

# DEVELOPMENT OF CONNECTIONS TO CONCRETE-FILLED RECTANGULAR TUBULAR COLUMNS

Zhihua Chen<sup>1,2</sup>, Ying Qin<sup>1,2</sup> and Xiaodun Wang<sup>2,\*</sup>

<sup>1</sup> Key Laboratory of Coast Civil Structure Safety of China Ministry of Education, Tianjin University, Tianjin, China

<sup>2</sup> Department of Civil Engineering, Tianjin University, Tianjin, China

\*(Corresponding author: E-mail : maodun2004@126.com)

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**ABSTRACT:** Concrete-filled rectangular tubular column composite frame systems with steel beams have been widely used in moment-resisting frames for engineering practice. This paper reviewed a variety of connection details to concrete-filled rectangular tubular (CFRT) columns that have been developed by different researchers. The research on CFRT connections was divided into three phases. The first phase dates back to the late sixties of twentieth century, when the steel moment-resisting frames were regarded as one of the most ductile systems. The second phase is defined as the period between middle nineties and the beginning of the twenty-first century, during the early stage of which the Northridge earthquake and Kobe earthquake occurred and the conventional knowledge of traditional connections were subverted, leading to the requirement of paying more attention to the investigation of connection behavior under seismic loading. The third phase passes through the following year up to the present. During this phase, various connection alternatives were proposed and studied. Based on the summary of previous studies, the future developments were presented at the end of the paper.

**Keywords:** Concrete-filled rectangular tubular column; Development, Steel beam, Connection, Three phases, Future work

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## 1. INTRODUCTION

Concrete filled rectangular tubular (CFRT) columns are structural members that combine two materials in one member. They have the beneficial merits of steel, such as high tensile strength and ductility, and of concrete, such as the high compressive strength and stiffness. Structures with CFRT columns are widely used in engineering applications such as bridges, high-rise buildings, underwater structures and so on [1,2]. In addition to the advantages mentioned above, the CFRT structures can reduce the time and cost of construction by serving the tube as the framework for casting concrete. It makes the most efficient use of the steel as it is placed at the perimeter of the section, providing the highest contribution to the moment of inertia. The steel tube provides the confinement to the concrete, which puts the concrete under a tri-axial state of stresses and enhances the performance of concrete. Even more, the steel prevents concrete from spalling. At the same time, the concrete infill prolongs local buckling of steel tube by preventing inward buckling, thus increasing the stability and strength of the column as a system [3].

However, the advantages of utilizing concrete-filled tubular columns may still remain unexploited due to the lack of design guideline on appropriate cost-effective and construction-efficient connections between concrete-filled tubular columns and steel H-shaped beams. This dearth of information is even more pronounced with regards to connections to CFRT columns.

The CFRT column-to-beam connections are broadly classified into two categories [4]. The most convenient way is directly attaching the steel beam to the column tube or through the diaphragm plate. For the other connection category, the beam flange, the web or the entire cross-section are penetrated through the steel tube or the beam end is welded with anchorage which is embedded in the CFRT column. Connections to the face of the steel tube include: welding the beam directly to the tube skin, using web angles or shear tabs to connect the beam to the tube, providing diaphragms and variations on these details. Connections with embedded elements include: through bolting beam end plates, and continuing structural steel shapes into and through the column. Analysis of test data suggests that embedding connection components into the concrete core alleviates high shear demand on the tube wall, which may improve the seismic performance of the connections [5].

## 2. FIRST PHASE-PRE-NORTHRIDGE CONNECTION STUDIES

Since 1960s, engineers began to regard welded steel moment-frame buildings as being among the most ductile systems. They believed that the steel moment-resisting frames were invulnerable to earthquake-induced structural damage and they should be limited to moderate yielding and localized buckling of the steel components and not induce collapse at all [6]. As to the CFRT column systems, they considered that it was more convenient to connect the beam to the steel tube using welding materials without any embedded members. Much attention was paid to the strength and failure modes of fully-welded connections at that time.

Previous research on CFRT column systems include the experiment taken by Furlong [7] which involved assessing the strength of CFRT beam-columns. The results demonstrated the benefits of filling the steel tube with concrete. The concrete infill prevented local buckling of the steel tube and enhanced the strength of the specimen compared to hollow steel tube column-to-beam one.

Ansourian [8] tested connections with exterior stiffeners, as shown in Figure 1 for connection details. Two specimens were welded with tension plates. These specimens failed by fracture of the V-butt weld connecting the tension plate to the tube. Another two specimens were fabricated with the tension flange force transferred as a compression force to the other side of the tube. The remaining specimens were shop welded but assembled using high strength bolts. Most of these specimens experienced panel zone failure after extensive deformation of the tube.

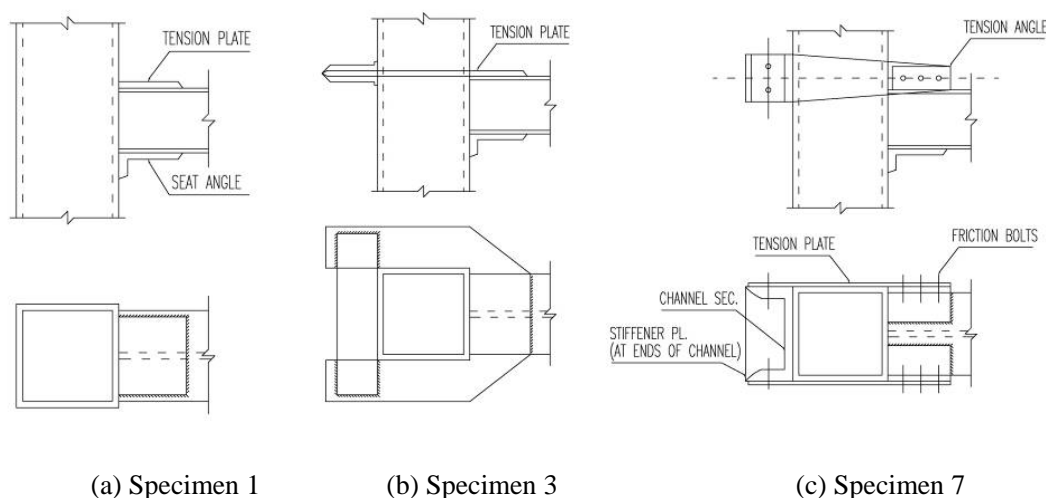


Figure 1. Connection Details Tested by Ansourian [8]

Tomii and Sakino [9-10] conducted monotonic and cyclic load tests on CFRT beam-column specimens with various  $b/t$  ratio, the axial load level, the shear span ratio, the steel yielding strength and the concrete compressive strength. The test results indicated that the increase in the  $b/t$  ratio or the axial load level lead to the decrease in the ductility of the specimen. Analytical equations to evaluate the loading capacity of the connections were also developed.

Matsui [11] developed a method to design the wide flange beam-to-CFRT column connections with exterior and interior stiffeners. Six specimens were tested to verify the strength formula. The connection details are shown in Figure 2. The connections were designed to have yielding developed in the stiffener and panel zone. The test results indicated that the specimens had excellent performance when the stiffeners were designed by these proposed formulas.

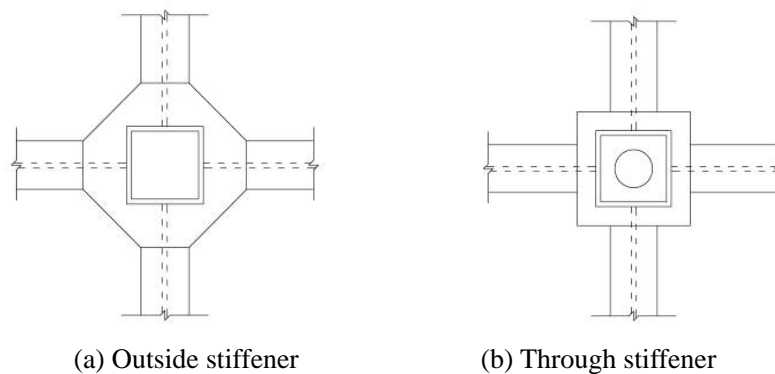


Figure 2. Connection Details by Matsui

Kanatani, et al [12] developed through-bolted moment connection as an alternative to diaphragm connection, aiming for evaluating out-of-plane deformation of the connections and eliminating difficulties in field welding. As shown in Figure 3, four types of connections were studied. The monotonic load tests showed that the split tee connection was able to perform better than diaphragm connection in terms of strength. The result of cyclic load tests demonstrated that through-bolts and split tee did as good as, or even better than internally and externally welded stiffeners in transferring force from beam to column. When the steel tube width-to-thickness ratio ( $b/t$ ) is 42, the failure was caused by local buckling of column flange regardless the present of concrete.

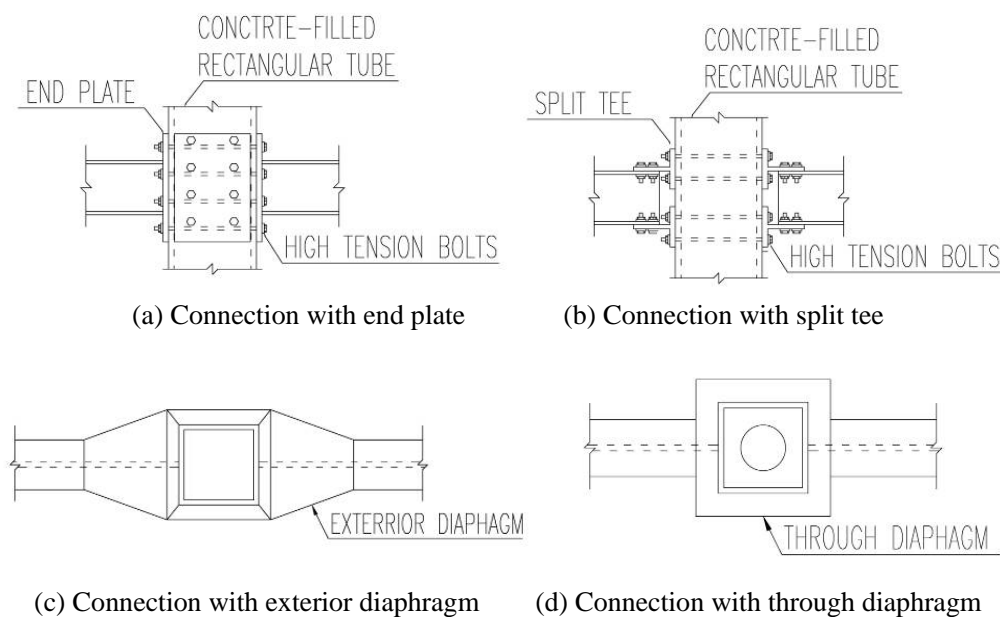


Figure 3. Connection Details Studies by Kanatani et al.

Prion and McLellan [13] tested similar bolted connections; however, end-plates were fully welded to the girder. These endplates were attached to the CFRT using bolts continuous through the tube column. Results suggested that good shear capacity was obtained from the through depth bolts, however, it was noted that the bolts were subjected to shear and bending stress due to the large eccentricities.

Azizinamini [14] suggested a new through-beam connection. A certain height of the column tube, together with a short beam stub passing through the column and welded to the tube, was fabricated in the shop to form a tree column, as shown in Figure 4. This “tree column” was transported to the field and the floor beams were then spliced to it. One cruciform specimen was tested under monotonic loading only. Results suggested that the beam web within the joint experienced a shear type failure, thereby activating a concrete compressive strut. This strut acted as a diagonal stiffener to assist the beam web in resisting joint shear. A finite element analysis was undertaken to analyze the proposed detail, and tentative guidelines for the design of such joints were proposed.

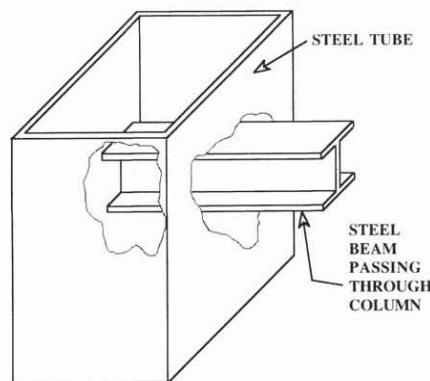


Figure 4. Through Connection Detail

### 3. SECOND PHASE-PRIOR STUDIES TO IMPROVE CONNECTION BEHAVIOR

The second phase began in 1994, when the Northridge earthquake occurred on January 17, 1994, followed by the Kobe earthquake on January 17, 1995. Engineers' conventional knowledge that steel moment-frame buildings would behave in a ductile manner was challenged. Observation of damage sustained by buildings indicated that, in many cases, brittle fractures initiated within the connections at very low levels of plastic demand, and some time, the structure still remained elastic. Many cracks started at the weld zone of the bottom beam flange. It was found that welding the beam directly to the steel tube prohibited the formation of the plastic hinge in the beam and induced severe stresses at the beam-to-column connection. It was urgent to pay more attention to the investigation of seismic behavior of these connections. Since then, researchers have extensively evaluated the inspection of affected connections, the repair of damaged connections, the upgrade of existing connections to improve their future performance, and the design of new connections to provide reliable seismic performance [15, 16].

Considering the importance of developing design guideline of composite structures, U.S. - Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures was formed [17]. Research in Japan concentrated on the connections with interior, exterior or through steel plate diaphragms, as shown in Figure 5. Investigation was made on the strength, ductility, and behavior of the connection, as well as the effect of temperature on the connection performance, the ultimate resistance of advanced connection method, the material properties of steel and weld metal, the

effect of welding heat, the geometry of weld access hole and other weld details, and the elimination of weld access hole [18]. On the U.S. side, Lehigh University and The University of Texas at Austin took the work of researching the connections to rectangular tubular column. And it was decided that the research at Lehigh University would focus on the design and development of the connection and the research at The University of Texas at Austin would focus on the interior joint shear force transfer mechanism, by failing of the joint [19].

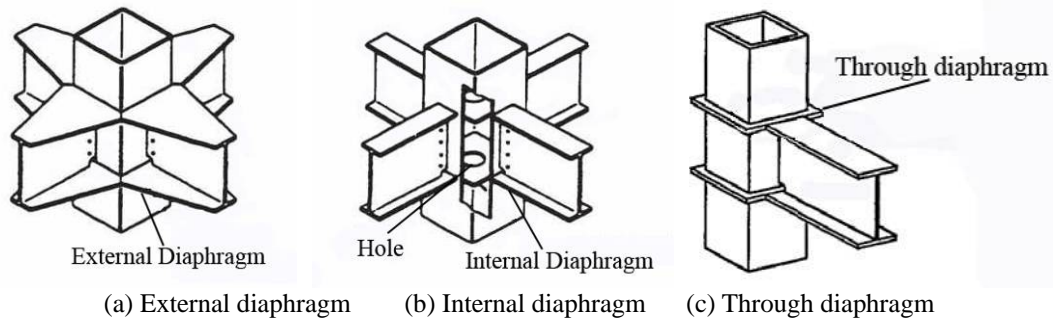


Figure 5. Typical CFRT Column-to-beam Moment Connections in Japan

Morino, et al [20] tested planar and three-dimensional subassemblies consisting of CFT column and wide flange beams, as given in Figure 6. Diaphragm plates, with the same thickness as the beam flange, passed through the column and had openings for proper concrete casting. Two types of failure mode were expected in the experiment: shear failure of the panel zone and flexural failure of the column. It was observed that the panel-failing mode was more stable and exhibited more energy dissipation capacity compared with the column-failing mode.

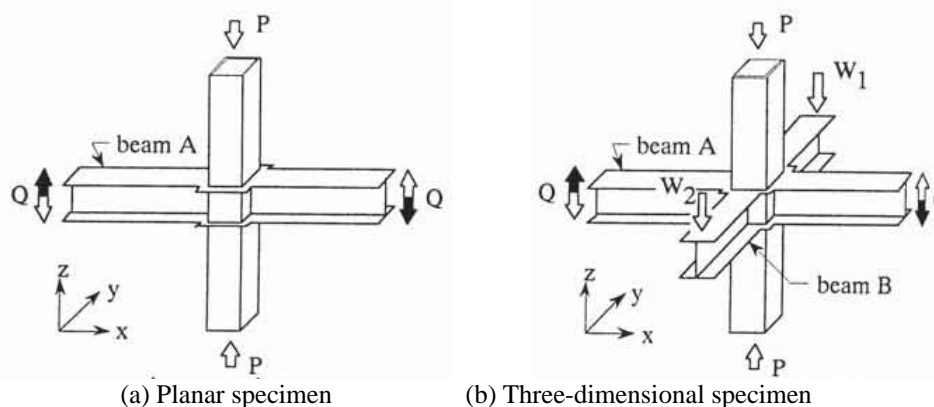


Figure 6. Schematic View of Test

Matsui and Kawano [21] suggested the connection using vertical stiffeners instead of diaphragm for external joints, as shown in Figure 7. The later one has the high structural reliability of columns, but the size of the external diaphragm may place limits on the design of exterior frames for the building. The proposed new type of connection was expected to overcome the disadvantage of the exterior diaphragm. It was observed that this connection type had sufficient capacities to gain a stable structural behavior and had superior seismic performances to the usual outer diaphragm connection system.

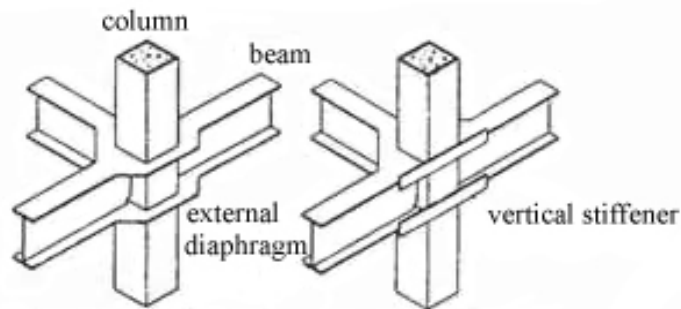


Figure 7. Beam-to-column Connections Studied by Matsui et al.

Viest [19] proposed the connections that utilize anchor bolts, embedded elements, and steel through-beam connection possibilities. The connection detail was shown in Figure 8. According to Viest's study, welding beam directly to the steel tube should be avoided to prevent: (a) separation of the steel tube from the concrete core due to flange tensile forces, (b) large residual stresses in the steel due to restraint of the other connecting elements, and (c) possible compromise of the confinement due to the additional stresses on the steel tube.

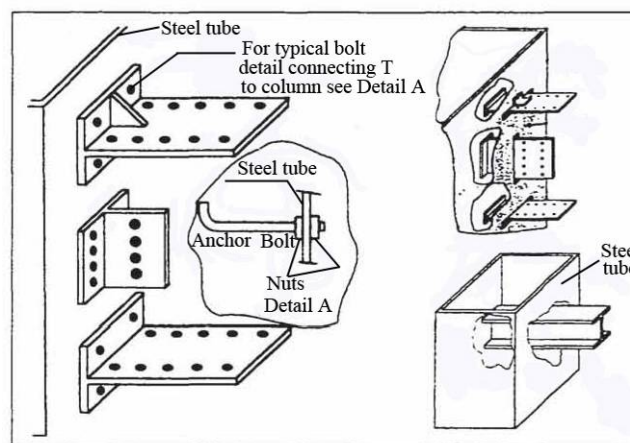


Figure 8. CFT Connection type by Viest

With respect to computational research geared for analyzing complete composite CFT systems, Hajjar et al. [22-23] presented a fiber-based distributed plasticity finite element formulation to perform three-dimensional monotonic analysis of square or rectangular concrete-filled steel tube (CFT) beam-columns. The stiffness-based beam-column element formulation accounted for all significant geometric nonlinearity exhibited by CFT beam-columns and interlayer slip between the steel tube and concrete core, which was extended to cyclic analysis of composite CFT frames. Details of the steel and concrete constitutive models were provided in their paper.

France [24] conducted experiments to learn the behavior of connection between universal beam and concrete filled tubular columns using endplates bolted directly to the column face with ordinary bolts screwed into the threaded holes formed using the flowdrill process. The test results were compared with those from a parallel series of tests in which the tubes were unfilled and substantial increase in the resistance of the column in the compression zone was observed, which forced the rotation axis of the joint moving towards the compression flange of the beam and resulted in the greater moment capacity in the joint.

Fujimoto, et al [25-26] conducted a series of wide flange beam-to-CFRT column connection tests. A total of eleven one-half scale CFRT column-to-wide flange beam interior and exterior connections were tested under cyclic loading, as illustrated in Figure 9 for the connection configurations. These specimens utilized high strength material, i.e., up to an unconfined compression strength of 110 MPa for concrete and up to a tensile strength of 809 MPa for structural steel, in order to expand the application of the CFRT column system to the field of high performance materials. The test results showed that the elastic stiffness of CFRT connections matches the theoretical value given in the current AIJ design formula regardless of the material strength and the ductility of CFRT connections using high strength materials was sufficient.

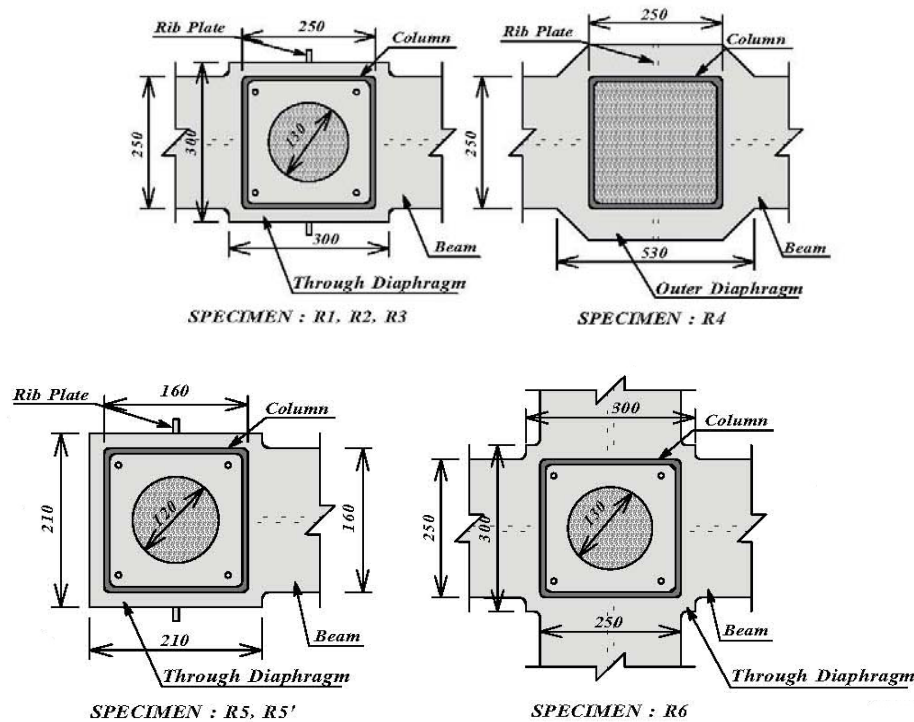


Figure 9. Details of Specimens

Ricles, et al [27] carried out the full-scale experiments to learn the inelastic cyclic behavior of connections in square CFT column-WF beam MRF systems, supported by the U.S.-Japan Cooperative Research Program on Composite and Hybrid Structures. The tested connections details, including interior diaphragms, exterior extended structural tees and split tees, were shown in Figure 10. The test results indicated that welded connection with interior or exterior structural tee diaphragms and bolted split-tees have exceptional cyclic strength, stiffness, and ductility. The best performance was obtained in both welded and bolted connections when the details minimized the possibility of strain concentrations developing in the connection area, whereby beam flange fracture was inhibited.

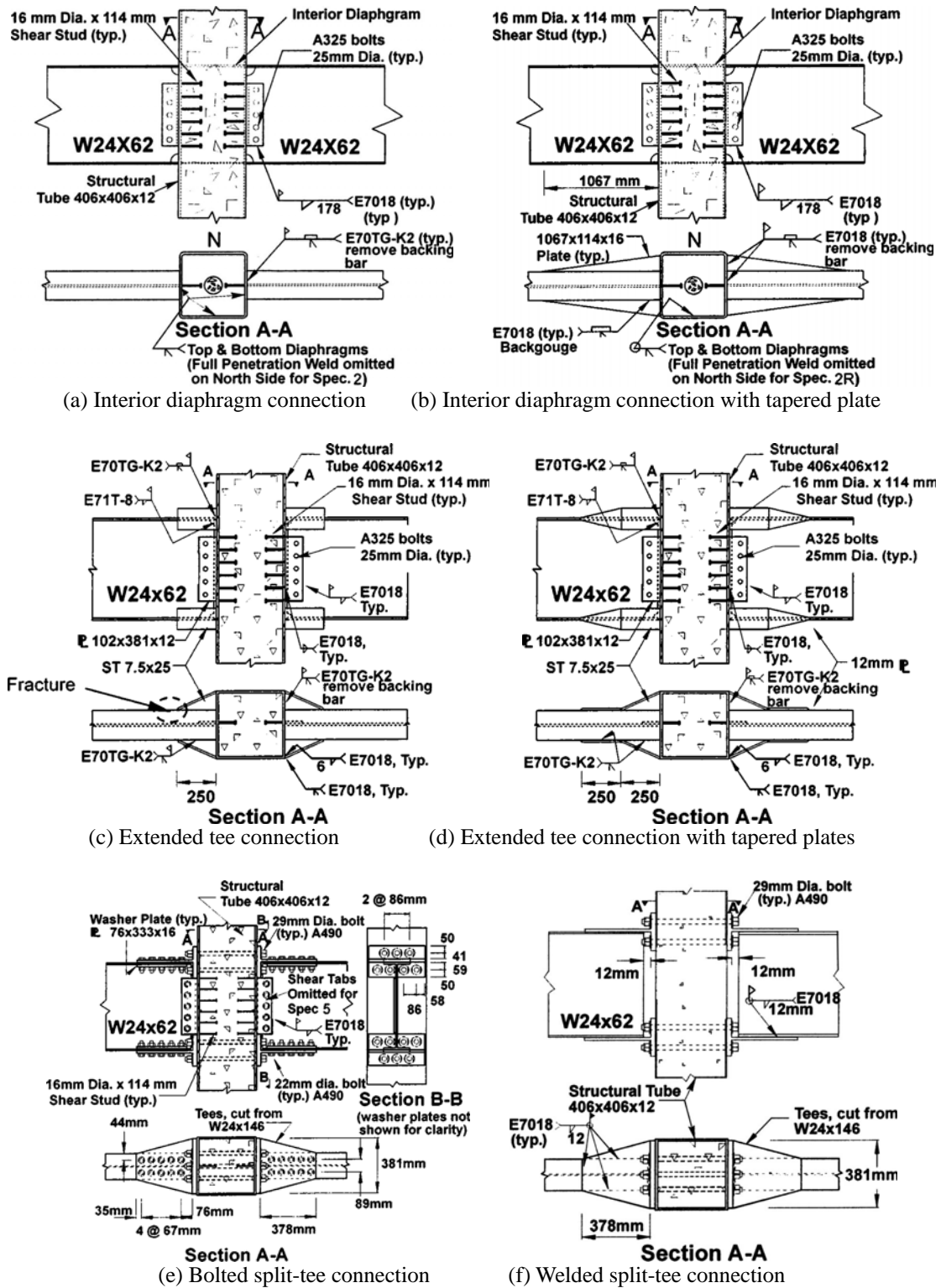
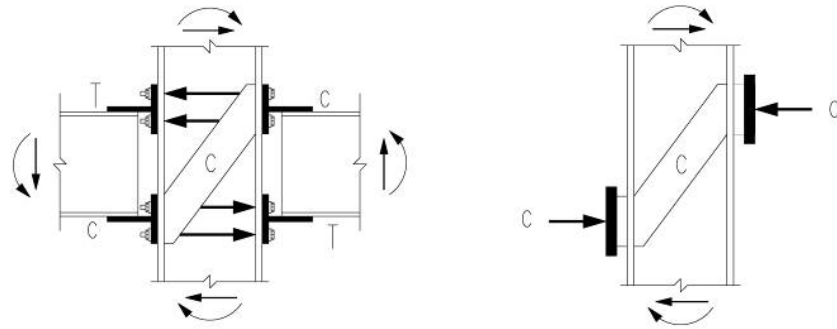


Figure 10. Connection details by Ricles

Koester, et al. [19] took the investigation with the purpose of identifying the force transfer mechanism and failure modes associated with the split-tee through-bolted moment connection detail investigated by Ricles et al. Fifteen CFT moment connections, idealizing the panel zone of the split-tee through-bolted connection by simulating tee forces against the joint, were designed and tested, as shown in Figure 11. Failure was observed to include a combination of panel zone shear distress and localized bearing failure at the location of the reaction blocks against the steel tube surface. New model and equation were developed for panel zone shear calculation.



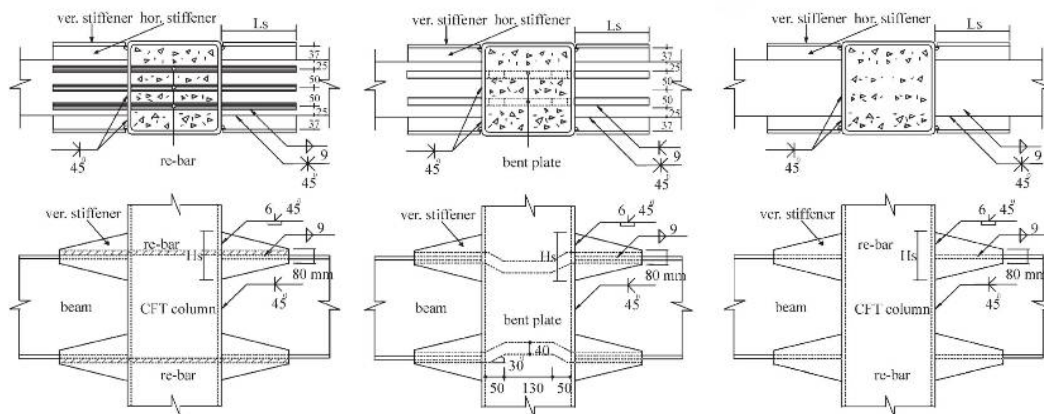


(a) Actual panel zone (b) Panel zone modelled in Test Setup  
Figure 11. Idealization of Connection Zone by Koester et al.

#### 4. THIRD PHASE-NEW STUDIES TO DEVELOP CONNECTION ALTERNATIVES

Research on the CFRT column connection intensified in the third phase in the 2000's when researchers focused on developing various connection configurations. Since then, comprehensive investigations on the behavior and performance of new types of CFRT column connections under monotonic or cyclic loading have been conducted by a number of researchers.

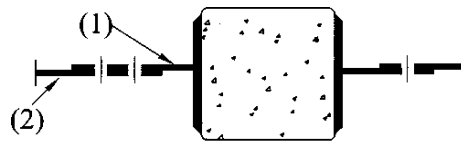
Kang [28] studied the CFT column to H-beam welded connections that were reinforced externally with T-shaped stiffeners at the junction of the column and beam, and with a reinforcing bar or bent plate which penetrated a column. The details were shown in Figure 12. The results of the tests demonstrated that an increased stiffener length was more effective than an increase in the area of penetrated elements for the criteria of both strength and stiffness.



(a) T-stiffener with re-bars (b) T-stiffener with bent plates (c) T-stiffener connection

Figure 12. Test Specimen by Kang

Al-Roda [29] carried out tests on four full-scale composite T-cleat connections, as shown in Figure 13. The T-cleats were welded to the column section using fillet weld along the toe of the T-cleat flange. On the other side, each T-cleat was connected to the beam web by either a single or double row of four grade 8.8, M20 bolts. Two steel beams were unsymmetrically loaded. The test results showed the moment carrying potential of T-cleat connections to concrete-filled tubular columns.



(1) T-Cleat (2) Beam web

Figure 13. Rectangular Section with T-cleat

Shin [30] focused on the experimental and analytical behavior of CFRT column to H-beam welded moment connections with external T-stiffeners. Three types of failure modes, horizontal stiffeners failure, vertical stiffener failure and beam failure, were obtained. The connections reinforced with T-stiffeners having 130% of strength to beam flanges exhibited stable hysteretic behavior and good ductility. The force transfer mechanism was given in Figure 14.

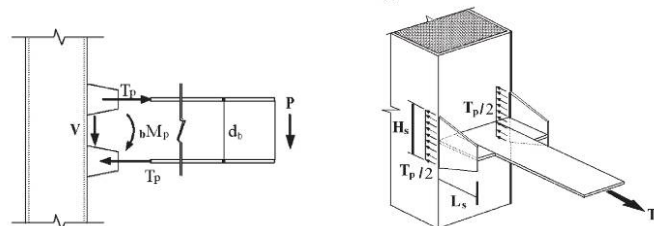


Figure 14. Force Transfer Mechanism of Connection with T-stiffener

Chung, et al. [18] developed the connection proposed by Matsui [18], in order to apply this connection system not only to external joints but also to inner joints, as shown in Figure 15. It was found that this connection had sufficient capacities exceeding the full plastic strength of beam and it had possibility as a new connection method for steel moment-frames.

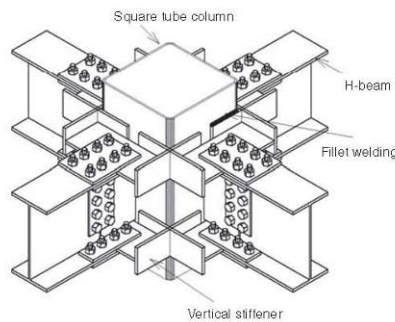


Figure 15 Beam-to-column connection with vertical stiffeners

Fukumoto [31] conducted tests on the panel zone within steel beam to CFRT column moment connections made from high-strength material to investigate their elastoplastic behavior. A nonlinear shear force-deformation model for predicting the elastoplastic behavior of the panel zones was proposed. A method for evaluating load resistance was also proposed, in which a new theoretical compression strut mechanism is utilized, taking into account the confinement of the tube flange.

Wu, et al. [32] proposed a new design of bolted beam-to-column connections for CFRT as shown in Figure 16. A mechanical model was established in order to derive theoretical equations for calculation the stiffness, the yielding shear strength and the ultimate shear strength of the panel zone. And the test results demonstrated that the bolted connections had superior seismic resistance in stiffness, strength, ductility and energy dissipation mechanisms.

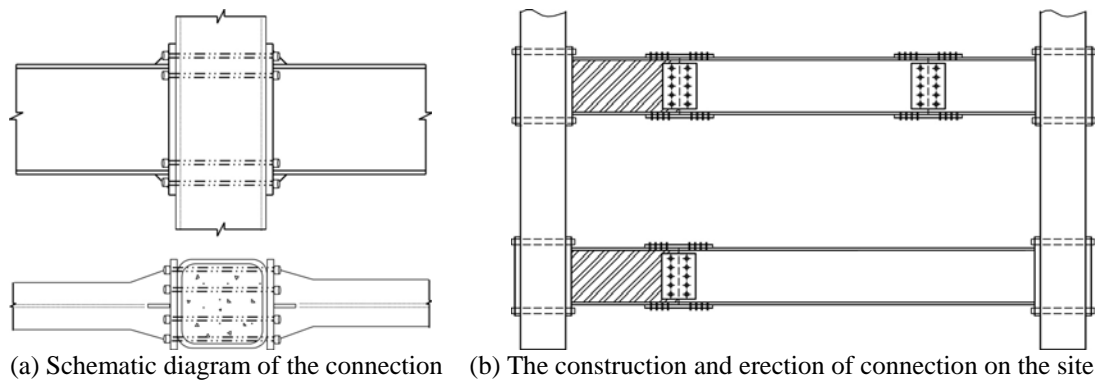


Figure 16. The Proposed Bolted Connection by Wu

Park, et al. [33] described the force transfer mechanism and the cyclic performance of wide flange beams to square concrete-filled tube column joints reinforced with stiffening plates around the column. The force transfer mechanism at the joint was assessed using an analytical yield line method. The test results showed that the derived nominal strength equation provided a reasonable prediction and total rotation of 0.04 rad which was required for special moment resisting frames could be obtained.

Choi [34] focused on a moment-rotation relationship for CFT frames composed of beam-column connections of exterior diaphragm with four rectangular plates. A function formula of the moment-rotation curve for the connection was established, using a three-parameter power model and a least-mean-square technique. The initial rotational stiffness of beam-to-column connection was determined by slope from zero to the analytical results.

Huang [35] studied the nonlinear FEM models of outer diaphragm connection between concrete-filled square tubular columns and steel beams involving geometric large deformation and material nonlinear. Joint behaviors and stress distribution were analyzed under the monotonic load. The results indicated that some of the end moments of beams were transformed to the column tube web and the core concrete at the panel zone by the outer diaphragm connected to the column web. Others were directly transformed to the column tube flange and the core concrete by the diaphragm near the column corner. Serious stress concentration occurred in diaphragm near the column corner. The specimen was failed because compressed flanges were buckled and the plastic hinges were formed at narrowest section.

Wu [36] proposed bidirectional bolted beam-to-column connections for CFRTs. A mechanical model was established to derive theoretical equations for calculating the stiffness, the yielding shear strength and ultimate shear strength of the panel zone, and it was verified by a series of cyclic loading experiments. The experimental results demonstrated that the bidirectional bolted connections had superior earthquake resistance in stiffness, strength, ductility and energy dissipation mechanism.

Cheng [37] investigated the seismic performance of four steel beams to CFRT column connections with floor slabs, including two interior and two exterior joints. The seismic behavior of new connection details such as the taper flange or larger shear tab in the beam-end was investigated to prevent complete joint penetration welds (CJP) of the girder flanges from the unexpected brittle failure found in the latter after the Northridge earthquake. The slab effect on the shear transfer in the panel zone might be neglected.

Park, et al. [38] proposed a new detail of partially restrained composite connection (PR-CC) which could be applied to concrete-filled tubular structures incorporating the effect of composite slabs and the performance for construction work. A welded bottom beam flange connection (WP) was proposed to enhance the capacity of the bottom of the connection and to improve ductility and fabrication. In addition, a reduced beam section (RBS) was adopted for the bottom beam flange to examine its effect on ductility. A seat-angle connection with penetrating bolts was also suggested and compared with the welded bottom beam flange connection. The detail was shown in Figs. 17 and 18. Both monotonic and cyclic loading tests were conducted on the five full scale specimens to compare and evaluate their ductility characteristics.

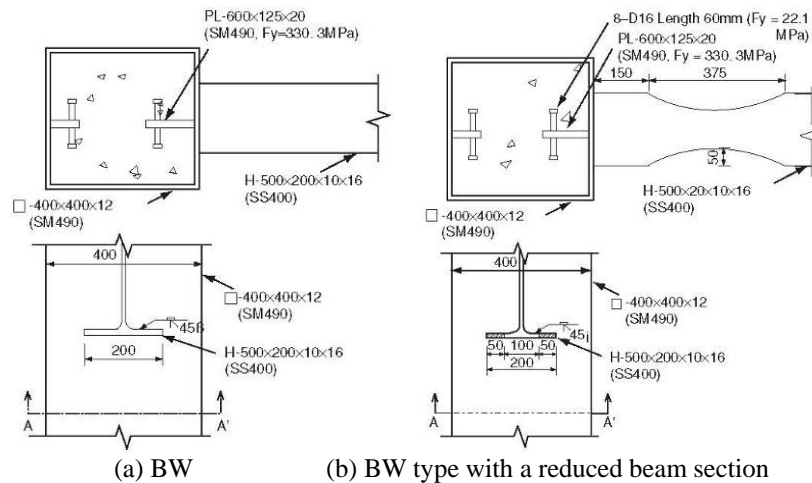


Figure 17. Proposed Bottom Connection Details

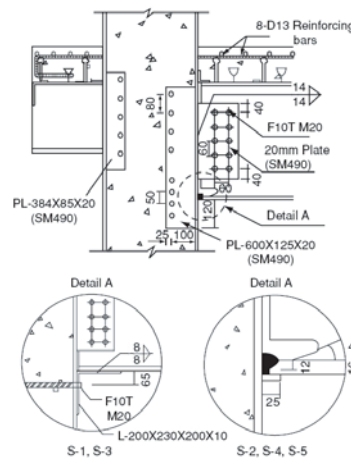


Figure 18. Proposed Connection Details

Shin [39] studied connections reinforced with T-shaped stiffeners attached to the beam flanges. The specimens were divided into three series: TS series specimens reinforced with T-shaped stiffeners only, TSD series specimens with RBS beams in addition to the stiffeners, and TSH series specimens with small holes in the stiffeners. All the specimens developed plastic rotations in excess of 3% rad, suggesting that the ductility capacity of the specimens exceeds the requirements for special moment frame connections in the AISC seismic provisions. The tapered horizontal stiffener elements, RBS cutouts and the horizontal stiffener holes were effective in reducing the stress concentration at the tip of the horizontal element. However, some of the specimens failed by a premature fracture in the HAZ of vertical element welds, suggesting that strain hardening should be considered for the design of T-stiffeners.

Choi [40] proposed a new CFRT column-to-beam connection with combined-cross diaphragm (Figure 19), featuring a column flange penetration in the major-axis direction and an interior diaphragm in the minor-axis direction. Simple tension tests were performed in order to evaluate the initial stiffness and strength of the connections. The test results demonstrated that the new connection was not inferior to the traditional one in terms of initial stiffness and ultimate strength. Additionally, stress concentration on the connection could be alleviated by improvement to the detail.

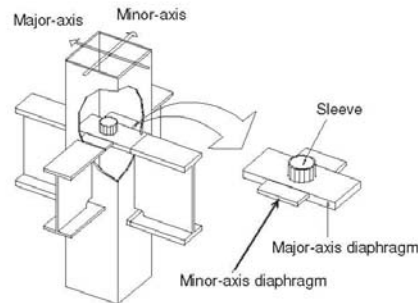


Figure 19. Connections with Combined-cross diaphragm

Nie [41] did research on the flexural capacity of connections composed of concrete-filled square steel tubular columns and steel concrete composite beams with interior diaphragms or anchored studs. Analytical models were proposed to take into account the effects of axial load, concrete slab, middle interior diaphragm, beam and column width condition, and punching shear failure mode. Formulae in different conditions were established based on these models.

Wang [42-43] carried out tests for bolted moment joints connecting CFT column to H-shaped steel beam using high-strength blind bolts, as shown in Figure 19. The cruciform specimens were under monotonic or cyclic loading to investigate the static or seismic performance, stiffness degradation, energy dissipation and failure modes of the blind bolted connection. The test parameters varied were the column section type and the thickness of the end plate. The results showed that the proposed connection displayed not only reasonable strength and stiffness, but also excellent hysteretic behavior in terms of their moment-rotation response, strain distributions and energy dissipation. It was a reliable and effective solution for moment-resisting composite frame structures.

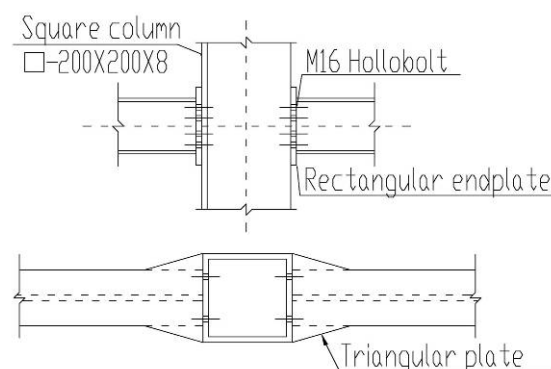


Figure 19. Square CFST Connections

Choi [44] studied the development of the through type concrete filled square steel tube column to beam connection, reinforced with an asymmetric lower diaphragm, which could be used in weak-earthquake regions such as Korea. The proposed connection was shown in Figure 20. Simple tension tests and cyclic loading tests were taken out. The horizontal T-bar and stud bolts in the vertical plates were designed to transmit the tensile stress from the bottom flange of the beam to the

filled concrete. All the test specimens satisfied the 0.01 radian inelastic rotation capacity requirements for the composite ordinary moment frame (C-OMF) of the AISC seismic provisions.

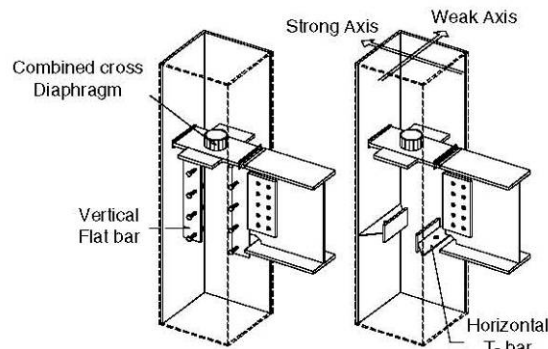


Figure 20. Supposed Connection Detail

Jones [45-46] presented simple hand calculation methods for fin-plate to rectangular column connections under tensile loading or bending and shear loading based upon defining a rigid plate deformation pattern for the column face and then applying the virtual work principle. The simple hand calculation method was compared favorably with a large range of finite element simulations. The proposed method could be used in the component based method for joints involving a fin-plate component in tension or in shear and bending.

Park [47] improved the detail for a CFT square column-to-beam partially restrained composite connection (PR-CC). The bottom beam flange was welded to the column tube to prevent brittle fracture at the bottom of the beam flange, as shown in Figure 21. This type was evaluated to exhibit equal or more ductility than the existing type.

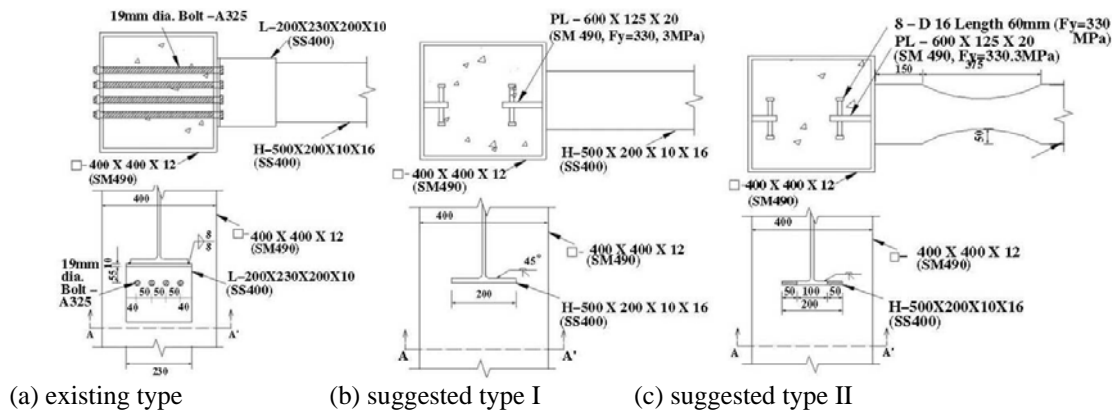


Figure 21. Bottom Connection Details of Specimens

Zhao [48] proposed a computationally efficient macromodeling scheme to simulate the nonlinear behavior of composite structural connections consisting of steel-concrete composite beams and concrete-filled steel tubular (CFST) columns. The model adopted fiber-based stress-strain relations that enabled the consideration of strength and ductility for confined concrete and local buckling of the steel tube. The flexibility of the composite-beam-to-CFST-column connection was modeled as a panel zone. Compared with both overall response and local actions with those obtained from test results, the computational efficiency of such an approach made it a viable methodology for application in the nonlinear analysis of complete composite building systems composed of steel-concrete beams and composite columns.

Hu [49] studied the performance of composite-moment frames with smart partially restrained (PR) CFT column connections. The innovative PR connections utilized the recentering properties of super-elastic SMA tension bars and the energy dissipation capacity of low-carbon steel tension bars, as figured out in Figure 22. Simplified user joint elements based on the mechanical modeling approach were formulated in an effort to simulate the realistic behavior of bolted connections. The performance of the proposed frame was compared with the conventional welded frame in terms of time history response, residual roof drifts and inter-story drift ratios. It was observed that frames with the PR composite connections showed superior performance.

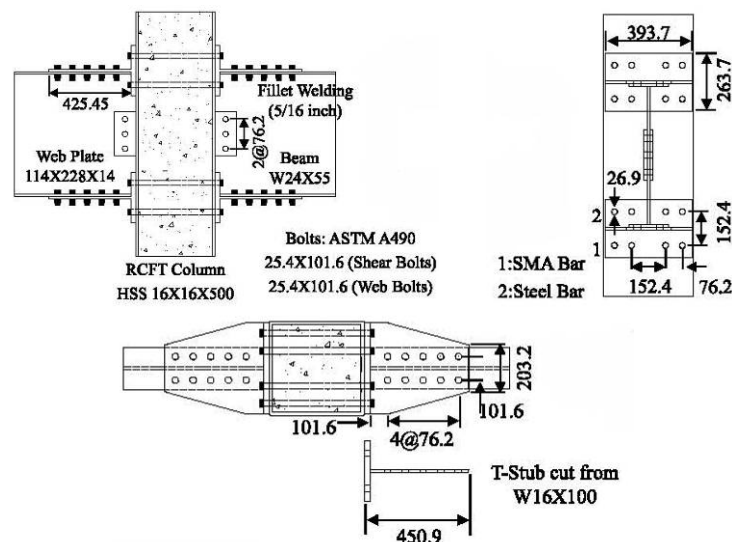


Figure 22. Smart PR-CFT Connection Model (T-Stub Connection Detail)

Mirza [50] investigated the performance of beam-column flush end-plate connections when using blind bolts. The strength on medium rise buildings in regions of medium to high seismicity was studied. It was found that the maximum strength capacity, as well as ultimate displacement ductility, was satisfactory and it was unsafe to estimate the actual strength capacity using code provisions when large hysteretic displacements governed the structural response. Moreover, adequacy of standardizing increased earthquake return periods within structural design connections was investigated.

Tizani [51] presented a blind-bolted connection to concrete-filled square hollow sections using a modified blind-bolt that addressed the issue of flexibility of the blind-bolt connector as well as that of the tube face. An experimental program was conducted to measure the resulting connection stiffness with varied connection endplate type, column thickness and concrete strength. It concluded that the connection was able to develop the required stiffness for it to be used as a rigid connection in braced frames.

## 5. SUMMARY AND CONCLUSIONS

CFRT column composite frame systems with steel beams have been widely used in moment-resisting frame systems for engineering practice. This paper has presented a brief summary of connection details that have been developed from the viewpoints of structural performance, economy and productivity.

Based on the previous research, it can be seen that considerable amount of work has been done to optimize the connection details. However, it is far from satisfactory. Both theoretical analysis and experimental data need to be expanded on the seismic behavior of these types of connections. The future developments could be as follows:

- (1) It is necessary to develop the most suitable model of the load-deformation relationship for predicting the yielding and ultimate flexural and shear strength of connections to CFRT columns.
- (2) The configuration and behavior of fully-bolted connection should be investigated. Fully -welded open beam-to-CFRT column connections have been widely studied by many researchers. However, the cost and inspection implications associated with on-site welding, and their critical performance under cyclic loading remains as potential problems for this type of connections. In contrast, bolted connections can provide similar or even more favorable behavior than their fully-welded counterparts under various loading conditions.
- (3) The viability of connections between CFRT columns and HSS beams should be explored. HSS beams are beneficial because of their reduction in surface area and decrease in lateral bracing requirements compared with open sections. Furthermore, connections with HSS beams can be a challenge. The complex, unusual configuration of connections can pose geometrical and access difficulty for fabricators and workers, and reinforcement such as horizontal stiffeners may not be feasible to include on closed sections.

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