

The following project components are currently under way:

1. Determine the mechanical properties of the high-strength concrete and steel, at normal and elevated temperatures.

2. Establish the strength performance of short and slender columns subjected to axial loads and bending moments. Develop suitable design formulas.

Fig. 6. Long-term tests with simple beam, simple beam with a negative moment and continuous beam.
(Figures courtesy of Professor Gianluca Ranzi)

3. Determine the performance of the high-strength materials and the composite columns under fire conditions, with and without fire protection, by tests and numerical analyses. This will include load level and eccentricity, boundary conditions and fire protection thickness.

4. Evaluate the creep and shrinkage behavior of the columns and develop design guides for high-rise construction.

Fatigue Behavior of Tubular Connections Fabricated with Enhanced Partial Joint Penetration Welds: This project is sponsored by McDermott International Inc., Nippon Steel Engineering Inc. and the American Bureau of Shipping Asia Pacific. The project director is Dr. Peter Marshall.

The project aims at developing a convenient weld detail for the next generation of tubular structures, such as offshore platforms, offshore bridges, crane structures, and so on. The detail must ensure simple but high-quality control and, at the same time, provide satisfactory fatigue safety. Among the current weld details, welding from the outside of the joint has significant practical advantages but makes quality control very difficult when attempting to ensure satisfactory weld performance. Welding from the inside of the joint is not possible in many cases. Whereas the complete joint penetration weld has been used successfully for many large structures, it has significant practical problems. On the other hand, single-sided welds with backing bars have fewer defects, but the root discontinuities can be very severe.

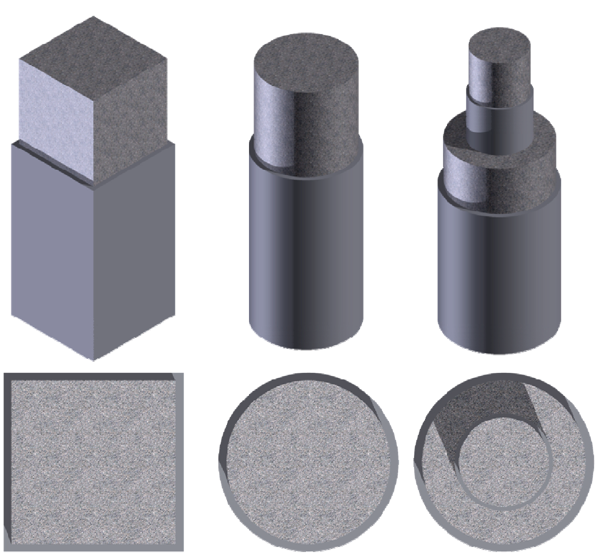


Fig. 7. Ultra-high-strength steel and concrete composite columns. (Figure courtesy of Professor Richard Liew)

The project also aims at developing a new type of single-sided partial penetration weld that uses a part of the brace wall thickness as the backing for the weld. Large-scale joints will be fabricated using an automated, numerically controlled procedure for the preparation of the weld joint surfaces. To date, the experimental work has demonstrated the effect of the weld treatment on the enhancement of the fatigue crack, the potential for weld cracking and the approach to estimate the fatigue crack propagation life. It has also been possible to estimate the effect of overloading to retard the fatigue crack propagation.

Lightweight Composite Sandwich Panels Subjected to Extreme Loads: This project has been supported by the A*STAR Science and Engineering Research Council and by the Marine Port Authority of Singapore. The project director is Professor Richard Liew.

The initial results of this work were reported in the "Current Research" paper of the second quarter 2009 (Bjorhovde, 2009). In particular, the development of a new type of shear connector, the J-hook connector, was a critical feature of the sandwich panels.

The studies have now been expanded to include tests for fatigue, impact and blast loads. Design equations for fatigue have been developed, using the test results to predict the fatigue life for different load ranges (Dai and Liew, 2010). Impact tests have also been performed, demonstrating that the sandwich panels are capable of resisting higher impact loads with smaller deformations than equivalent stiffened steel plates. The sandwich panels also demonstrate better blast performance with less damage. Figure 9a shows the impact test setup; Figure 9b illustrates the post-blast test deformations of a stiffened plate panel and a sandwich panel.

The sandwich panel evaluations are now being extended to fire conditions and arctic environment conditions, to address the full range of marine structure considerations. Design recommendations will be developed.

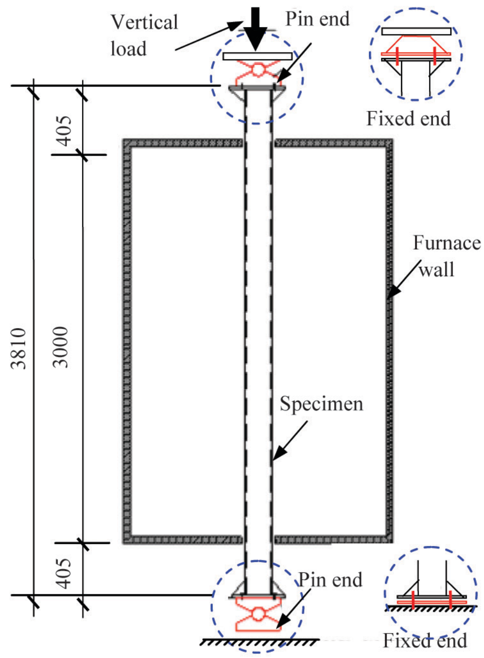
SOME CURRENT RESEARCH WORK AT NANYANG TECHNOLOGICAL UNIVERSITY, SINGAPORE

Residual Stress in High-Strength Steel Joints: This is a major project that has been funded by Regency Steel Asia Pte Ltd., Singapore. The project directors are Professors S.-P. Chiew and C.-K. Lee.

Residual stresses in mild- and medium-strength steel shapes and plates have been studied extensively (Ziemian, 2010). This is not the case for high-strength steel, although the data for shapes and plates in lower strength steels may certainly be used, since the value of *E*, the modulus of elasticity, is the same for all strength levels. However, for fatigue considerations, the residual stress magnitudes and distributions in high-strength steel-welded joints are needed, in particular because of the increasing use of such materials. The project was therefore arranged as a two-stage study, as follows:

1. Determine the welding residual stress distributions in a series of plate-to-plate joints. This will include finding the effects of various geometric and welding parameters on the residual stress values near the weld toe. The measurements were made using the well-known hole drilling method (ASTM, 2008).

2. Assess the residual stress effect on the fatigue performance of welded tee joints, including the influence of preheating, plate thickness and joint angle.

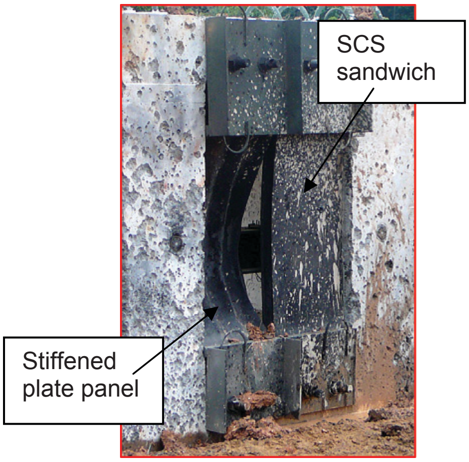


(a)

(b)

Fig. 8. Fire testing of ultra-high-strength composite columns: (a) test assembly; (b) failure of composite column. (Figure courtesy of Professor Richard Liew)

(a)



(b)

Fig. 9. (a) Impact test setup and post-test deformation for sandwich panel; (b) post-blast-test deformations of stiffened plate panel and sandwich panel. (Photos courtesy of Professor Richard Liew)

Stage 1 has been completed; stage 2 is currently under way. Parametric studies are being performed to determine the effect of welding parameters, welding speed and the number of passes (Jiang et al., 2011). Analytical models are being developed, along with measurements of *E* values and yield stress magnitudes as these properties are influenced by temperatures from 100° C to 800° C (212° F to 1,472° F). Subsequently, the stress concentrations associated with various loading cases will be monitored. Fatigue tests will be performed to determine the through-thickness formation of cracks and their propagation.

Experimental and Numerical Studies on Steel Beam-to-Column Connections Subjected to Sudden Column Removal Scenario: The project directors for this study are Professors T.-C. Fung and K.-H. Tan.

This is one of several disproportionate collapse studies currently being conducted around the world. The subject obviously is very important; the real impact of the various findings will be found in the building codes and design standards that are subsequently modified to reflect the phenomena. The study is somewhat unusual in the way the researchers have decided to focus on the dynamic response of the beam-to-column connection, following the sudden removal of a column in the structure.

The physical testing and the accompanying numerical analyses specifically address the response of the connections to interior columns with beams framing from both sides. As shown by the schematic test assembly in Figure 10, the beams are subjected to a uniformly distributed load, and the connection is supported by a quick-release mechanism. This is intended to reflect the sudden removal of a column. Using a series of typical beam-to-column connections, such as single web-plate connections and flush end-plate (small plate thickness) connections, the initial results show that the maximum displacement of the web-plate connection is significantly larger than what is found in a static test.

Static and dynamic finite element simulations are currently under way. It is anticipated that the simulations will also provide data for the energy absorption and the stress distribution in the connection components. These characteristics are very difficult to measure during the tests.

Figure 11 shows the physical setup for the tests. The quick release mechanism is shown next to the “loop” detail in the upper right of the photo.

Fatigue Study of Partially Overlapped Circular Hollow Section K-Joints: This study has been sponsored by the Singapore Ministry of Education. The joint project directors are Professors C.-K. Lee, S.-P. Chiew and S.-T. Lie.

As observed by the researchers, the project was motivated by the fact that a well-designed partially overlapped circular hollow section (CHS) K-joint could outperform its gapped counterpart, both for ultimate strength and cost effectiveness. However, relatively little research has been dedicated to the fatigue performance of these joints. It was decided to focus the project work on the responses of two carefully designed, full-scale partially overlapped joints. Static tests have been conducted to determine the stress concentration factors. Fatigue tests under cyclic loading were then performed until a through-thickness crack had formed; the crack propagation rate was monitored.

Finite element geometric models were analyzed in a large-scale parametric study, comparing gapped and partially overlapped CHS K-joints under different loading conditions (Lee et al., 2011a). The results show that the overlapped joints will outperform the gapped joints under pure or primarily axial loads; the reverse is true when pure or primarily bending is applied. A new method has been developed for the prediction of the stress concentration factor for tubular joints; it has been found to be more reliable and accurate than the traditional parametric regression method (Lee et al., 2011b).

ACKNOWLEDGMENTS

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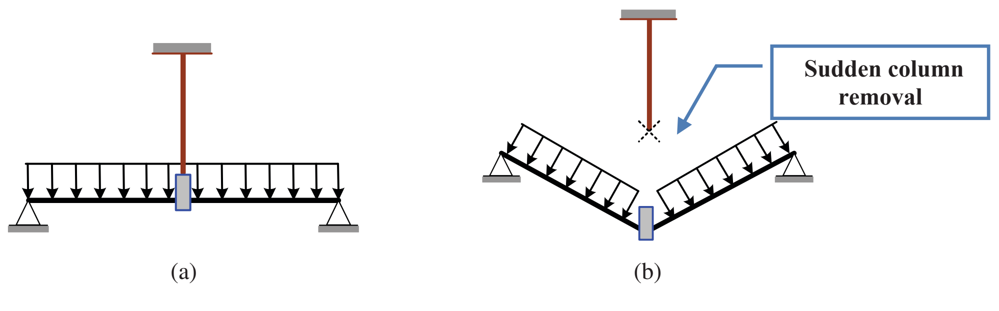

Fig. 10. Schematic of sudden column removal. (Figure courtesy of Professors T.-C. Fung and K.-H. Tan)

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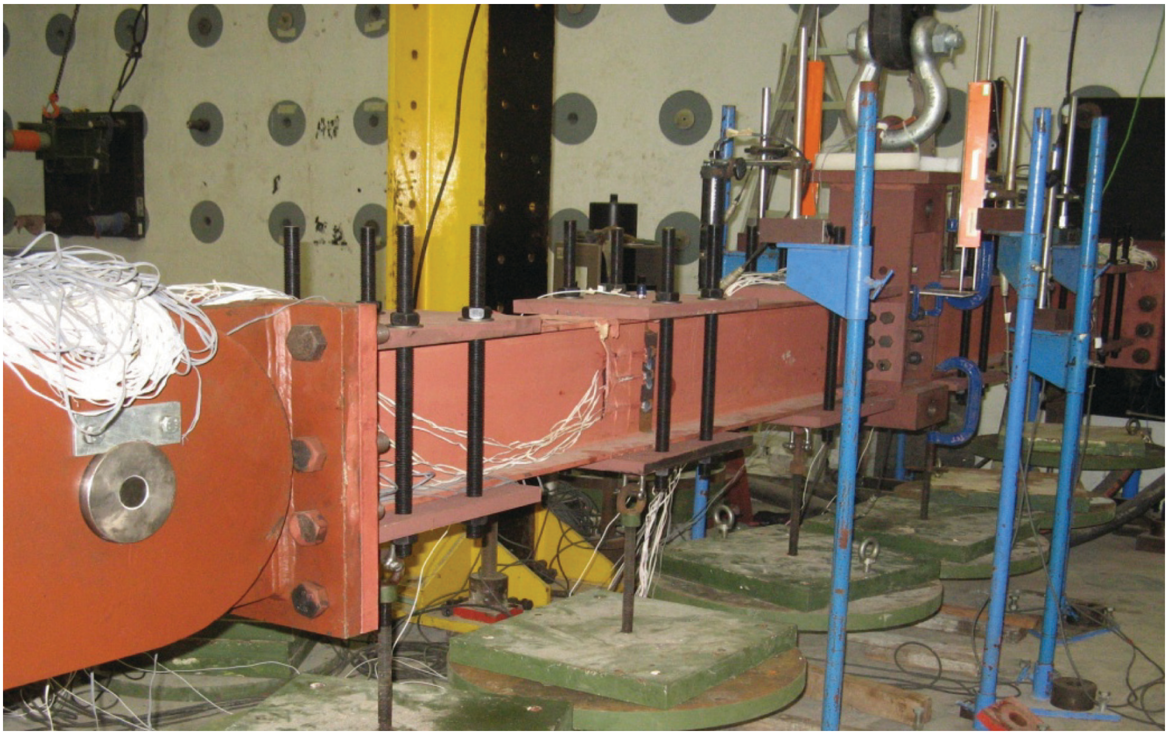

Fig. 11. Details of test setup for collapse after column removal. (Photograph courtesy of Professors T.-C. Fung and K.-H. Tan)

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