

Current Steel Structures Research

No. 26

REIDAR BJORHOVDE

This quarter's paper focuses on a selection of current research projects at some of the leading Chinese universities. The descriptions will not discuss all of the current projects at the schools. Instead, selected studies provide a representative picture of the research efforts and demonstrate the importance of the schools to the country and indeed to the efforts of industry and the profession worldwide.

The universities and many of their structural steel researchers are very well known in the world of steel construction: Tsinghua University in Beijing, Tongji University in Shanghai and the Polytechnic University of Hong Kong. Some other projects at these institutions have been discussed in previous "Current Steel Structures Research" papers, but the studies that are presented here reflect major, long-time efforts in a number of areas of industry and transportation systems of the country. Much of the work is tied to the aggressive programs of the government of China to improve and expand the infrastructure, including electrical power stations and related structures, and, of course, highways and railroads and numerous bridges to span the rivers of China. Some of the design work for various structures has been performed by prominent international companies, including many American firms. A number of the technical solutions have certainly been based on the results of international research, including many American projects, but over the past several years, the magnitude of the Chinese research efforts within universities and governmental organizations has been very significant.

In true forward-looking fashion, the researchers at the institutions that are featured here have been active for many years, as evidenced by their leading roles in the design standards development efforts of China, including the independent codes of Hong Kong. Large numbers of English-language technical papers and conference presentations have been published, contributing to a collection of studies that continue to offer practical solutions to complex problems for designers as well as fabricators and erectors. Not the least important, these efforts complement and expand on ongoing work in other areas of the world. Thus, the collaboration

between Chinese researchers and their colleagues in Australia, Japan, Korea, Singapore and the United States (to mention just a few countries) is extensive. The broad sharing of knowledge that is taking place promises significant results, not the least of which will be related to issues of finance and the sheer cost of research.

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.

SOME CURRENT RESEARCH WORK AT TSINGHUA UNIVERSITY IN BEIJING, CHINA

For many years Tsinghua University has been one of the leaders in many areas of structural engineering research. The university is sometimes referred to as the "MIT of China." There have been numerous principal contributors, and the faculty of the Department of Civil Engineering of Tsinghua University, now with the leadership of Professor Lin-Hai Han as chair, has been very active in the development of solutions to many technical problems. In particular, since 2005 Professor Han and his colleagues have conducted extensive studies of the performance of concrete-filled steel tubular (CFST) members, including the response of columns and beam-columns and beam-to-column connections subjected to seismic effects as well as fire temperatures. Numerous papers have been published, some very recent (Han et al., 2011; Li and Han, 2011; Tao et al., 2011). Funded by the National Natural Science Foundation of China (NSFC), initially the program examined the behavior and strength under monotonic as well as cyclic loads, including the important issue of residual strength following fire exposure. Long-term effects such as concrete creep have been examined, along with the influence of member preloading.

Major efforts are currently under way at Tsinghua and Tongji universities addressing the strength and behavior of very high strength members. These studies will be addressed here.

Performance of CFST Beam-to-Column Connections:

The current focus of the research program examines the behavior of CFST columns connected to steel beams and steel-reinforced concrete (SRC) columns to SRC beams. Both of these options reflect typical construction practice in China. The developments examine the lifetime behavior

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

of such elements and connections, using a loading sequence that includes initial loading, heating, cooling and postfire loading on the assembly. Figure 1 provides a schematic of the full-scale testing arrangement.

Using finite element modeling and parametric evaluations, the model results were verified by the full-scale tests. The computational results were then used to analyze the mechanical characteristics of the connections, including stress distributions, stress resultants and moment-rotation data. These evaluations have been utilized to develop simplified formulations for the residual stiffness and strength ratios for the assemblies.

Subsequent to the first series of tests and evaluations, the response of the composite connections under seismic loading was also studied. This work focused on CFST columns with steel beams, using external diaphragms for stiffening

and load transfer mechanisms. CFST columns connected to reinforced concrete beams were included in these tests and analyses. Figure 2 shows the full-scale test setup for the latter. The accuracy of the finite element models was verified by the tests, including the cyclic behavior performance, following extensive parametric analyses. The studies now aim to determine the behavior and strength under the combined effects of fire and structural loading, including seismic loads, for structures that have survived a fire. The concepts and approaches will be extended to full composite frames.

Performance of High-Strength Steel Structures: This is a long-term (since 2006) research effort that has been funded by the National Natural Science Foundation of China (NSFC). The project directors have been Professors Yongjiu Shi and Gang Shi.

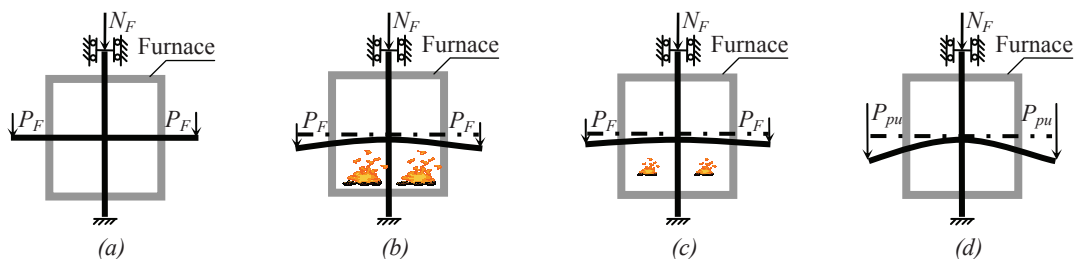


Fig. 1. Lifetime loading sequence for composite beam and column and beam-to-column connection tests: (a) initial loading; (b) heating; (c) cooling; (d) postfire loading. (Drawing courtesy of Professor L.-H. Han)

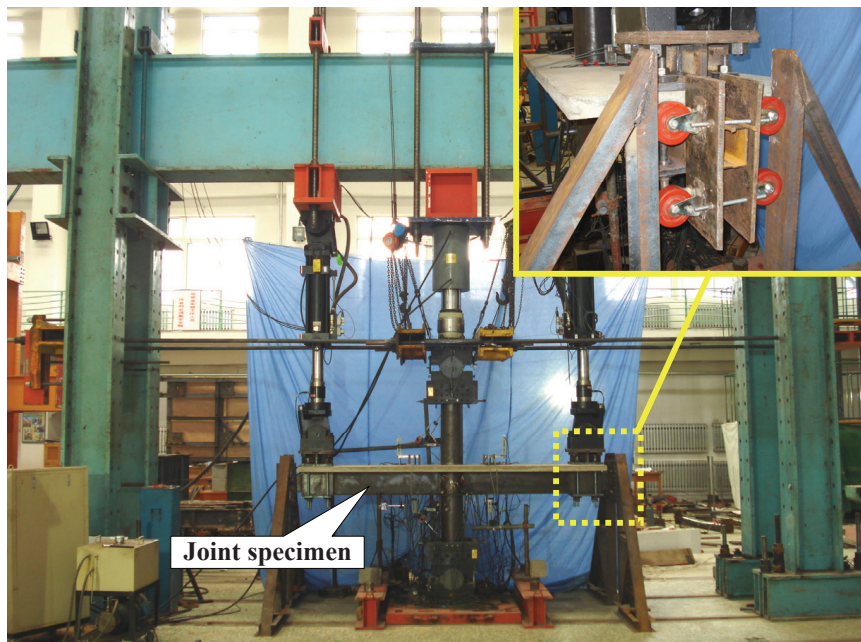


Fig. 2. Test assembly for CFST column and reinforced concrete beam in a beam-to-column connection test. (Photo courtesy of Professor L.-H. Han)

As in other areas of the world, the most common grades of steel for building and bridge structures in China have been 250 to 350 MPa (36 to 50 ksi) yield stress materials, with the occasional use of higher grades [up to 460 MPa (65 ksi)] for certain applications. For the past few years, there has been great interest in using steels with higher yield stress levels, but at the same time it has been recognized that the design code criteria have been based on tests and analyses with yield stress values at lower levels. This is, of course, the same situation as is found in other areas of the world. The current multiyear project is an aggressive effort to establish performance criteria for steels with yield stress larger than 460 MPa (65 ksi). The database has been extended to include tests of columns and connection elements in 690 and 960 MPa (100 and 140 ksi) yield stress steel (Girao and Bijlaard, 2008), with additional examinations of the performance capacities of very high strength connections (Bjorhovde, 2008). The work is now being extended to assess the strength and behavior data for members and connections under fire and seismic conditions.

It should also be noted that significant studies on the same subjects are being conducted at Tongji University in Shanghai. These will be detailed later in this paper.

Because there are no hot-rolled shapes available in the higher grades of steel, welded built-up shapes are used. The

current studies include residual stress measurements, using the well-known sectioning method, and full-scale tests of stub columns as well as long columns are conducted. Local and overall buckling limit states are established, with extensive parametric evaluations using finite element modeling. The tests have verified the analytical results. Figure 3 shows a stub column test in 65 ksi steel; Figure 4 shows a long column test.

Certainly, the types and details of the individual tests and the analytical results that have been established agree with compression member studies conducted elsewhere, but the performance of all of the high-strength members do provide new data.



*Fig. 3. Stub-column test of shape with slender web and flange elements in 65-ksi yield stress steel.
(Photo courtesy of Professor Gang Shi)*



*Fig. 4. Long column test of welded built-up shape in 65-ksi yield stress steel.
(Photo courtesy of Professor Gang Shi)*

The physical testing and finite element analyses have been extended to welded and bolted connections, including limit states, deformation capacities, ductility and robustness. The work is now being extended to seismic effects and will include the development of suitable constitutive models for the steel, accounting for the gradual deterioration of the members and the connection elements.

SOME CURRENT RESEARCH WORK AT TONGJI UNIVERSITY IN SHANGHAI, CHINA

Tongji University is another major Chinese research university, with extensive programs in all areas of construction. The researchers in the building and bridge research groups are very well known internationally, and the analytical and physical testing facilities are excellent. Numerous papers have been published in international journals and conferences; the following is but a small example (Li and Mativo, 2000; Li, 2004; Wang and Li, 2008).

Analysis and Design of High-Strength Steel-Fabricated Columns: This long-term project has been directed by Professor G.-Q. Li.

Using 65-ksi yield stress plates, welded built-up H-shapes and box shapes were fabricated for the physical testing, and the residual stress distributions were determined using the hole-drilling method as well as the sectioning method. The distributions were used as imperfections for the analytical examinations.

A total of 26 full-scale columns were fabricated, using 11-mm ($\frac{7}{16}$ -in.) and 21-mm (approximately $\frac{7}{8}$ -in.) plates. With centrally and eccentrically loaded specimens, using slenderness ratios of 35 to 70 for the square box sections and 40 to 80 for the H-shapes, the agreement with the finite element solutions was very good. Additional evaluations are now being conducted to develop improved column strength criteria for static loads.

In addition to the various tests and analyses for compression behavior, a total of eight columns were tested for constant axial load and cyclic bending. The test setup is shown in Figure 5. The hysteretic responses of columns with varying slenderness ratios were determined by tests; these data were used together with analytical results to arrive at the cyclic behavior of the high-strength columns. Seismic code criteria are currently being developed.

Fatigue Performance of Welded H-Beam with Corrugated Web: This project has been directed by Professor G.-Q. Li.

Beams with corrugated webs have become very attractive for bridge girders as well as for crane girders, for reasons of structural strength and stiffness as well as construction economy. The contribution of the web is a major consideration, and the resistance to local buckling that is afforded by the corrugated web is very significant. But the questions

related to the fatigue performance of dynamically loaded members are very important, considering the geometry of the web and some of the welding details that may offer limited dynamic resistance.

Four girders were fabricated as test specimens, using trapezoidal corrugations. Figure 6 shows the test setup. During the testing, the webs were subjected to concentrated cyclic loads with a constant stress amplitude, applied at midspan. The tests were designed to adhere to the criteria of the Chinese steel design code. The girders had the same overall and cross-sectional dimensions; the corrugation profiles varied, with different symmetries. Specifically, one of the specimens was designed with a 10-mm ($\frac{3}{8}$ -in.) deviation away from the centerline of the web, aiming to take into



*Fig. 5. Testing for seismic behavior of welded H-shape column.
(Photo courtesy of Professor G.-Q. Li)*

consideration how the performance would be affected by the installation of a crane girder. All of the tests are conclusive—to the effect that the fatigue life of a girder with a trapezoidal corrugated web is significantly longer than that of a girder with a traditional flat web.

The findings and the design recommendations have now been incorporated into the Chinese code for steel structures.

Construction Process Analysis of Large and Complex Spatial Steel Structures: This project has been directed by Professor Y.-F. Luo.

Professor Luo makes the observation that state-of-the-art steel structures are often large in dimensions and scale with complex and distinctive structural systems. Further, and very importantly, the researchers note that

- The construction process is complicated and time-dependent on the system and its elements.
- The magnitude and distribution of the loading on the structure is highly nonlinear and time-dependent.
- The construction process has a significant influence on the final loading behavior and indeed the strength and behavior of the structure.

However, in spite of these facts, current analysis techniques usually do not take into account the variations of the nonlinear response of the structure during the construction process. Two early studies did just that, but they were not expanded (Griffis, 1986; Vallenilla and Bjorhovde, 1990).

To resolve these issues, Professor Luo's study aims at developing analytical procedures that will recognize the effects of the time-dependent response to provide an approach for how to predict the loading behavior and how to control the construction process. The examination will proceed in the following steps:

1. Identify the main construction process parameters and the roles they play at various stages of construction.
2. Using the initial numerical model for the structure, update the real-time model for the during construction.
3. Examine the limit states of the structure during construction and the potential “prewarning” indicators for the structural behavior.

Behavior, Strength, and Construction of Cold-Formed Steel Structures: This project is a long-duration, comprehensive study of cold-formed steel structures and the standards that are needed for the Chinese industry. The project directors are Professors Z.-Y. Shen and Y.-Q. Li.

The original Chinese cold-formed steel structures design and fabrication industry was based on very small thickness materials that were also typical in the United States and other countries. Steel grades with yield stresses of 36 and 50 ksi were preferred, and material thicknesses between 2 and 6 mm (approximately 0.1 and 0.25 in.) were the norm. Local and overall buckling, effective widths and local material property variations were, therefore, paramount considerations for the design codes. Today's materials for cold-formed elements use thicknesses less than 1 mm (0.04 in.) and up to 20 mm ($\frac{3}{4}$ in.), and steel grades are available with yield stress up to 550 MPa (80 ksi), albeit with ductility limitations. This is the situation that is also the case for the rest of the world. The development of the Chinese cold-formed steel structures design standard was largely based on the American Iron and Steel Institute's *Specification and Manual* (AISI, 2007; 2008), as is actually the case for most such codes in the world today. It is now been revised to reflect the housing needs of the population as well as the expansion of the construction industry in general. It is anticipated that the new code will be adopted soon.

Responding in particular to the needs for residential construction in many areas of China, the project focuses on the following engineering and construction needs:

- Testing and analytical evaluation of the mechanical behavior, strength and stability of the typical thin-walled (less than 2 mm) cold-formed cross-sections, including some built-up members (double Cs) as well as thin-walled tubular shapes.
- Development of reliability and limit states design criteria for such cold-formed members.



Fig. 6. Testing of girder with trapezoidal corrugated web.
(Photo courtesy of Professor G.-Q. Li)

- Development of the characteristics of strength, behavior and design of cold-formed steel trusses.
- Testing of single shear connections with self-drilling screws and various dimensions of plates, fastener patterns and grades of steel.
- Performing monotonic and cyclic shear tests of 16 composite wall specimens with different aspect ratios, types of sheathing, grades of steel and sizes of openings to assess ductility and seismic energy dissipation.
- Shaking table tests for three full-scale models of two-story residential buildings, using different grades of steel for the studs and different sheathing boards.

Figure 7 shows one of the buildings that will be tested.

The evaluation of the larger thickness (6 to 20mm) cold-formed elements is proceeding, aiming for the development of the following data:

- Material property variations and residual stress distributions for various open and closed cross-sections.
- Analytical and experimental data for the strength and behavior of typical members and cross-sections.



Fig. 7. Full-scale two-story building to be tested on shaking table.
(Photo courtesy of Professors Z.-Y. Shen and Y.-Q. Li)

- Hysteretic behavior of bracing members and eccentrically loaded columns.
- Cyclic behavior, strength and limit states for typical connections between thick-walled cold-formed members.

SOME CURRENT RESEARCH WORK AT HONG KONG POLYTECHNIC UNIVERSITY IN HONG KONG, CHINA

The Hong Kong Polytechnic University is one of the premier universities in Hong Kong. With a large academic staff, good laboratories and especially fine computational facilities, this school has a first-class reputation for advanced graduate and undergraduate programs. Like a number of the major Chinese universities, the graduate courses in some areas of study are offered in English, lending significant advantages to its graduates. In addition, the university enjoys very close collaboration with the many national and international design firms with offices in the city. Equally important are the joint efforts between the university and the highly competent staff of the Hong Kong Buildings Department (HKBD), through which an outstanding limit states steel design code was developed (HKBD, 2005).

Direct Analysis for Structures in Steel, Composite and Reinforced-Concrete Construction: This is a major project that has been led by Professors S.-L. Chan and Y.-P. Liu.

Following the 2005 publication of the new steel design code for Hong Kong, direct analysis has been used extensively for the design of steel structures. The approach that was developed for the code is highly reliable and efficient, just as has been found for the direct analysis method of the AISC *Specification* in the United States. The research team at HKPU has now extended the method to hybrid steel and concrete frames, where the approach is applied to bare steel, composite steel-concrete and reinforced-concrete systems. Using a single code, originally developed for steel, structural analysis is now performed without the use of several codes—thus becoming safer, more efficient and more economical. This is accomplished in true, efficient hybrid form in terms of strength, stiffness and structural robustness. Of course, individual limit states for members and connections in the different materials still have to be checked.

Time will tell whether the combined application of the code will succeed in broadly applicable fashion, but the initial responses from the design community are favorable. The key is the consideration of member as well as structural second-order effects, because these do not depend on the construction material (Chan, 2001; 2006). Thus, biaxial stress resultant surfaces can be formulated for steel or concrete, as required, and the resulting capacity surfaces can be incorporated directly into practical second-order analysis and design procedures.

Modeling of Long-Span Composite Beams with High-Performance Materials and Deformable Shear Connectors:

This is a long-duration project under the direction of Professor K.-F. Chung and his research team. Previous work by Professor Chung reflects much of the initial thinking (Chung, 2006). At this stage, the project aims for improved structural accuracy and efficiency of long-span composite beam design, incorporating practical construction features.

Using test data for simply supported and continuous beams, suitable two- and three-dimensional models have been developed. The models have the following features:

- Geometric and material nonlinearities are represented, including initial geometric and mechanical imperfections.
- Deformable shear connectors with limited ductility are represented, including nonlinearity at the interface of steel and concrete.
- The steel is modeled as an elastoplastic high-performance material, including various levels of strain hardening.
- Advanced reinforced-concrete models reflect normal weight material, with normal to high-strength concrete.
- Complete ranges for different failure criteria of the materials are represented, including steel stress levels, concrete strains, overall beam deflections and slip of the shear connectors.
- Effects of shoring during construction are incorporated.

Figure 8 illustrates the undeformed and the deformed two- and three-dimensional models, including distributions and intensities of the von Mises stresses.

Following extensive parametric evaluations, the major findings of the study are as follows:

1. For beams with 100% shear connection, the full flexural capacity is developed, and the shear connector slip is generally less than 1 mm (0.04 in.).
2. For beams with a partial shear connection, the shear connector slip is typically in the range of 2 to 5mm (0.08 to 0.2 in.) when the requisite moment capacity has been reached. As expected, the slip will be smaller for unshored beams.
3. For partially composite beams with spans larger than 20 ft and deep, wide-flange shapes ($d > 18$ in.), slip in the range of 5 to 10mm (0.2 to 0.4 in.) will occur when the shear connection is less than 50%. The moment capacity is typically reduced by 5 to 10% of the design values.
4. For composite beams with 100% shear connection and different material grades for the concrete and steel, the moment capacity is increased by 20 to 70% if the yield stress of the steel is increased from 50 to 65 ksi and 100 ksi. The self-weight is not increased.
5. The common plastic moment stress block gives accurate moment capacities for a wide range of steel and concrete materials.

The researchers are currently developing improved composite beam design expressions for use with the design

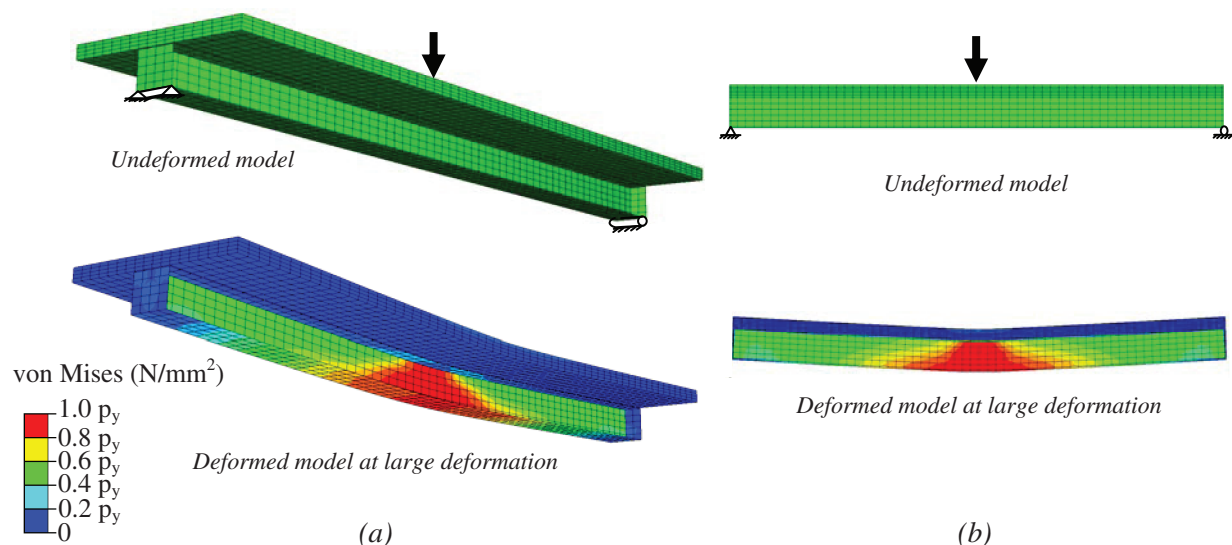


Fig. 8. Two- and three-dimensional composite beam models: (a) three-dimensional model; (b) two-dimensional model. (Drawing courtesy of Professor K.-F. Chung)

standards. In addition, vibrations induced by foot traffic are examined, with the aim of providing suitable methods of analysis and realistic performance criteria.

Enhancing the Performance of Steel Structures with Fiber-Reinforced Polymers (FRPs): This project is a wide-ranging investigation with Professor J.-G. Teng as the director. While the original work focused on the use of FRPs to improve the response characteristics of reinforced-concrete structures, for the past number of years, in-depth studies have been addressing a range of subjects aimed at enhancing the performance of steel structures. The project has focused on the strengthening of existing steel structures, but also providing for the efficient use of FRPs and steel in hybrid applications. Several subprojects have been undertaken, as follows:

Strengthening of Steel Structures with FRP:

1. *Debonding failures in FRP-strengthened steel structures:* Typically, the FRP has been bonded to the steel through some form of adhesive. The subject has been addressed in a number of studies, including
 - a. An experimental evaluation of the effect of the surface preparation of the steel.
 - b. a combined experimental and analytical examination of the full range of behaviors for the FRP-to-steel interface, using linear and nonlinear adhesives.

The key results have shown that adhesion failure can be avoided if the steel surface is grit-blasted before bonding. Using finite element analysis, reliable bond-slip models have been developed for the linear as well as the nonlinear adhesives. The agreement with the experimental results is very good.

2. *FRP confinement of hollow and concrete-filled steel tubes:* These types of elements are commonly used in various structural applications. One of the governing limit states for columns is local buckling of the tube wall near the member end, and FRP jackets have sometimes been used to prevent this type of failure. The project was a combination of testing and analytical evaluations, which demonstrated that the confinement of the steel by the FRP could be an effective solution. Basically, the FRP jacket delayed or completely suppressed the local buckling failure, while also providing for a significant improvement of the column behavior and strength. As part of the study, an accurate stress-strain model was developed for use with monotonic as well as cyclic loading for the confined concrete.

Hybrid FRP-Concrete-Steel Double-Skin Tubular Members: Figure 9 shows typical examples of the cross sections of some double-skin tubular members (DSTMs). The use of

FRPs for such members was invented by Professor Teng; it has attracted significant attention.

Briefly, as can be seen, the outer tube is FRP and the inner tube is steel. The tube can be left unfilled (as shown in Figure 9) to maintain a lower mass. Briefly, the FRP provides the confinement for the concrete as well as additional shear strength of the member. These members may be pre-cast or built on site.

In addition to the high corrosion resistance of the member as provided by the FRP skin, these members offer high ductility, a high weight-to-strength ratio, and ease of construction. Beam-to-column connections can be built relatively easily by removing the FRP in the immediate area and connecting directly to the steel through the concrete.

The DSTM researchers have performed a number of full-scale member tests for axial compression, bending and eccentric compression. The results have demonstrated effective confinement of the concrete between the outer FRP tube and the inner steel tube. Further, the members are highly ductile under pure compression as well as combined bending and compression. Finally, a simple and practical design procedure has been developed; it has been adopted by the Chinese code for infrastructure application of FRP composite materials.

Currently, the behavior and strength of DSTM members under cyclic loading is being examined, using full-scale tests as shown in Figure 10. Conclusions will be forthcoming.

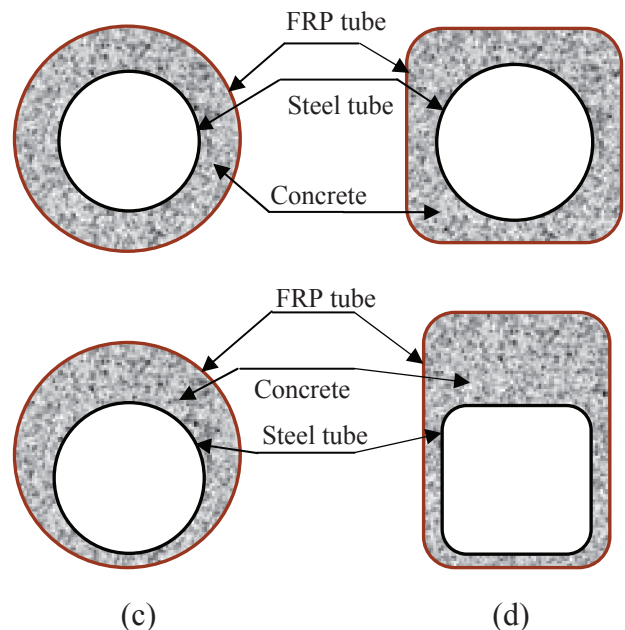


Fig. 9. Typical double-skin tubular member (DSTM) cross-sections.
(Drawing courtesy of Professor J.-G. Teng)

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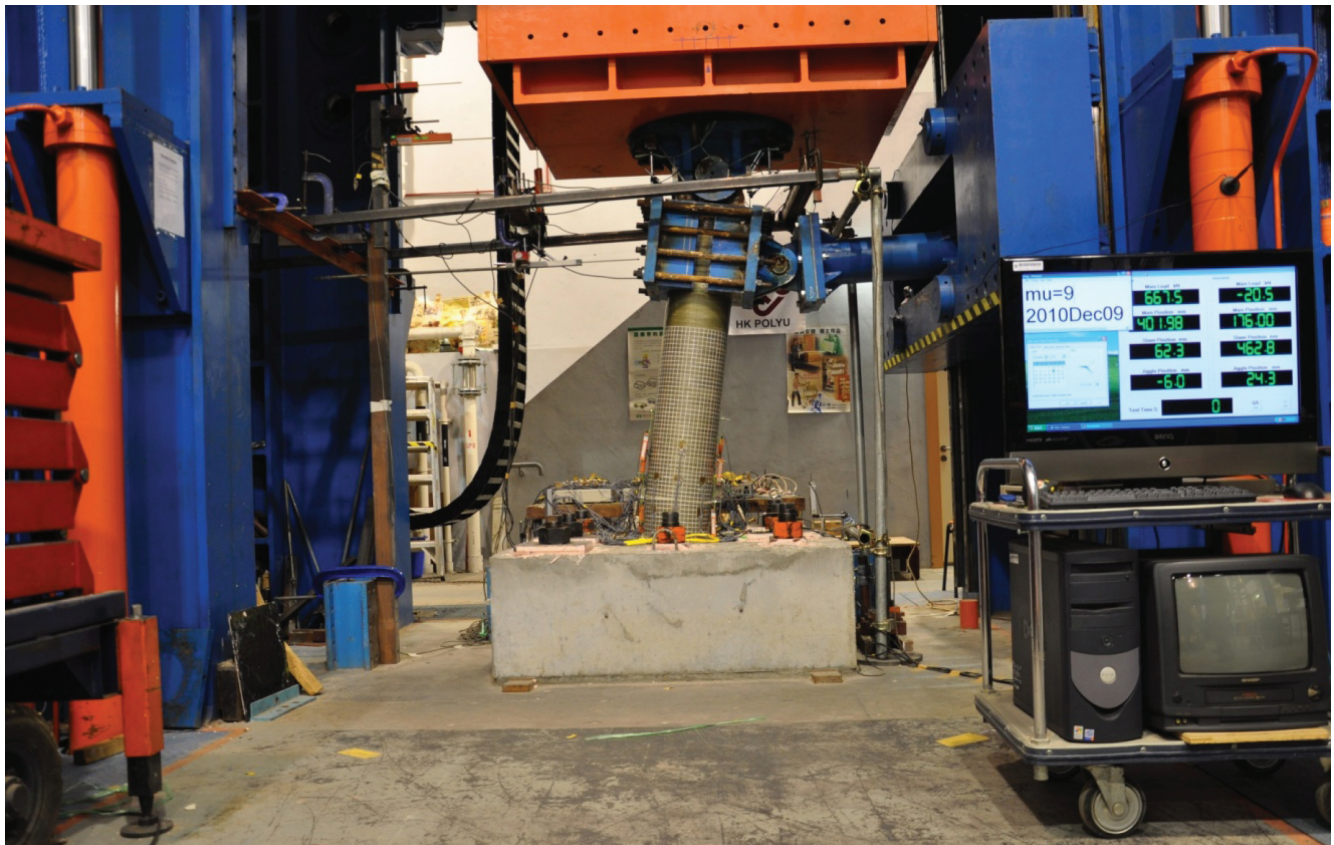


Fig. 10. Full-scale cyclic lateral loading test of a hybrid DSTM.
(Photo courtesy of Professor J.-G. Teng)

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