Concerning flat slab to column connection

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Abstract

A brief review of flat slabs and the flat slab-column connection concentrating on parameters influencing connection behavior including punching shear, shear and flexural reinforcement, connection ductility and so on is presented below.

0.1 Punching shear

Early foundations for punching shear design was laid in Talbot (1913) though through examination was not carried out until much later (Elstner and Hognestad, 1956; Moe, 1961) without moment application that are reviewed in detail by Ghoreishi et al. (2013); Yang et al. (2011); Hamada et al. (2008). On the other hand Kinnunen and Nylander (1960) proposed that flat slab punching strength is related to slab flexural deformations in the column vicinity that was further improved by Shehata and Regan (1989); Broms (1990).

Concrete strength, longitudinal reinforcement ratio and slab thickness have been accounted as main influential factors for punching shear performance of slab column connections(Yitzhaki, 1996; Regan, 1981; Tian et al., 2008; Marzouk and Hussein, 1991) that are considered in punching shear capacity estimation calculations in various national codes(GB 50010, 2010; ACI 318, 2019; BS 8110, 1997; EN 1992-1-2, 2004).

Column connection region behavior in reinforced concrete elements is characterized by flexural crack developments at incipient loading stages (1a and 2c).

Typically with low reinforcement ratios at an ultimate state these cracks may govern connection behavior leading to a potential yield of longitudinal reinforcement (3c) (Hallgren, 1996). If flexural behavior doesn't govern and with reinforcement stresses nigh on bar yield stress, flexural cracks would propagate into shear cracks leading to a failure mode defined as flexural punching(fib, 2001).

In case of high reinforcement ratios the slab behaves stiffer with reinforcements bearing lower stresses and higher stresses concentrated in the inclined concrete compression zone developed near the column (3a)(Hallgren, 1996). Punching shear failure is described as the development of a diagonal crack with variable inclination starting from the

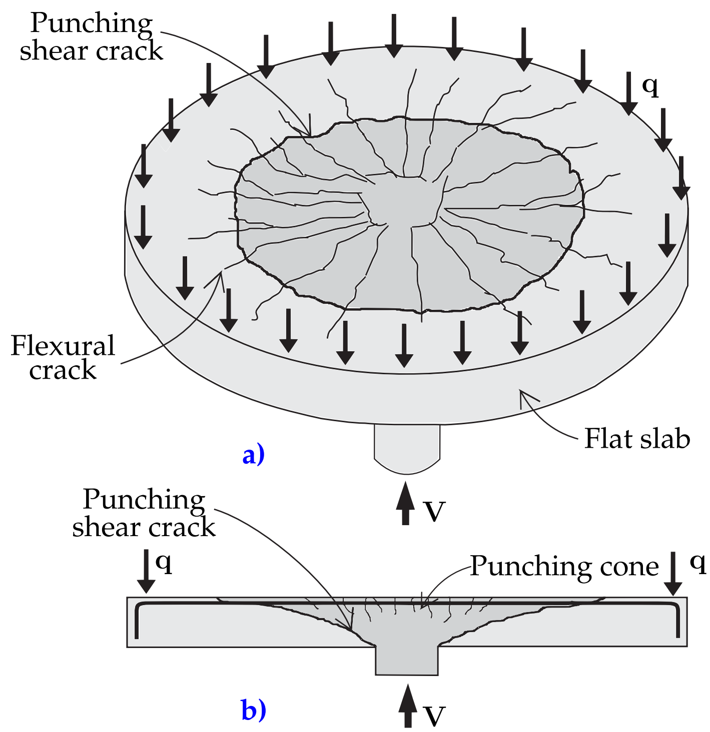

Figure 1: Isolated interior flat slab-column connection region and typical punching shear failure surface, adapted from Bompa and Onet (2015): a) Isometric view; b) Section view.

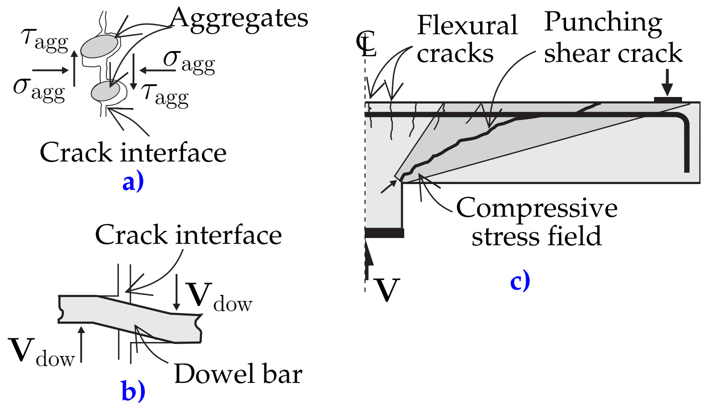

Figure 2: Slab-column connection cracks, adapted from Bompa and Onet (2015): a) Aggregate interlock; b) Dowel action; c) Compression field.

column face on the slab compression side and ending at the slab tension face resulting in the dislocation of a conical body of concrete slab (1) (Regan, 1986).

Typically in concrete members shear is carried by

- the interlock and frictional resistance of the cracked interface aggregates against crack slip and growth(Walraven and Reinhardt, 1981),
- dowel bar shearing(Dei Poli et al., 1987, 1992; Ince et al., 2007; Paulay and Loeber, 1974; Taylor, 1970),
- transmission through the concrete section compression zone(Chana, 1987),
- and residual stress transfer through the crack tip(2 a,b)

Stress distribution in the column-slab connection region governs punching shear crack inclination angle and the slab punching shear strength is governed by the amount of shear carried or resisted by the cracked interface. The inclination angle and punching shear capacity depend on member geometry[1] and structural parameters[2]. As the inclination angle reduces and the cracked interface parallels the slab faces further, the interlocking surface widens, also more bars get involved in dowel action thus larger amounts of shear are transferred.

Zheng et al. (2023) Carried out a thorough nonlinear finite element study verified based on 14 test results out of the literature and simulating 49 slab-column connections evaluating shear span ratio and slab aspect ratio effects.

Tomaszewicz (1993) investigated the punching shear behavior of normal weight and light weight concrete slabs in

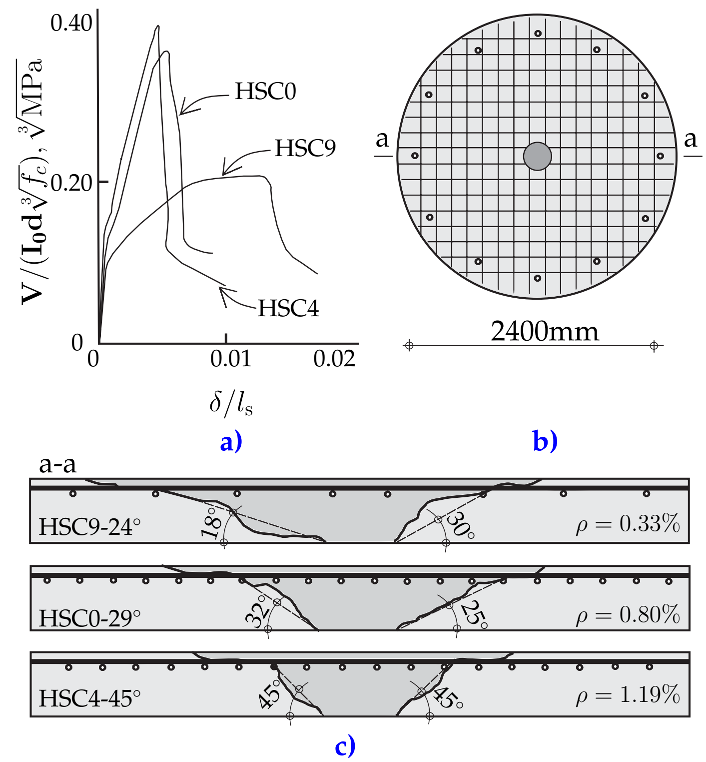

Figure 3: Test results (HSC0, HSC4, HSC9) carried out by Hallgren (1996), adapted from Bompa and Onet (2015): a) Structural response; b) In-plane geometrical configuration; c) Sectional view of saw cuts.

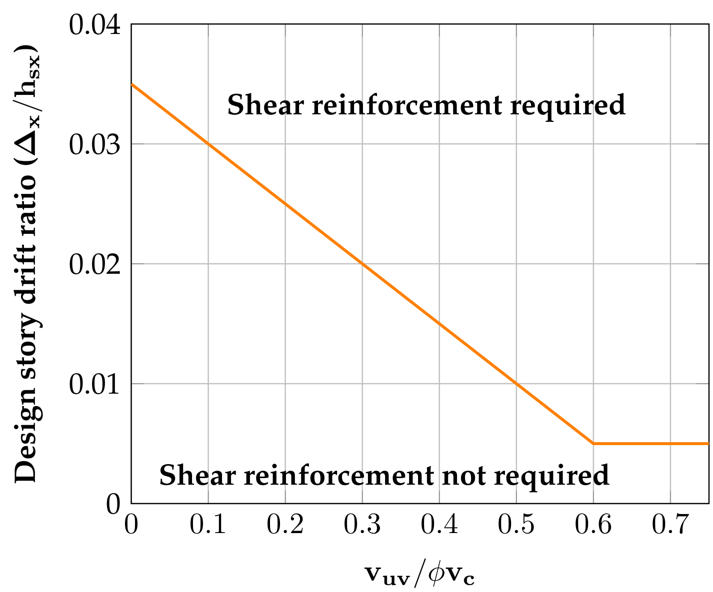

Figure 4: Slab shear reinforcement requirement criteria, recreated from ACI 318 (2019).

[1]Depth, slenderness, column dimensions to slab thickness ratio.

[2]Material strengths, aggregate properties, reinforcement layout and so on.

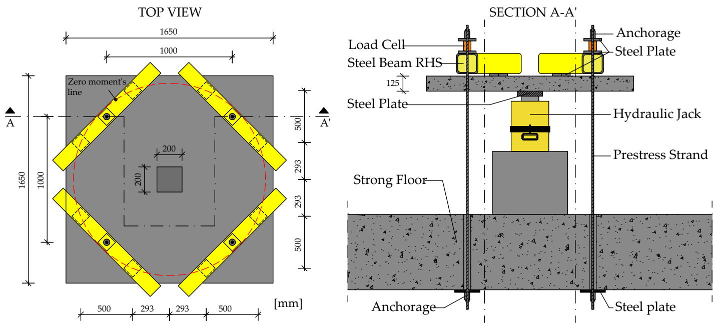

Figure 5: Test setup(Inacio et al., 2015).

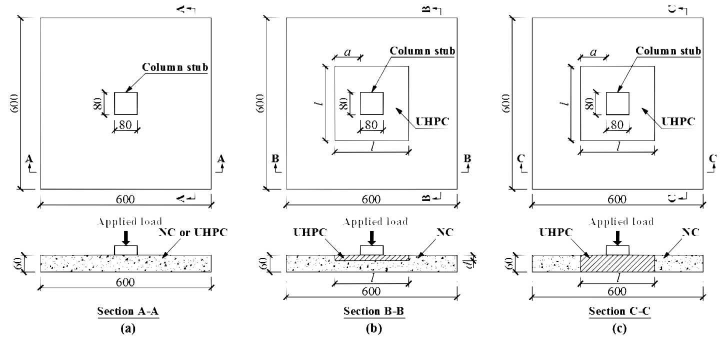

Figure 6: Test setup(Qi et al., 2021).

an experimental study pointing out that simple extentsion of design methods to these cases would lead to an overestimated punching strength. Emam et al. (1997); Marzouk et al. (2001) studied high strength and light weight concrete application in flat slabs. Hallgren (1996); Hallgren and Kinnunen (1996) applied high strength concrete (HSC) to flat slabs and observed a 60% punching strength increase compared to identical normal strength concrete (NSC) slabs. Inacio et al. (2015) carried out an experimental study(5) over HSC flat slabs without shear reinforcement testing four specimens, one of which was built with NSC. Significant load capacity increase compared to the reference NSC specimen was observed and the results furthermore indicated that longitudinal reinforcement increase had a positive influence on punching shear capacity(Inacio et al., 2015). Kadhim et al. (2021) showed punching shear capacity improvement with UHPC use in flat slabs without shear reinforcement through a nonlinear finite element procedure implementing DSS (year) verified against Saleem et al. (2011); Zohrevand et al. (2015).

Qi et al. (2021) carried out concentrated load tests on eight similar flat slab specimens in three groups to study UHPC depth and area influence on flat slab punching shear behavior the application of which at full depth(6) over the critical section area transformed the brittle punching shear failure mode into a ductile punching shear-flexure one while limited depth UHPC application over this area ended in brittle failure.

Ramos et al. (2022) tried high-performance fiber reinforced concrete (HPFRC) application in slab-column connection vicinity as a substitute for shear reinforcement with four specimens under combined gravity and horizontal reversed cyclic loading in which connection drift capacity substantially improved compared to reference specimens and the HPFRC reinforced specimens performed better than specimens with HSC. Ricker et al. (2017) carried out ten punching tests on slab-column connections with double-headed studs as shear reinforcement nine of which had fiber reinforced UHPC units in the slab-column connection compression zone(7) that reached significantly higher failure loads compared to normal specimens. Liu et al. (2023) improved punching shear performance of flat slab-column connections utilizing star-shaped steel plates (SSPs) in addition to engineering cementitious composites (ECC) replacing joint core concrete with five 1/2-scale connection specimens(9). Another concrete behavior improvement approach for slab-column joints has been introduced through the use of steel fiber additives in the concrete mix as studied by Gouveia et al. (2018, 2014); Abdel-Rahman et al. (2018); Ju et al. (2015) that improves a plethora of structural characteristics in addition to punching shear strength including load bearing and flexural capacities along with structural stiffness and connection ductility.

Carbon fiber reinforced polymer (CFRP) sheets were implemented by Harajli and Soudki (2003) in a series of punching shear tests on slab-column connections as an additional reinforcement which led to significant improvements in flexural stiffness and strength along with higher connection shear capacity. CFRP and epoxy were successfully adopted by Robertson and Johnson (2004) for damaged slab-column connection repair within a limited damage state. CFRP sheet efficiency in flat slab-column connection strengthening and rehabilitation/repair subjected to monotonic shear and unbalanced moment was nvestigated by Polies et al. (2010) which despite loss of ductility showed promising restoration of connection ultimate load capacity and stiffness. Esfahani et al. (2009) studied punching shear behavior of slab-column connections strengthened with CFRP sheets with variant width that resulted in way too conservative values based on ACI 318 (2014) suggestions. Punching shear behavior of CFRP grid reinforced concrete slabs was investigated by Huang et al. (2020) while Abdullah et al. (2013); Saleh et al. (2019); Akhundzada et al. (2019) investigated punching shear behavior of flat slab-column connection bonded with CFRP laminates. Hamoda and Hossain (2019) carried out a numerical assessment of slab-column connection with extra CFRP bars.

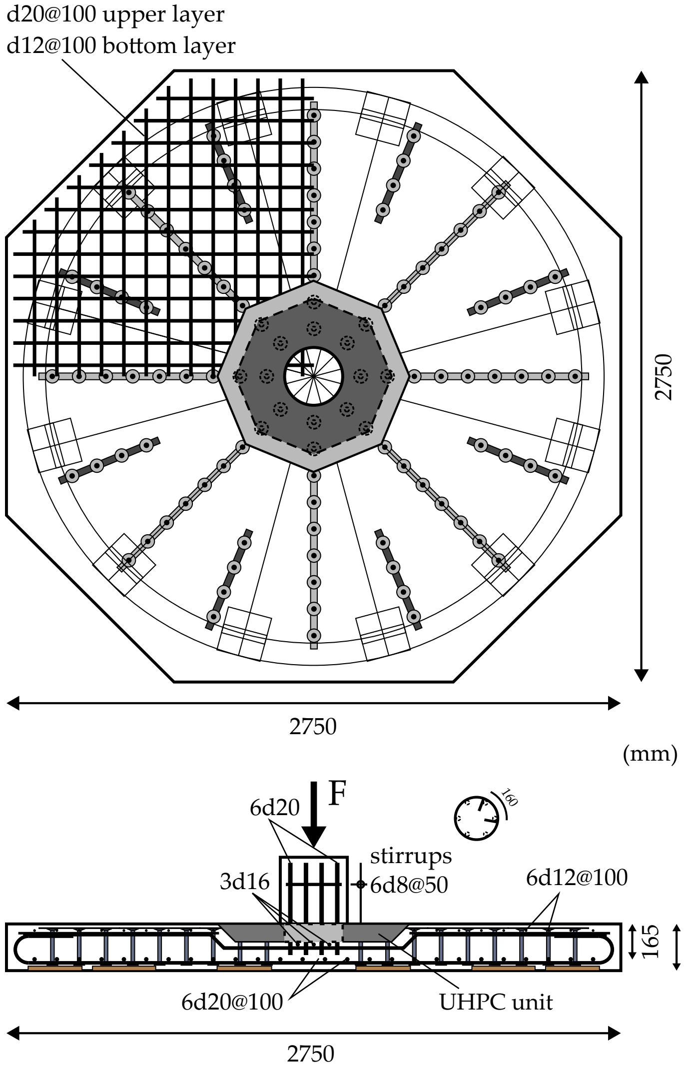

Figure 7: Layout of flexural reinforcement and double-headed studs for test specimen DUHPC2(Ricker et al., 2017).

1 Steel column-flat slab systems

Concrete filled steel tube (CFT) columns have become more prevalent in construction practice during the last couple of decades providing relatively higher strength and ductility(Morino, 1998), reduced labor costs, less formwork, lower reinforcement requirements and ease of concrete pour compared to conventional reinforced concrete columns (Yan, 2011; Wang, 2014).

The main disadvantage though lies in the discontinuity due to the smooth interface between the reinforced concrete slab and the steel or CFT column which is quite troubling when considering punching shear and punching shear resistance improvement alike what is practiced for concrete columns would not be applicable without mechanical means of connecting the steel column to the reinforced concrete flat slab.

This gave rise to research aimed at providing proper connection detail between the slab and CFT column to alleviate shear transfer most of which focused on using shearheads(Satoh and Shimazaki, 2004; Lee et al., 2005, 2008; Yamaguchi et al., 2008; Eder et al., 2010, 2011, 2012; Ju et al., 2013; Kim et al., 2014; Yan and Wang, 2014; Bompa and Elghazouli, 2016; Lee et al., 2019; Li, 2012; Wang and Li, 2013; Yan et al., 2008) in the form of either I, T, rectangular steel tube or channel sections or shear studs welded on the column connection perimeter extending into the slab section(Yu and Wang, 2018), while a combination of these was also reported (Lee et al., 2008).

Satoh and Shimazaki (2004) carried out three series of experimental studies on interior slab-column connections to evaluate lateral, punching shear and torsional behavior for a newly proposed connection(10). Lee et al. (2008) carried out full-scale tests on CFT column to RC flat plate connections subject to gravity loading aimed primarily at bettering connection detail and secondarily proposing a semi-analytical model of punching behavior for the proposed connections(12). Specimens with post-punching bars in Lee et al. (2008) exhibited higher punching shear capacity and stiffness compared to those without that was attributed to better reinforcement of the concrete compression zone by these bars thus delaying concrete crushing while flexular anchoarge and shear key alterations had minor effects on punching shear capacity. In order to evaluate vertical load resistance capacity of a new CFT column-flat plate connection under various loading conditions Yamaguchi et al. (2008) tested three series of specimens fourty-six in total.

In Yan and Wang (2014); Lee et al. (2005, 2008) top and bottom reinforcement were passed through the steel columns via provided holes which improves connection post-punching behavior and load bearing capacity. Following an experimental program Chen et al. (2020) carried out six full-scaled tests of interior slab-column sub-

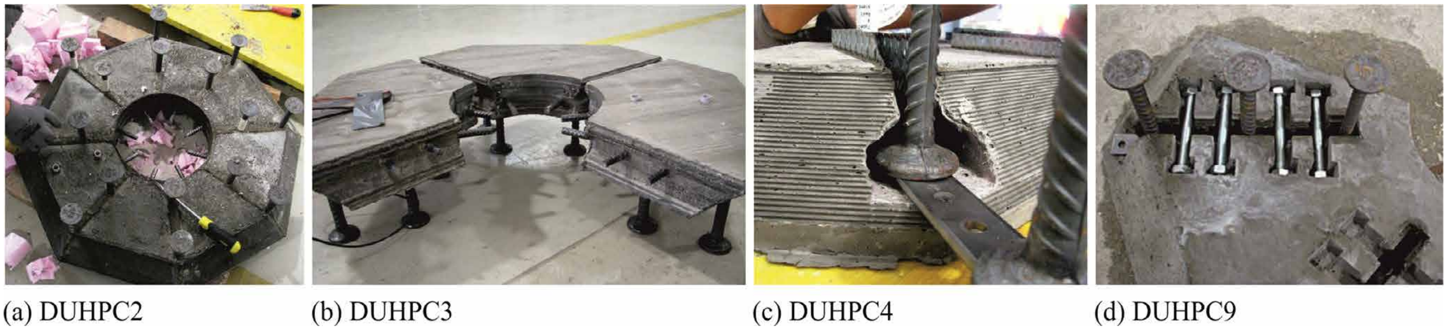

Figure 8: UHPC units(Ricker et al., 2017).

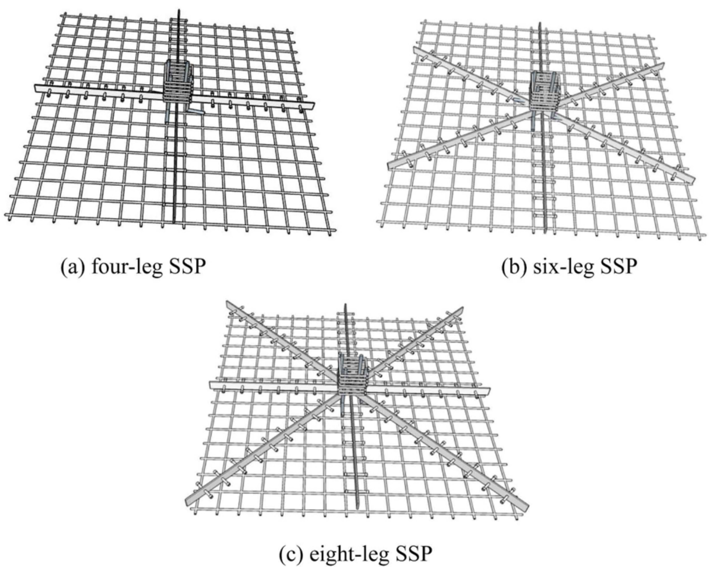

Figure 9: SSP arrangement and configurations(Liu et al., 2023).

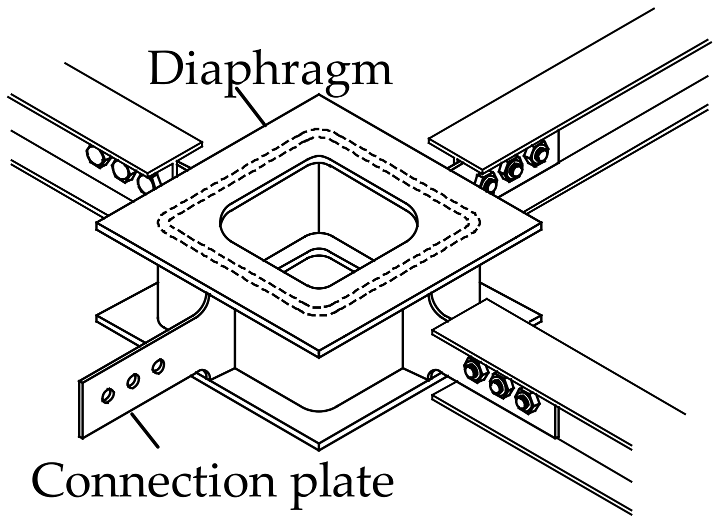

Figure 10: CFT column-flat plate connection studied by Satoh and Shimazaki (2004); Yamaguchi et al. (2008).

assemblages under monotonically increased gravity loading with negligible eccentricity to study differences between reinforced concrete and CFT columns(21) and also shear enhancement around the CFT column(20). Test results showed that composite connections exhibited comparable punching shear strengths and failure modes while shear enhancement around the CFT column effectively shifted the failure plane away from the column faces hence increasing connection punching shear capacity(Chen et al., 2020).

Rafiee et al. (2021) conducted a reversed cyclic loading test on a half-scale post-tensioned (PT) flat slab-steel column specimen to examine the seismic details of their proposed exterior connection(22).

Yu and Wang (2018) focused on developing a steel tubular column-flat slab connection following an experimental and numerical approach using shear studs welded around the column (23) as a simpler and more cost effective option compared to what had been proposed eariler by Lee et al. (2008);

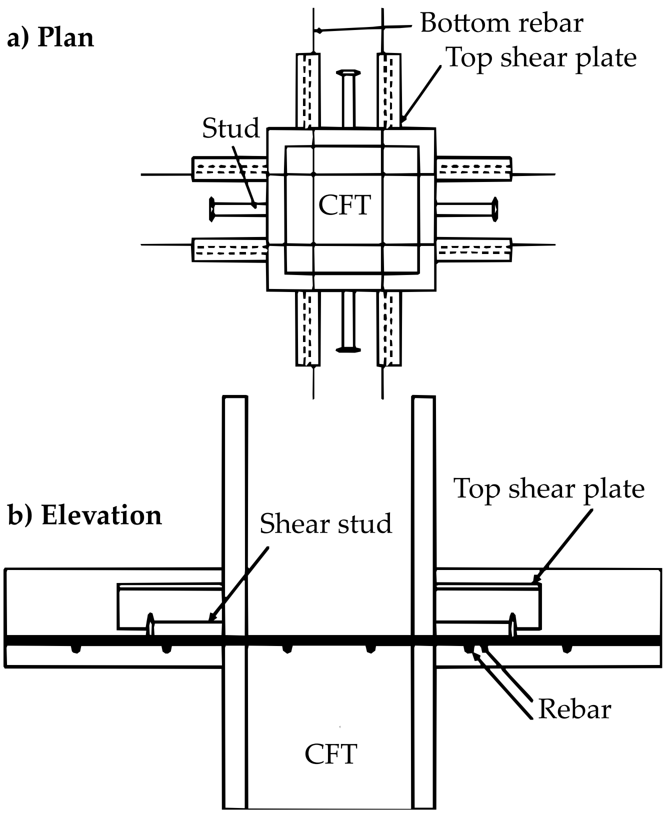

Figure 11: CFT column-flat plate connection proposed by Lee et al. (2005).

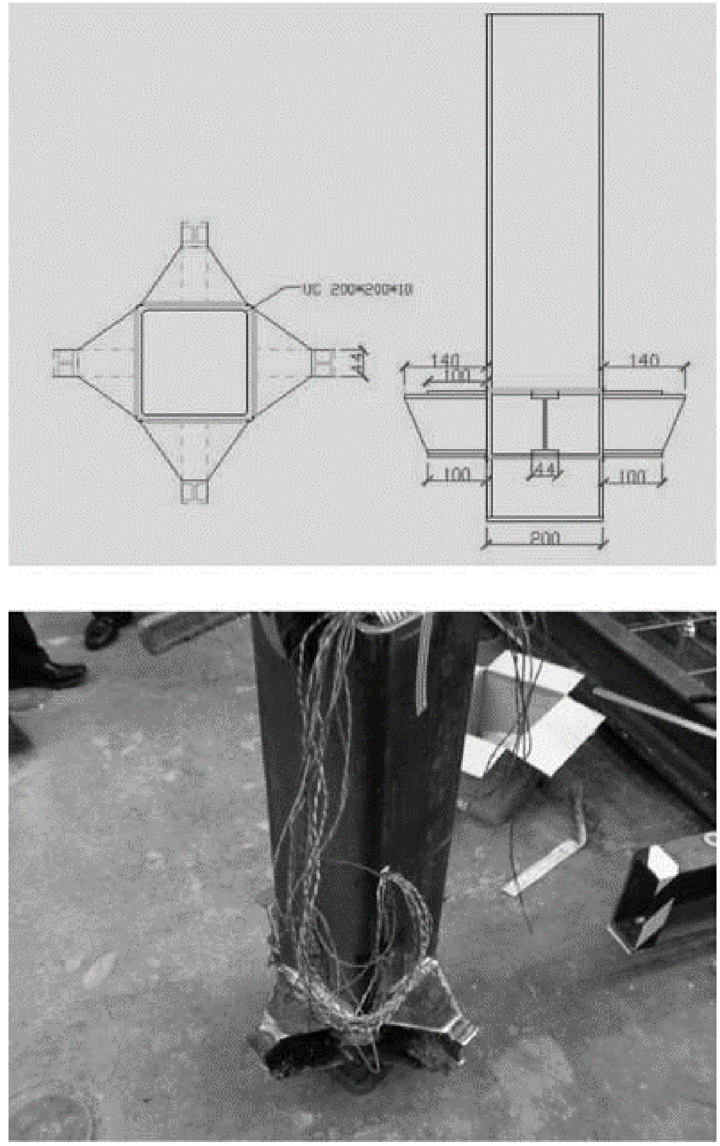

Figure 13: Yan et al. (2008) shearhead specimen.

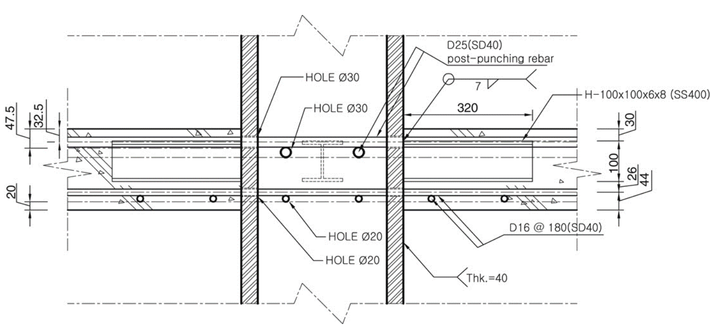

Figure 12: FPP-SH CFT column-flat plate connection specimen(Lee et al., 2008).

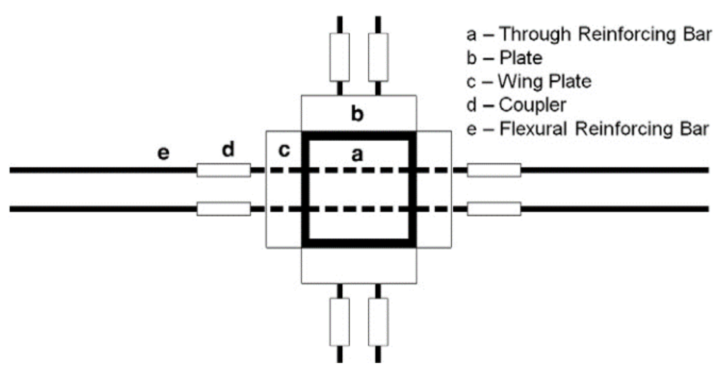

Figure 14: Detail proposed by Ju et al. (2013).

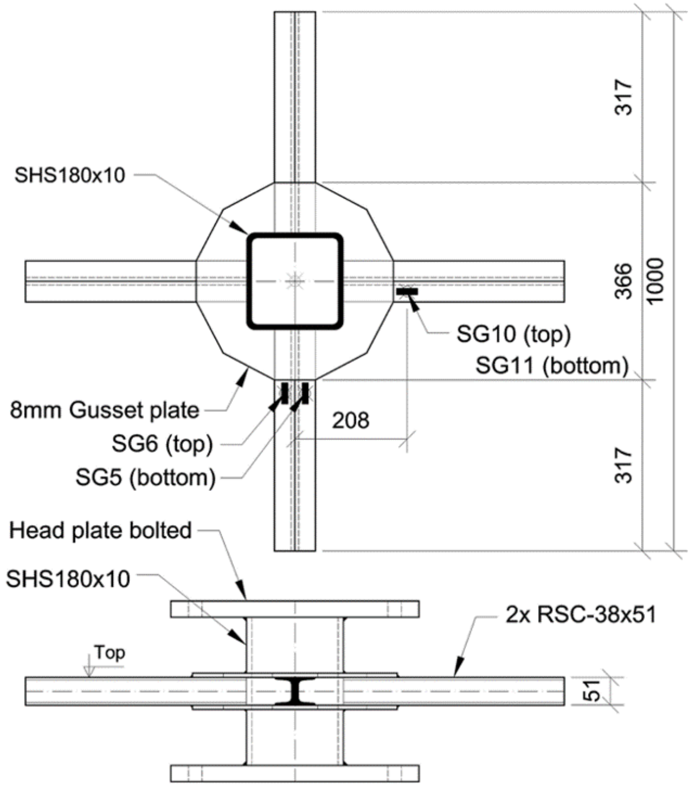

Figure 15: Shearhead detail studied in Eder et al. (2010, 2011).

Yan (2011); Yan and Wang (2014, 2016) shown in 24. Yan and Wang (2016) ran an extensive parametric numerical study investigating punching shear resistance of hybrid steel tubular column to reinforced concrete flat slab connection using shearhead arms in which study parameters included column shape, shearhead arm properties and slab reinforcement. (Yu and Wang, 2020) in a subsequent numerical and analytic investigation proposed an innovative shear connection for flat slab to steel column connections using welded shear studs, steel plates and bent-up bars(25) that evolved out of Yu and Wang (2018). Zhang et al. (2018) proposed a new connection mechanism between prefabricated reinforced concrete flat slab and square steel tube column(26) through an experimental test followed by a complementary numerical simulation. The connection inhibits plastic deformations in the cantilever beams which are replaceable after an earthquake(Zhang et al., 2022). A total of nine simply supported slab-column connection specimens were subjected to vertical load by Zhou et al. (2021) in addition to a finite element study to investigate punching shear behavior of slab-column connections embedded with steel skeletons which changed the mode of failure from punching shear into flexural punching(27). Punching shear performance of edge steel column to flat slab connection via a modified shearhead assembly was investigated by Ngekpe et al. (2019) through experimental

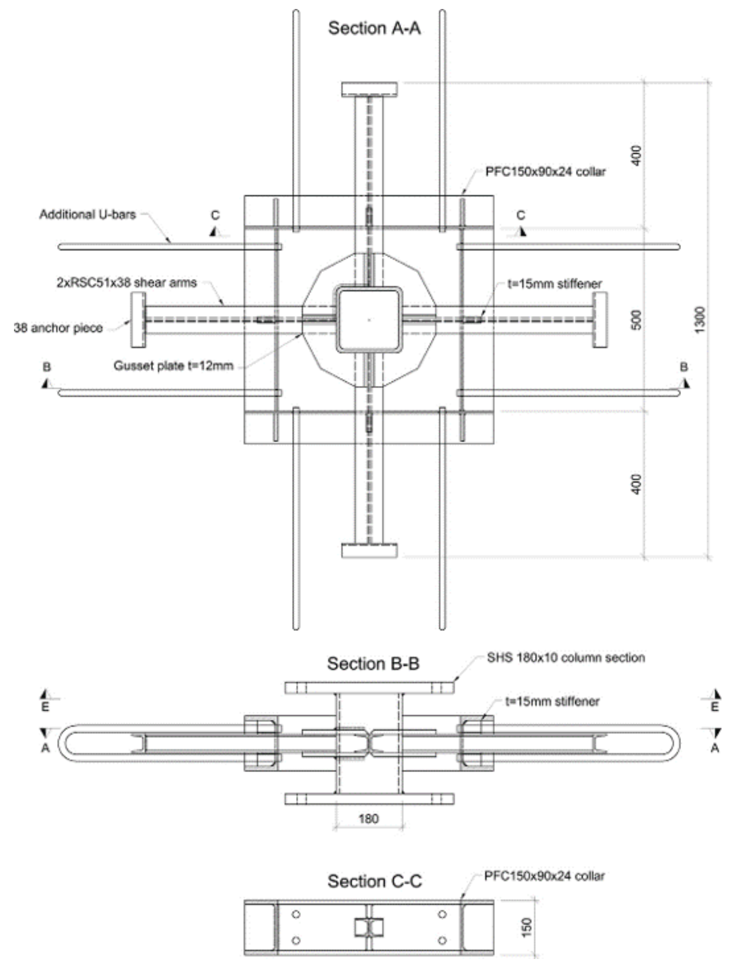

Figure 16: Shearhead detail studied by Eder et al. (2012).

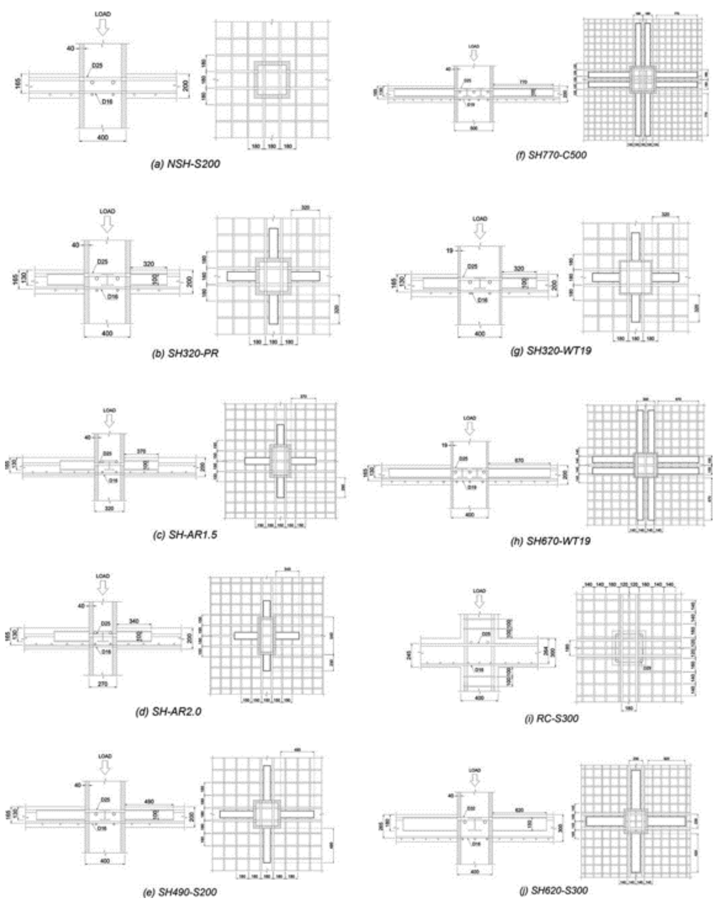

Figure 17: Kim et al. (2014) test specimens details.

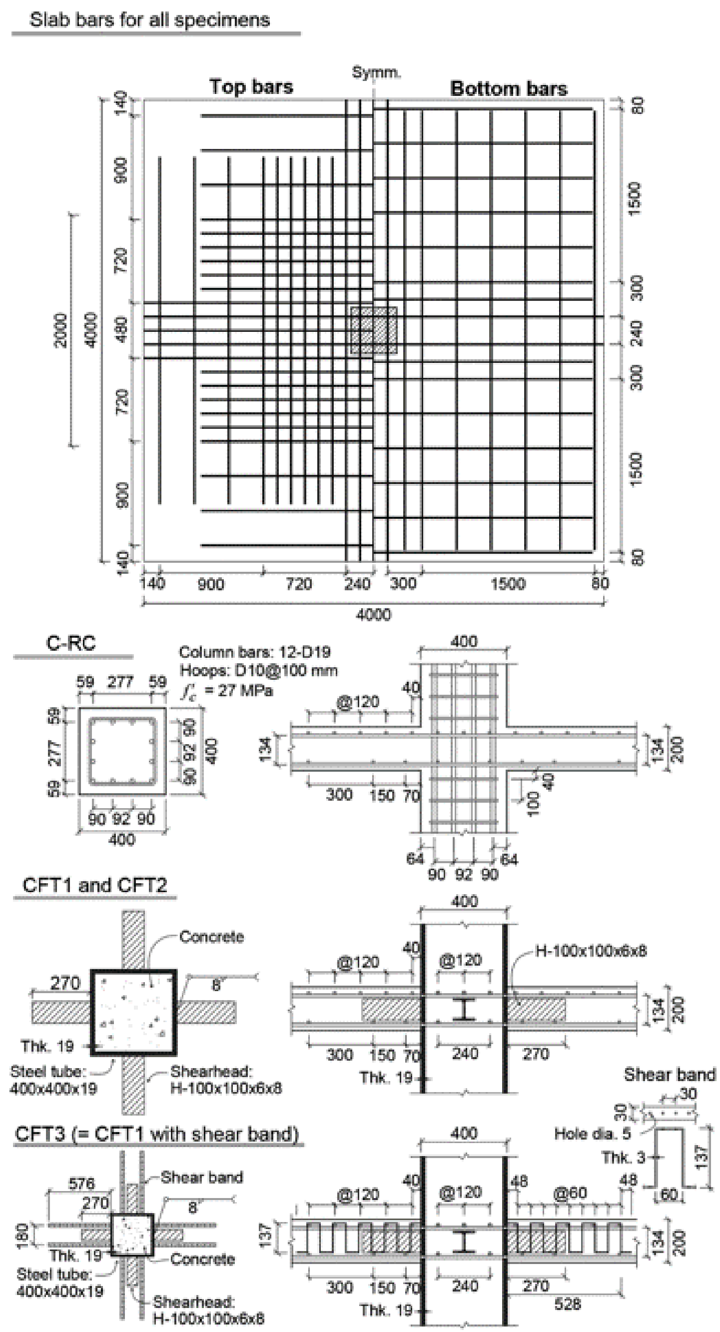

Figure 18: Lee et al. (2019) specimen details.

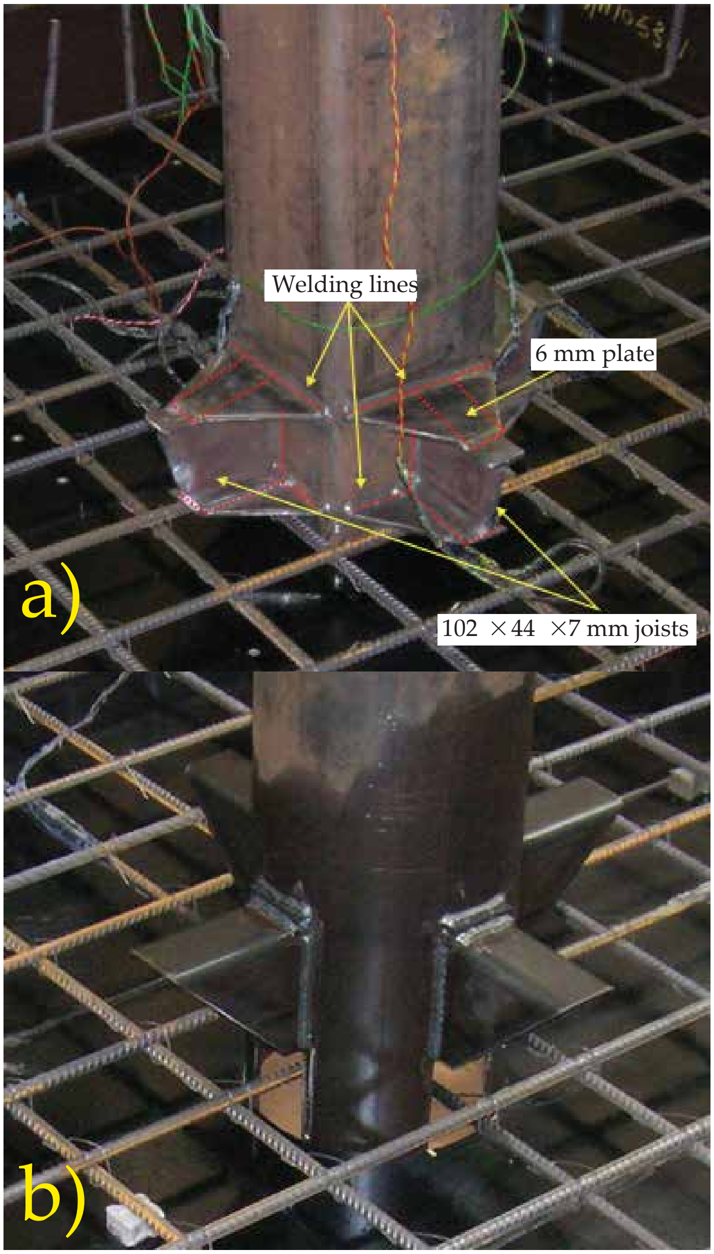

Figure 19: Test specimens in Yan and Wang (2014).

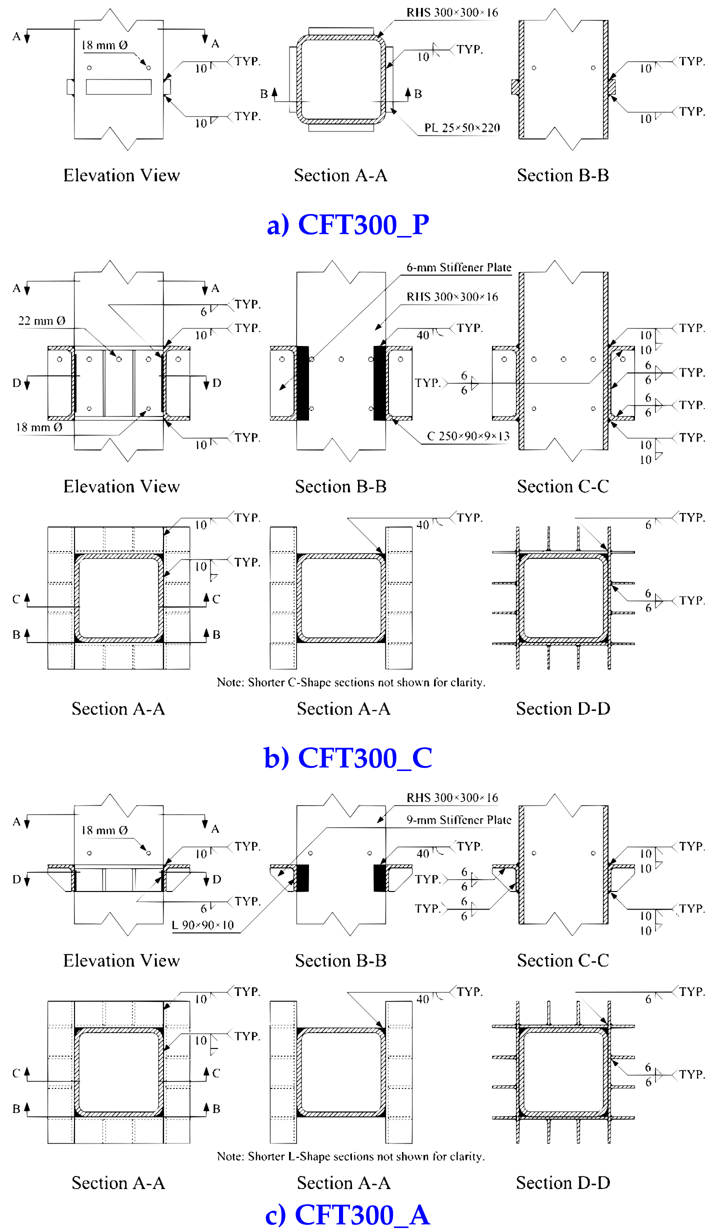

Figure 20: Shear enhancement detail(Chen et al., 2020).

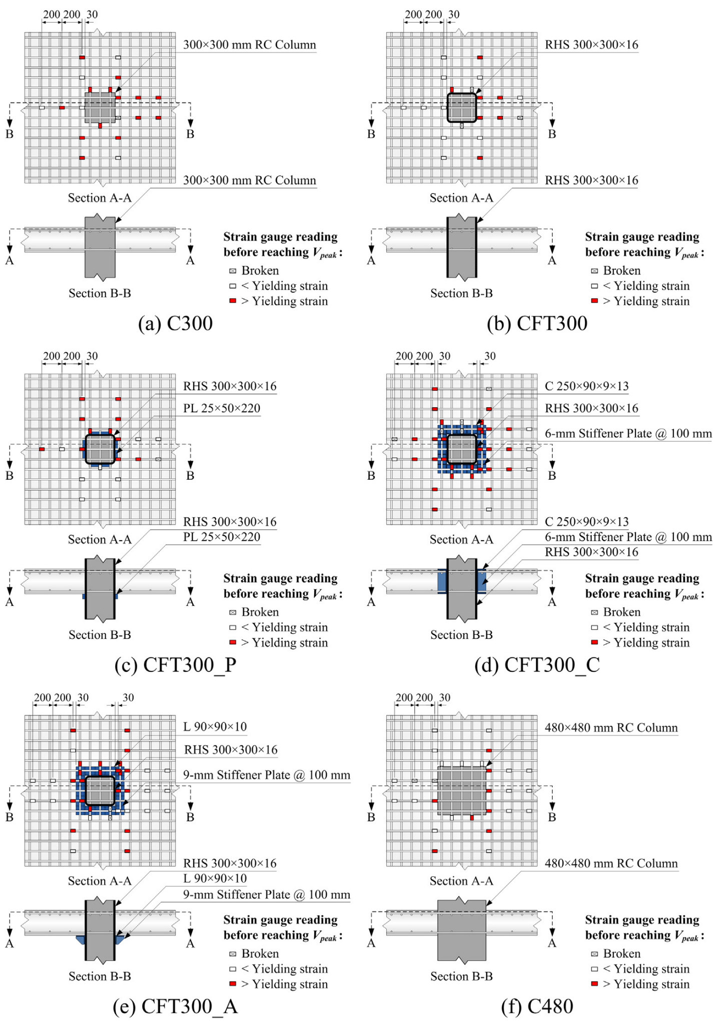

Figure 21: Slab-column connection detail(Chen et al., 2020).

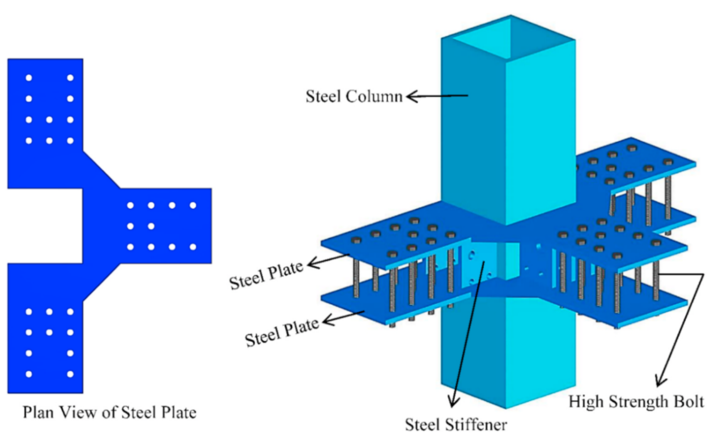

Figure 22: Propose flat slab to steel column connection configuration(Rafiee et al., 2021).

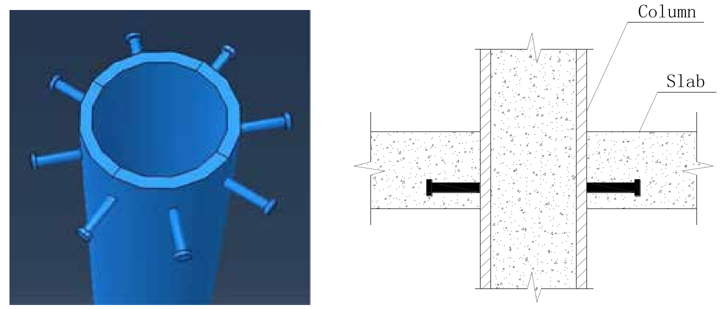

Figure 23: Shearhead configration proposed by Yu and Wang (2018).

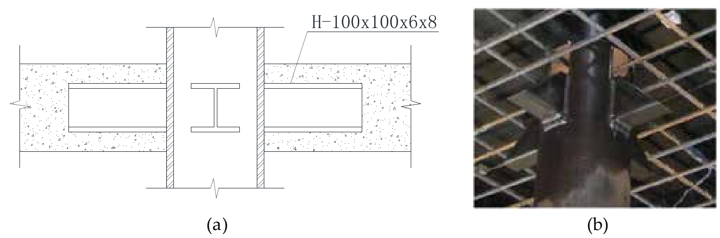

Figure 24: Shearhead configurations; a) Steel I shearhead sections welded on steel tubular column outer surface for reinforced concrete flat plate connection(Lee et al., 2008); b) Shearhead inserted into steel tube column slots(Yan and Wang, 2016).

testing and numerical simulations that ended in punching shear governed by shear regardless of shearhead connection robustness. Zhang et al. (2022) investigated seismic behavior of a prefabricated reinforced concrete flat slab to steel tubular column connection through 'I' shaped cantilevered beams introduced so as to enhance ductility and energy dissipation. Luu et al. (2022) proposed innovative slab to CFT column conections for unbonded post-tensionned concrete slabs through an experimental investigation conducting six large-scale tests(28). Chen et al. (2023) implemented steel plates as batten plates, confined plates and drop plates for a slab-column connection with a spatial steel drop panel in an experimental investigation varying drop plate size, batten plate length and whether drop plates have slits for five specimens under monotonically increasing gravity load to ascertain connection detail effects on the punching shear performance(29).

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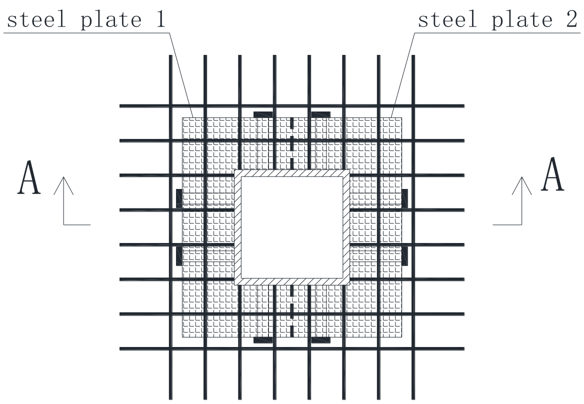
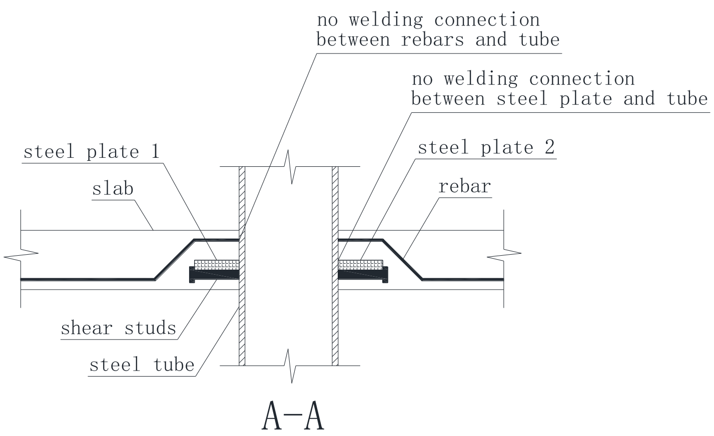


(a) Plan layout around connection



(b) Detailed elevation view

Figure 25: Proposed steel tube to concrete flat slab connection detail(Yu and Wang, 2020).

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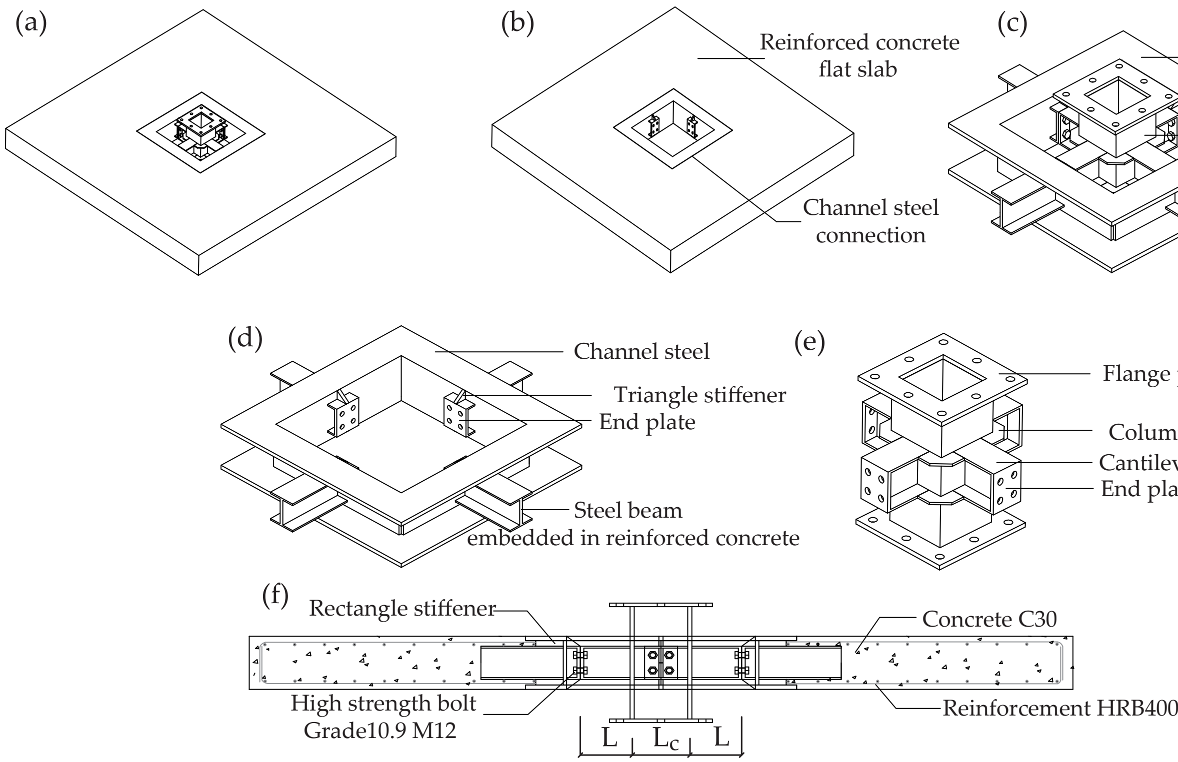

Figure 26: Configuration of prefabricated reinforced concrete flat slab to square steel tube column connection(Zhang et al., 2018): a) Slab-column connection; b) Reinforced concrete flat slab and channel steel section; c) Column base connection; d) Channel steel connection; e) Column base; f) Connection cross-section.

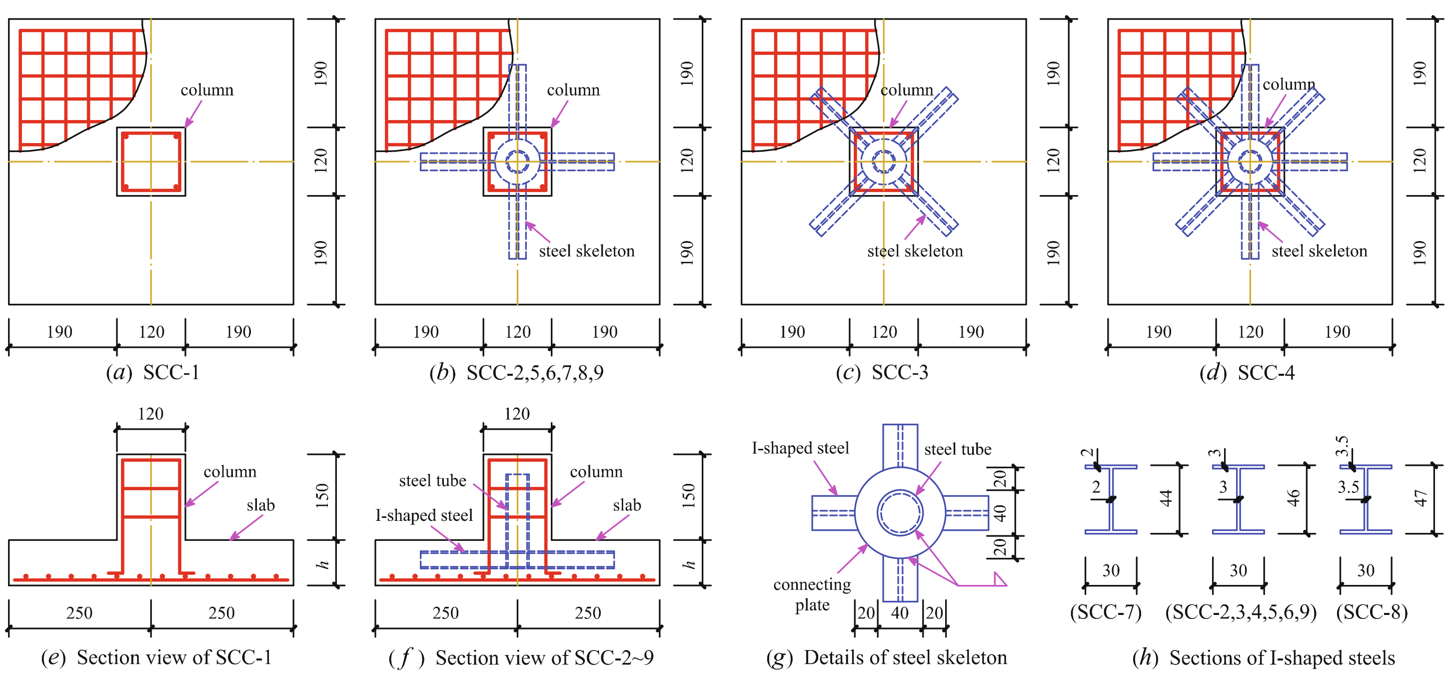

Figure 27: Specimen details(Zhou et al., 2021).

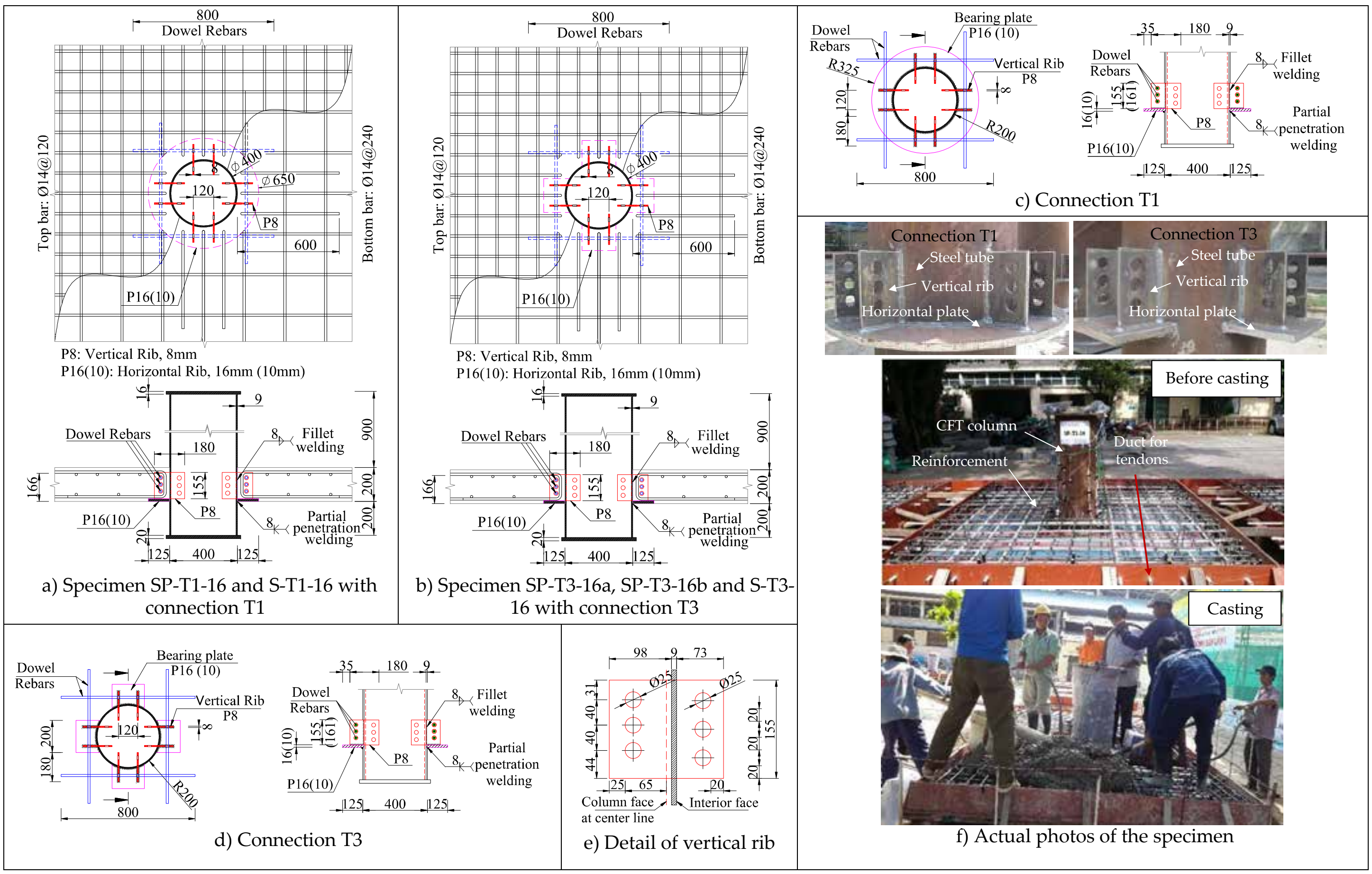

Figure 28: Flat slab-CFT column connection joint designs(Luu et al., 2022).

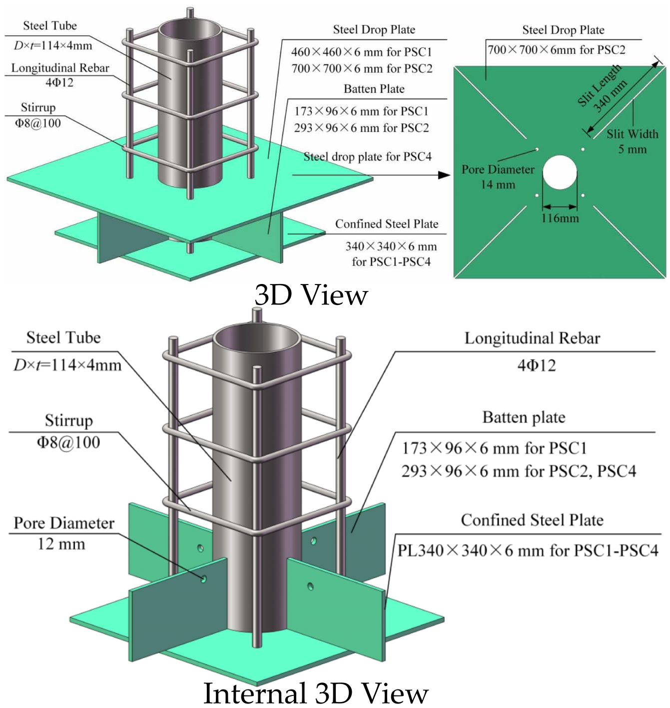

Figure 29: Spatial steel drop panel details for specimens PSC1, PSC2 and PSC4 (Chen et al., 2023).

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