Current Steel Structures Research

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As should be expected, the ultimate goal of much structural engineering research is the eventual incorporation of the key findings into design codes and related documents. The procedures for accomplishing such aims vary a great deal from country to country and within economical or geographical regions. Further, legal needs may override some potential criteria, as expressed by various code authorities. The interactions and complexities of the American system are legion, between the requirements for steel-framed buildings (AISC and AISI), the loading criteria (ASCE 7) and the overall legal framework of the building code (IBC, through ICC). Similar procedures are used in Canada, Australia, the European Union and its member countries, and many other areas. The combined complexity of the specifications, standards and codes is such that researchers ought to be intimately familiar with all of the needs that are expressed through such documents.

Aiming at improving structural efficiency, economy and above all performance for all forms of service requirements, a number of current studies are investigating novel applications of steel and composite elements and systems. Applied to buildings and bridges alike, some of the recent examinations extend well-known analysis and design concepts to uses of high-strength steel and composite members with high-strength concrete. Research work in China has developed testing and analytical procedures for cast steel connections, and design criteria have been developed through significant applications for traditional forms of steel construction such as long-span trusses. Further, structural ductility and fracture toughness are assessed through realistic and practical procedures, recognizing actual rather than theoretical needs.

Seismic considerations continue to be critical for many areas of the world, and a major effort in France is examining the behavior and strength of certain composite end plate connections. Including tests as well as extensive analytical evaluations, performance data are used in conjunction with the development of suitable models. The same research team is also developing innovative solutions for beam connections in short- and medium-span composite bridge structures. Two ongoing studies in Singapore address the use of very high strength concrete and steel in composite columns for high-rise construction, and a novel form of sandwich construction has been developed that makes use of a new type of shear connector. A recent project in the United States has examined the performance of slip-critical connections with fillers, an important application for many types of construction, especially when very heavy rolled shapes are to be utilized.

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.

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STRUCTURAL BEHAVIOR AND STRENGTH UNDER SEISMIC LOADS

Static and Seismic Behavior of Steel and Composite Bolted End-Plate Beam-to-Column Connections: This project has been conducted at the Institut National des Sciences Appliquées (INSA) in Rennes, France, with Professor Alain Lachal as the director. Financial support is provided by the French Ministry for Infrastructure and Transport through the Research Management Program.

Focusing on the moment-rotation behavior and the ductility and energy absorption capacity of the connections, full-scale tests and three-dimensional finite element analysis have been conducted (Lachal et al., 2008). Figure 1 illustrates the test setup for the two- and three-dimensional specimens. Special attention has been paid to the stress and strain data for the web panels of the connections, as well as the concrete slab in the vicinity of the column and especially the part of the slab that is strengthened by the haunches. The test loading procedure was done in accordance with the protocol of the European Convention for Constructional Steelwork (ECCS, 1986).

It has been determined that the nonuniform shear stress distribution in the column panel zone that was exhibited by the tests is confirmed by the theoretical analysis. Further, the haunch appears to provide a significantly improved cyclic performance of the connection, with a plastic energy absorption that is double that of a nonhaunch connection. The researchers also have concluded that there is no risk of low-cycle fatigue fracture of the weld between the end plate and the beam flanges. The stiffening effect of the composite slab increases the positive moment capacity by 60% in comparison with a nonhaunch connection; it also prevents flange buckling. On the other hand, for negative bending the presence of the composite slab only increases the moment capacity by about 30%, and it offers no reinforcing effect for the beam flanges.

Of significant interest for design considerations, the results show that the current Eurocode 3 (CEN, 2005a) criteria underestimate the strength and stiffness contributions of the column panel zone, especially when doubler plates that are thicker than the column web are used. In addition, the analytical evaluations demonstrate the “non-negligible” (Lachal et al., 2006) effects of tension stiffening and the use of preloaded bolts.

BEHAVIOR AND STRENGTH OF CONNECTIONS

Behavior of Slip-Critical Connections with Fillers: This is a project that has been conducted at the University of Illinois at Urbana-Champaign, with Professor Jerome F. Hajjar as the director. The project was sponsored by the American Institute of Steel Construction, W&W Steel Corporation and the University of Illinois, with in-kind support provided by Lohr Structural Fasteners and the University of Cincinnati.

Filler plates of various thicknesses are common in bolted connections when structural members of different depths are used. Lacking performance data for connections with very heavy shapes and slip-critical joints, a total of 16 full-scale tests of column splices were conducted to examine the slip and strength characteristics of connections with oversize holes. One of the tests used standard size holes, to establish a set of baseline data.

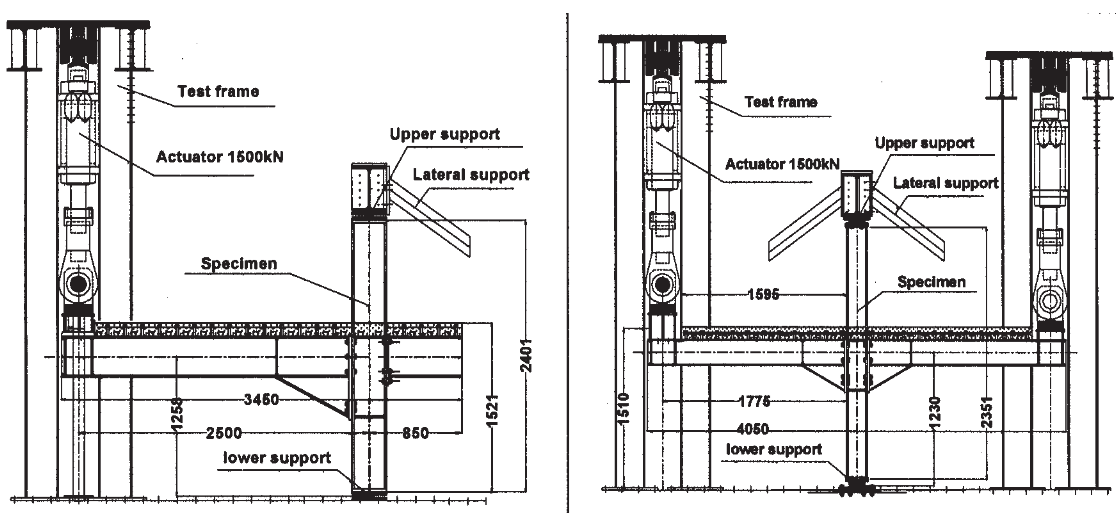
All of the test specimens used W14×730 stub column shapes; these were connected to W14×159, W14×455 and W14×730 shapes with 2-in. splice plates in addition to fillers (where necessary) of thicknesses from 1⅝ in. to 3¾ in. The filler configurations varied from undeveloped to partially developed and fully developed. Single-ply and two-ply fillers were used; the latter had filler thicknesses of 3½ and ¼ in. Some fillers were welded. Finally, the specimens were fabricated with turn-of-nut bolts or tension-control bolts.

Figure 2 shows one of the test specimens after failure, first by connection slip and then bolt shear fracture. This particular specimen had oversize holes and 1⅝ in. fillers. The researchers note that all of the test connections exhibited high resistance to slip, with only two of the cases falling below the predicted loads. Assessing these results along with data provided by other investigations, as reported in the literature, it is clear that the slip strength is reduced by the presence of undeveloped fillers, and this is independent of filler thickness and hole size. The slip strength reduction is particularly observed for connections with multi-ply fillers.

As expected, the bolt shear strength was much larger than the slip value, but the connection strength was clearly affected by the presence of any filler plates. The shear strength is initially reduced by the presence of thin fillers; for thicker fillers the strength is increased. Design requirements have been proposed to take all of these effects into account for compression splices.

Application of Connections Using Cast Structural Steel Elements: This project has been conducted at Tongji University in Shanghai, China, with Professor Yi-Yi Chen as the director. Support has been provided by the Tongji University through its research program.

The study reflects increasing attention to the use of cast steel elements in Chinese construction, many of whose



(a) Two-dimensional test

(b) Three-dimensional test

Fig. 1. Connection test specimens. (Courtesy of Professor Alain Lachal)

structures and connections tend to be very complex and not easily designed in accordance with current standards. A recent (2008) addition to the family of codes aims at facilitating the use of cast steel, but much work remains to be done (Chen et al., 2008).

Using three-dimensional finite element analysis and full-scale tests of cast connections for specific structures, the researchers have developed a practical methodology for these types of connections. One of the key difficulties with the use of cast steel has been the lack of reliable material standards, but that is now being overcome. For example, the recently published Chinese standard focuses on two grades of weldable cast steel, with yield stress values from 200 to 275 MPa and tensile strength values from 400 to 485 MPa (Chen et al., 2008). The properties are comparable to those of European cast steels, which have yield stresses between 240 and 300 MPa and tensile strengths from 450 to 650 MPa (EN, 2005b). The researchers observe that full plasticity criteria should not be used for the design of these types of connections. Rather, partial plasticity may be feasible, although the favored approach is elastic analysis (allowable stress design) accompanied by physical testing. The tests that have been conducted aimed in part at confirming these considerations, which are clearly conservative choices.

Several full-scale tests for connections in specific structures have been performed by the researchers. The details of the test specimens were determined following extensive three-dimensional finite element analyses. For example, Figure 3 shows the Laoshan Velodrome that was built for the 2008 Olympic Games, along with the structural details of the connection and the test setup.

Another example is shown in Figure 4, where the bottom chord connection to the pair of web members in a so-called beam-string truss was chosen for physical testing. The structure uses a pair of inclined (out-of-plane) trusses, connected to the single bottom chord by inclined verticals. It is noted that in addition to the cast steel part of the connection, the bottom chord and the inclined verticals are attached to the tubular elements of the casting by threads inside the tubes.

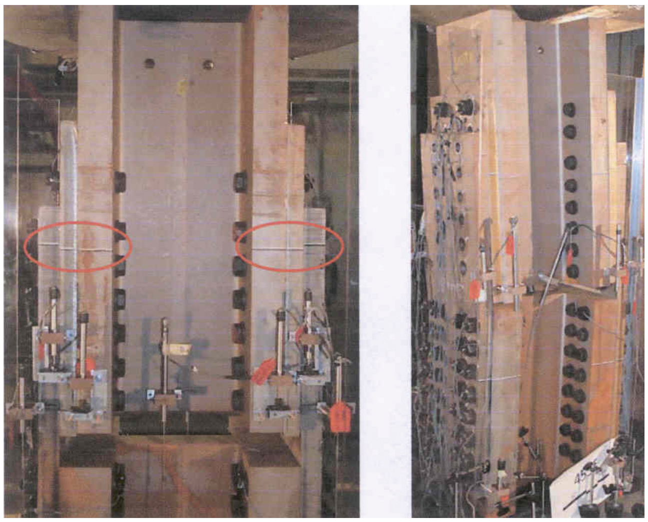


Fig. 2. Testing of heavy column splice with filler plates. (Courtesy of Professor J. F. Hajjar)

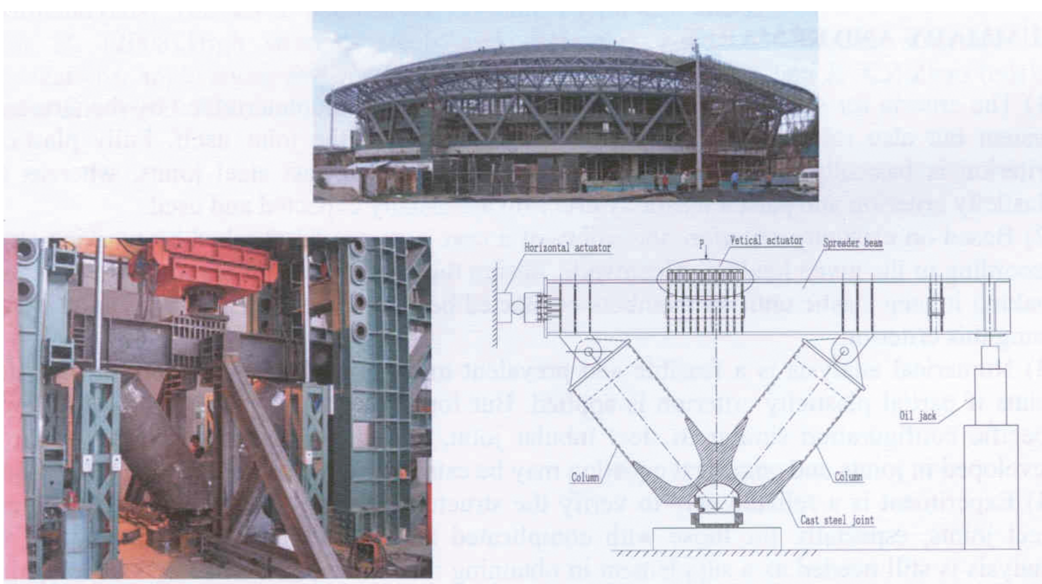


Fig. 3. Laoshan Velodrome structure and cast steel detail with test setup. (Courtesy of Professor Y.-Y. Chen)

The good correlation between test and theory for two of the critical locations within the connection is illustrated in Figure 5.

Significant additional tests and analyses have been conducted, including for more complex connection configurations. Detailed design recommendations will be forthcoming.

COMPOSITE CONSTRUCTION

Design of Composite Steel-Concrete Systems for Multi-Story Building Construction: This project is a major, long-term study being conducted at the National University of Singapore with Professor J. Y. Richard Liew as the director. Support has been provided by the National University of Singapore through its research program.

The project addresses composite member, connection and framing system issues in great detail, in addition to the performance of composite structural systems under fire and blast conditions (Liew, 2008). The strength and behavior of unique types of composite columns is of particular interest.

High-rise construction in Singapore uses composite framing systems extensively and with great innovation. The

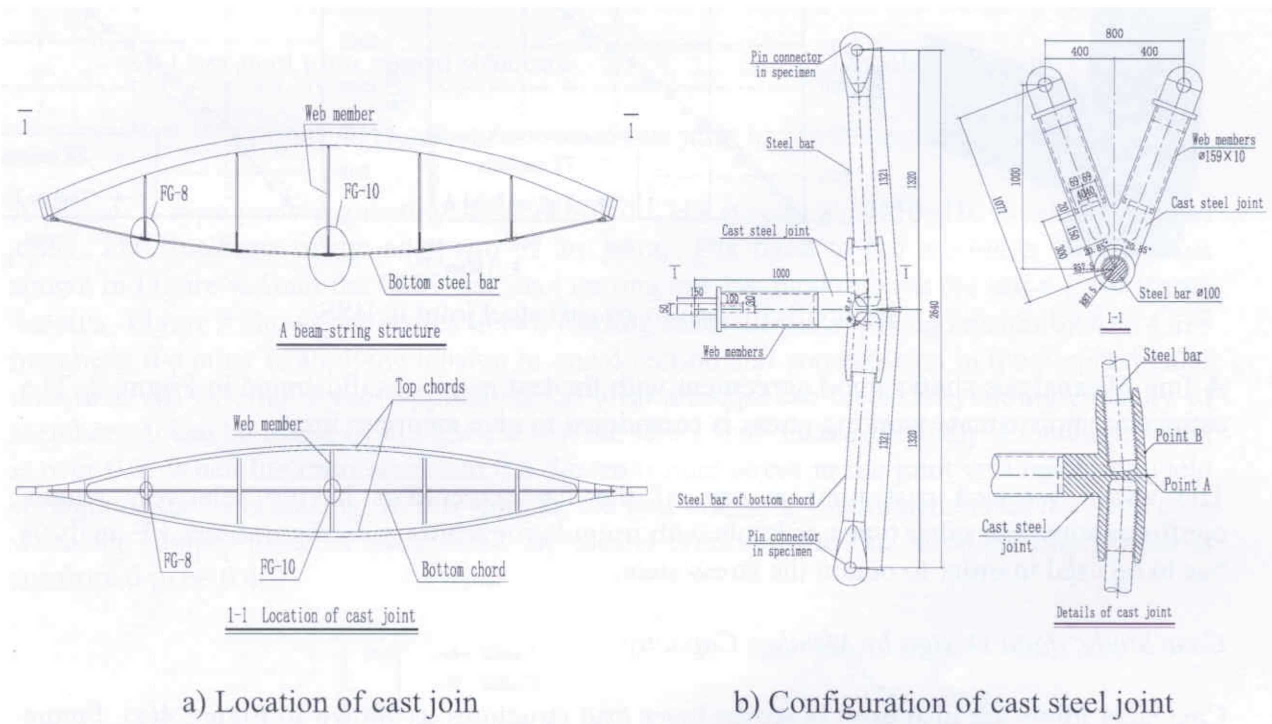


Fig. 4. Beam-string truss in elevation and plan, along with cast steel connection detail. (Courtesy of Professor Y.-Y. Chen)

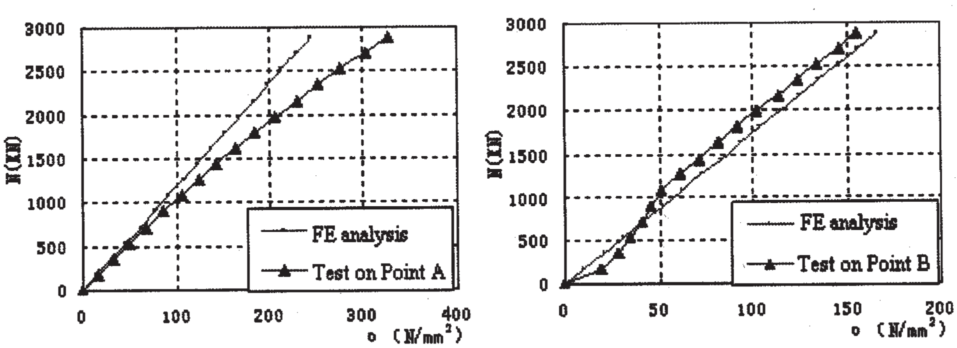


Fig. 5. Comparison of measured and computed stresses at points A and B (see Fig. 4). (Courtesy of Professor Y.-Y. Chen)

composite columns have enabled architects and designers to develop structures with larger usable floor areas and higher lateral load resistance. As shown in Figure 6a, concrete-filled round HSS was used to significant advantage for certain low- and mid-rise buildings, although the large wall thickness that was needed led to high construction cost. Further, the limitations for the sizes of the available steel cross-sections restricted the uses in high-rise frames.

The issues related to composite columns have effectively been resolved through the use of columns with either high-strength steel cores, as shown in Figure 6b, and especially with the use of an internal round HSS filled with ultra-high-performance concrete (UPHC), as shown in Figure 6c. Although the strength and fire resistance of the steel-core column in Figure 6b are high, the high-strength steel is expensive. The researchers observe that the tube-in-tube solution is a significant improvement in all respects, since normal strength concrete (5 to 7 ksi strength) may be used for the filling between the outer and inner walls of the two tubes. The UPHC is only used as the filling for the interior tube; the strength of this concrete material may be as high as 25 ksi (Liew, 2008).

This research work is continuing, including studies of the connections between the inner and outer tubular members, using various forms of shear keys. The use of shear keys between the concrete slab and the tube-in-tube column has produced an effective "slim floor" design that does not require additional fire protection. Primary analyses have demonstrated potential cost savings of the tube-in-tube column of 20 to 50% when compared to the solid steel core case.

Structural Performance of Steel-Concrete-Steel Sandwich Composite Structures: This is a major study being conducted at the National University of Singapore with Professor J. Y. Richard Liew as the director. The project has been sponsored by the Maritime and Port Authority of Singapore, Keppel Offshore & Marine Ltd. and the National University of Singapore.

As a low-weight, high-performance structural system with especially high resistance to impact and blast, steel-concrete-steel sandwich elements have been used for a number of applications since the early 1990s (Liew and Sohel, 2008). The original applications were bridge decks in long- and medium-span structures, although these solutions had a number of drawbacks in the form of bonding failure between the steel and internal concrete parts. Improved composite response through better shear connection features have made the sandwich elements very suitable for offshore and ship structures as well as caissons, core walls and submerged tunnel construction.

The key feature of a successful steel-concrete-steel sandwich element is the shear connectors that enable the components to function as an integral unit, along with the use of lightweight concrete. Traditional headed stud shear connectors may be used, and solutions such as the "bi-steel" sandwich panel have offered usable solutions. However, the difficulties with these two forms of construction are very significant insofar as constructability is concerned: it is simply very difficult to build and ensure satisfactory shear transfer between the steel and the concrete, and especially to pour the concrete itself. Prefabrication is a possible solution, but this offers practical problems due to the weight and physical sizes of the elements.

The novel and ingenious solution offered by the researchers is the development of a new form of shear connector, the J-hook connector, as illustrated in Figure 7. This is a patented detail and is essential to the construction and service performance of the sandwich elements. Extensive physical testing has been done, to examine the performance of the connectors and the sandwich system under tensile loading (perpendicular to the steel plate and longitudinal to the connectors), as well as bending and impact tests for

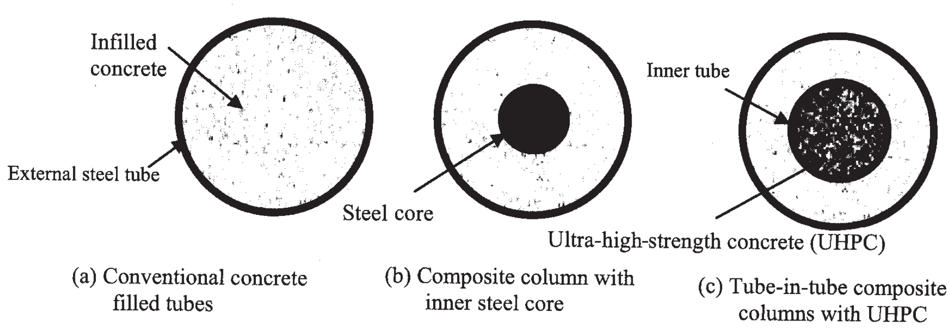


Fig. 6. Various tubular composite column cross-sections. (Courtesy of Professor J. Y. Richard Liew)

the sandwich elements. It has been found that the concrete cracking that was a serious difficulty for the original concept has been reduced significantly, and the blast and impact resistance is very high. The impact tests in particular offer very interesting results.

The research and development work will continue, with anticipated applications for numerous structures associated with maritime construction, improved bridge and roadway elements, and potential shear wall structures in buildings. Ductility issues will continue to be addressed, especially as it appears that adding steel or other fibers to the concrete mix will improve the overall response.

PERFORMANCE OF BRIDGE STRUCTURES

Innovative Solutions for Beam Connections in Small and Medium Span Composite Bridges: The project is conducted at the Institut National des Sciences Appliquées (INSA) in Rennes, France, with Professor Alain Lachal as the director. It has been funded by the Ministry for Infrastructure and Transport of France through the Research Management Program.

This is a longer-term project aimed at improving the economies of short- and medium-span bridges. Bridge designers in France have commonly used various forms of bolted end plates, and the study examines such connections as well as plates with stud shear connectors that are embedded into the concrete, and connections that are fully embedded into the concrete. Full-scale tests have been conducted, looking at the performance of the connections fatigue loading, followed by monotonic loading to failure. The researchers feel that this establishes a complete database that will be useful in further studies.

Extensive three-dimensional finite element analyses are being performed to correlate the analysis with the full-scale tests. The aim is to provide a complete analytical design method for the connections that are being tested, with potential extension to additional connections and other bridge types.

REFERENCES

Chen, Y.-Y., Zhao, X.-Z. and Tong, L.-W. (2008), "Research and Application of Connections of Structural Steel Casting," in *Innovations in Structural Steel,* Regency Steel Asia International Symposium, December 1, 2008, S.-P. Chiew, Editor, Nanyang Technological University, Singapore, pp. 88–102.

CEN (Comité Européen de Normalisation) (2005a), *Eurocode 3—Design of Steel Structures—EN 1993-1*, CEN, Brussels, Belgium.

CEN (Comité Européen de Normalisation) (2005b), *Steel Castings for General Engineering Uses—EN 10293*, CEN, Brussels, Belgium.

European Convention for Constructional Steelwork (ECCS) (1986), *Recommended Testing Procedures for Assessing the Behaviour of Structural Elements under Cyclic Loads*, ECCS Task Committee 1, Technical Working Group 1.3, Seismic Design, Report No. 45.

Lachal, A., Aribert, J.-M. and Loho, G. (2006), "Analytical and Experimental Investigations of Bolted Haunched Beam-to-Column Joints with a View of Seismic Design," *Advanced Steel Construction*, Vol. 2, June, pp. 135–160.

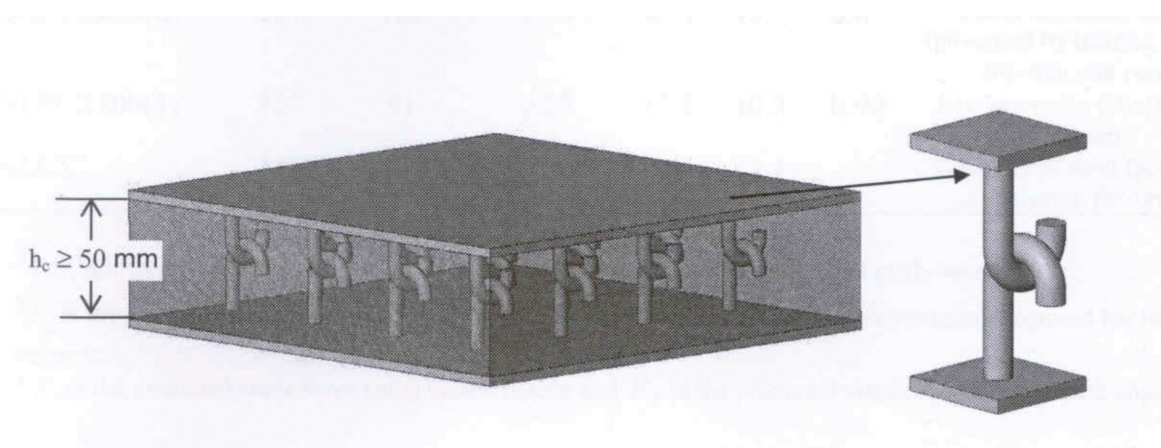


Fig. 7. Steel-concrete-steel sandwich element with J-hook shear connectors. (Courtesy of Professor J. Y. Richard Liew)

Liew, J. Y. Richard (2008), "Design of Steel-Concrete Composite Systems for Multi-Storey Building Construction," in *Innovations in Structural Steel*, Regency Steel Asia International Symposium, December 1, 2008, S.-P. Chiew, Editor, Nanyang Technological University, Singapore, pp. 124–191.

Liew., J. Y. Richard and Sohel, K. M. A. (2008), "Structural Performance of Steel-Concrete-Steel Sandwich Composite Structures," in *Innovative Design of Steel Structures*, Second International Symposium, December 5, 2008, Ben Young, Editor, The University of Hong Kong, Hong Kong, China, pp. 73–100.

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