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Form Follows Function - The Composite Construction and Mixed Structures in Modern Tall Buildings

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Abstract

The tall building and super tall building has been a common building type in China, with multiple functions and complex geometry. Composite construction is broadly used in tall building structures and constitutes the mixed structure together with concrete and steel constructions. The mixture of the constructions is purposely designed for specific area based on the analysis results to achieve the best cost-effectiveness. New types of composite construction are conceived of by engineers for columns and walls. Material distribution is more flexible and innovative in the structural level and member level. However the reliability of computer model analysis should be verified carefully. Further researches in the design and build of composite construction are necessary to ensure the success of its application. Composite or Mixture Index is suggested to be used as a performance benchmark.

Keywords: Composite construction, Tall building, Mixed structure, Mega column, Composite wall

1. Definition of Composite Construction

Composite construction is defined here as the construction with structural members with composite sections, in which two materials, (reinforced) concrete and steel section are bound to act together. Steel rebars are generally considered as part of (reinforced) concrete construction. Steel sections are hot-rolled sections or built-up sections with steel plates. The mechanism of the composite action, or the deformation compatibility between two materials, and the corresponding transfer of longitudinal shear force, are maintained through friction or shear connections at the surface where two materials meet. For many years composite construction has been widely applied in many types of structures. Originated from the steel construction, the most popular type of composite construction is the composite floor beam, in which the concrete slab on top of a steel beam is used as part of the beam section to reduce the steel usage.

The discussion below is mainly based on the design and construction practice in the recent tall or super tall buildings in China. Super tall here refers to building of height exceeding 300 m when the demand of lateral stiffness generally dominates the design of the structural system.

Modern tall and super tall buildings are complicated in several aspects. As the total floor area is generally very large, there are often several programs in one building e.g., office, hotel, apartment and retail. These programs have different requirement in the space composition like clear headroom, perimeter-to-core-distance and column grid. Secondly, the sophisticated three-dimensional geometric design software enables architects to apply richer architectural languages in tall buildings like curving, chamfering, edge cutting, twisting, hollowing, bridging, transferring, etc. which creating difficulties in finding the proper load path. It is therefore much more challenging to conceive a proper structural system to accommodate the functional requirement of the building to be built. Some criteria to be considered are listed below:

- The load path to satisfy the demands of gravity load transfer and lateral resistance; the latter mostly dominates for super tall buildings.
- The cost-effectiveness;
- The consistency with architectural form and the maximization of the space flexibility;
- A (reasonably) fast-track construction schedule when tall buildings are built basically in a one-dimensional manner;

Composite construction is obviously the perfect solution to satisfy the above for tall buildings. The steel section, with a continuous distribution of steel material, provides a stable high strength in axial and shear resistance in composite sections. The buckling of steel plates becomes much less important than that in steel construction. If concrete is poured in the steel box or tube, the confinement effect would increase the strength of the concrete. The fire protection is either unnecessary (for steel reinforced concrete or SRC section) or much less applied because of the thermal mass of the concrete (in concrete filled tube, or CFT

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section).

Composite construction is often used together with concrete and steel construction, which is generally called a mixed structure. This mixture of constructions provides the maximum capability and flexibility to meet the above requirement in modern tall building structures and therefore becomes the main trends in recent buildings.[1] The development is characterized in two aspects:

- A more flexible configuration of composite construction, concrete construction and steel construction.
- The new forms of composite construction.

2. A More Flexible Configuration of Composite Construction, Concrete Construction and Steel Construction in Tall Building Structure

Table 1 shows the material distribution of some tall buildings. Materials are utilized to their specific advantages. For example, beams are mostly steel section or composite section so that the beam depth can be minimized. The columns are normally composite to provide good stiffness and strength with a reasonable dimension. The composite wall, which embeds a normal concrete wall with steel plates along the centre-line, improves the shear strength and axial capacity significantly.

Normally tall buildings in China have to be designed as a dual system, which is often achieved by a core and a perimeter structure. The core is mainly made of concrete. A "high-performance" version of concrete core, with composite walls used in the lower portion of the core, is a mixed composite and concrete construction broadly used for tall buildings in high seismic zones and super tall buildings. This is introduced further in section 3.4 below. For the concrete portion of the core, it is also common to incorporate steel stanchions as hidden columns at the corner/end of the walls.

For this type of composite construction, steel sections are installed before the rebars are fixed. If the floor beam is steel also, it may be connected to the steel members in the core wall, and support the floor construction before the concrete is poured.

The moment frame or the framed tube, formed by orthogonally connected columns and beams, are the common configuration of the perimeter structure. In a mixed structure, there may exists many material combinations, from steel column + steel beam, composite column + steel beam, composite column + composite beam to composite column + concrete beam, and other variations. They vary in cost, construction speed, and structural performance. The final engineering design is a balance between all these factors, subject to the client's brief.

The stiffness of a moment frame is weak due to shear lag effect if considering the perimeter working as a three-dimensional tube. This may be slightly improved by intermediately strengthened by steel belt trusses, mostly at mechanical and refuge floor (Fig. 1). A multi-story (mega) bracing largely increases the stiffness of a frame (Fig. 2), though having obvious visual effect to the building. When the demand of lateral stiffness is very high, the material of all perimeter columns tends to be collected to the corner of the building to maximize the lever arm for lateral resistance. The perimeter structure therefore becomes a mega structure, with composite mega columns, steel or composite mega braces and steel beams or belt trusses (Fig. 3a). To minimize the blocking of the precious corner view,

Table 1. Material distribution of some tall building structures

Project Name	Material Distribution							
	Core			Perimeter				Outrigger
	Wall	Lintel	Frame/ Brace	Column	Beam	Diagonal	Belt Truss	
China World Trade Center 3A Beijing	Comp	S	S	Comp (SRC, CFT)	S	Comp (SRC,CFT)	S	S
Fortune Plaza Phase 3 Beijing	RC, Comp	RC, Comp		Comp (CFT)	S		S	S
Eton Center Dalian	RC	RC, Comp		Comp (SRC)	S	Comp (SRC)	S	
Tianjin Goldin117 Tower	RC, Comp	RC, Comp		S, Comp (CFT)	S	S	S	
Guangzhou IFC (West Tower)	RC	RC	S		S	Comp (CFT)		
Beijing WFC	RC	RC		Comp (SRC)	Comp (SRC)			
Guangzhou CTF Tower	RC, Comp	RC		Comp (CFT)	S		S	S
China Zun Tower, Beijing	RC, Comp	RC, Comp	Comp	S, Comp (CFT)	S	S	S	

RC=reinforced oncrete, S=Steel, Comp=Composite, SRC=Steel Reinforced Concrete, CFT=Concrete Filled Tube.

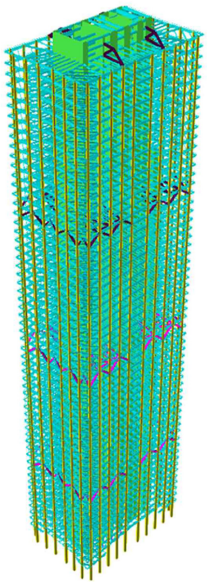


Figure 1. A perimeter frame strengthened with belt trusses (Beijing Fortune Plaza Phase 2 Office Tower).

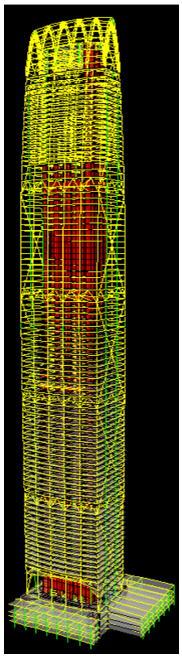


Figure 2. The multi-story bracing in Shenzhen Kingkey 100 Tower.

there may be two mega columns located close to the right corner which are connected as rigid as possible (Fig. 3b).

A less visible way to increase the lateral stiffness is to connect the core and one or multiple perimeter columns with truss-like outriggers, which are also located in mechanical or refuge floors. The columns connected to the core are those less stressed by the "web" frame of the perimeter tube due to the shear lag effect. This connection through

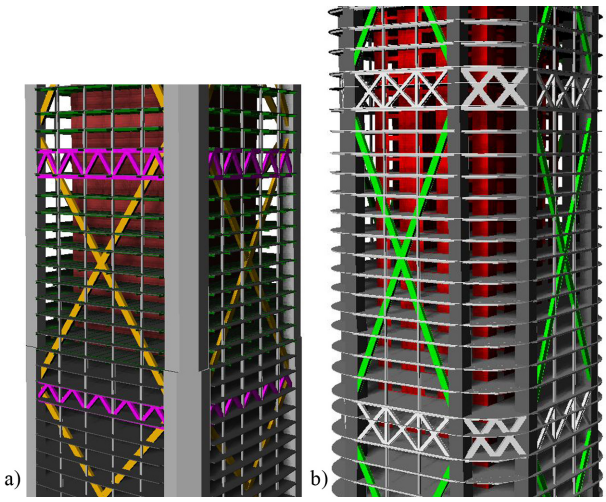


Figure 3. A blow-up view of the mega structure at the perimeter of a) Tianjin Goldin 117 Tower (perimeter beams are hidden for clearness) and b) Beijing China Zun Tower.

outriggers, although intermediate along the height, mobilizes the columns effectively to provide a large lateral stiffness. If integrated with the belt truss, the shear lag effect may be improved further by mobilizing multiple columns.

When individual mega columns are connected with the outriggers, the lateral system acts as a single system, i.e. the central core and stabilizing outrigger arms, rather than a dual system. The mega columns are mostly positioned on the grid aligned with the perimeter of the core so that the push-and-pull action by the mega columns on two sides of the core is effectively aligned. Fig. 4 shows the ICC tower in Hong Kong as a typical example. For seismic design in Mainland China a redundancy of lateral system is generally required and thus the perimeter structure should justify some degree of lateral stiffness and strength on its own. Some variations from the single system are therefore developed by such as i) adding more secondary columns to form a not-so-stiff-second-line-defense perimeter system,; or ii) adding mega bracing at the perimeter.

For all these core-perimeter structures classified as dual systems, the "first-defense" system may be either the core or perimeter, depending on which provides the majority of the lateral stiffness. This can be observed by comparing the story shear and overturning moment distribution figure of two different structures (Fig. 5 and 6).

Outriggers are mostly steel construction, while in some projects concrete or composite construction is also used. For the outrigger floors, the concrete core should be embedded with steel sections connecting the outrigger arms on both sides of the core. In the floors above and below the outrigger floor, the core may also need to be strengthened in accordance with the possible high stress.

This addition of composite construction may be used for those structurally demanding area only. The structural

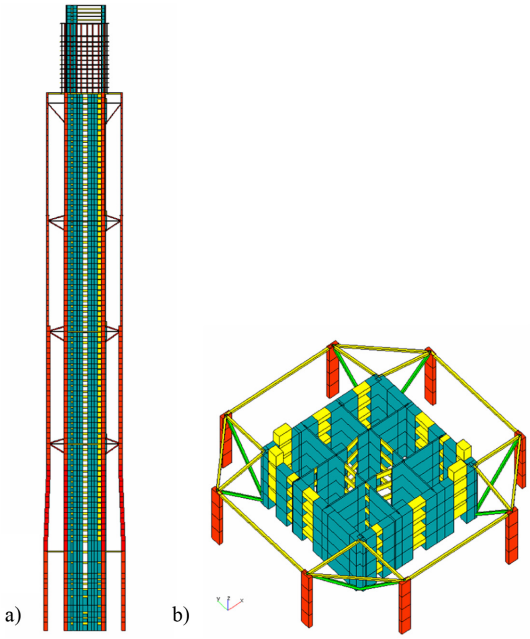


Figure 4. The single system with core-mega column-outrigger of Hong Kong ICC Tower. a) elevation; b) blow-up view of outrigger floor.

analysis software are now able to carry out comprehensive analysis for any complicated configurations, and the non-linear analysis is able to simulate the elasto-plastic behaviour of structural systems with the input of actual earthquakes. Engineers are now able to locate the specific "weak" area and enhance with a construction type with better performance. While it is based on complicated analysis nowadays, it should be noted that the structural concept and the knowledge of the behaviour of all these different construction types are important to evaluate the structural scheme. For seismic design, strengthening of local area may not always be good - more forces may be attracted and the adjacent non-strengthened area may become new vulnerable area. A smooth transition of strength and stiffness distribution is normally a good concept, for example gradually reducing the steel section area or number of steel members between a composite construction and a concrete one.

3. The New Forms of Composite Construction

In the member level, the composite construction differs much from one type to another: the shape, the location of the materials, the ratio of steel to concrete, depending on the actual demands changing from building to building.

3.1. Composite columns

As the composite column is used extensively in all kinds of tall buildings, there emerge many new shapes and configurations due to the architectural requirement. In a tall

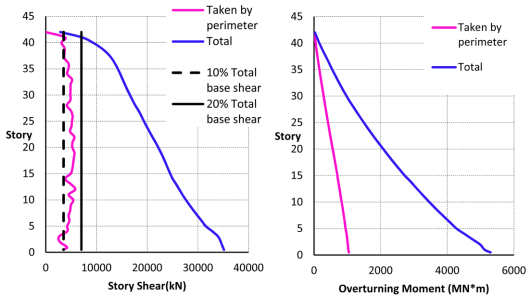


Figure 5. The shear and overturning moment of a structure with perimeter moment frame, in which the core is the major source of lateral stiffness.

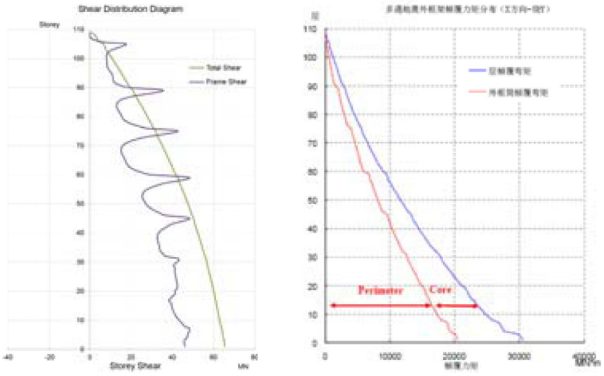


Figure 6. The shear and overturning moment distribution of a structure with perimeter mega structure, in which core is secondary in lateral resistency.

residential building, the SRC columns shape themselves in accordance with the room geometry (Fig. 7). The steel stanchions in SRC sections are generally less concerned of buckling as in steel construction, and thus are more freely distributed. It is however important to distribute evenly the steel plates within the concrete, so that the composite action is maintained through a large surface of steel-concrete interface. Due to the various shape and steel configuration, the strength analysis of such composite sections are generally carried out by finite element analysis assuming "plane-section-remains-plane" with the mechanical properties of the relevant materials modeled (Fig. 8). However the additional moment due to slenderness and second-order effect shall be considered explicitly and the consequent longitudinal shear shall be checked.

3.2. Composite mega columns

The mega columns are generally of composite, due to the demand of both substantial stiffness and strength. The section configuration of a composite mega column should simplify the connection with other members. Since the mega section may be very big (the biggest one over 60 m^2), it should be considered as a mini-structure with steel plates and concrete mass connected to each other through

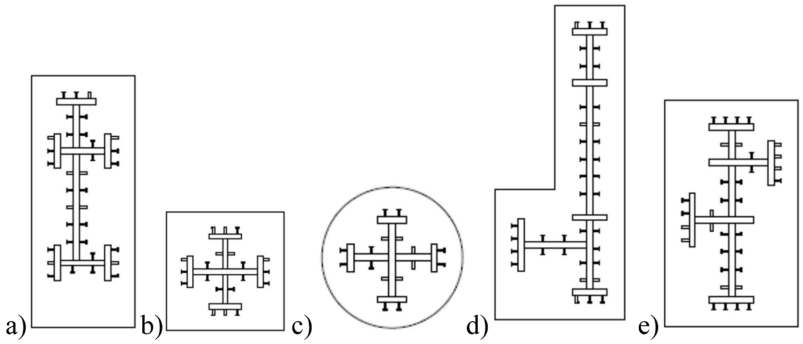


Figure 7. The various composite column shapes.

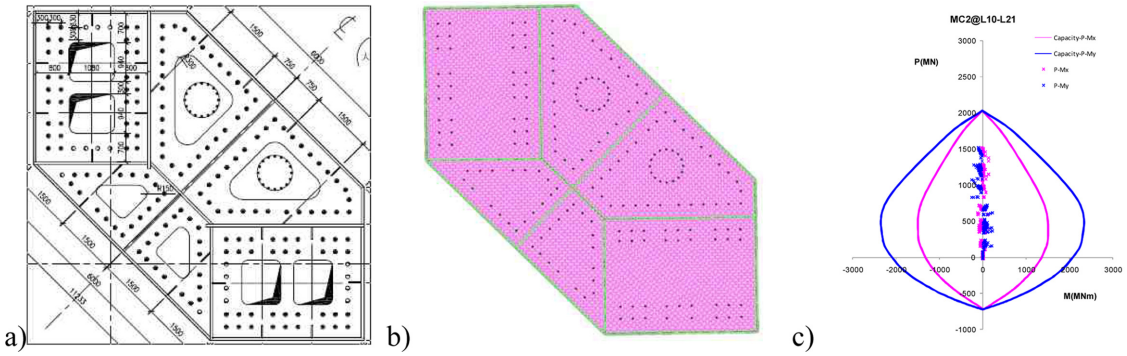


Figure 8. The sectional analysis of composite section. a) section; b) finite element model; c) the N-M curve.

welds and shear stud/bonding layers (Fig. 9). Such load paths shall allow the external forces be successfully distributed to the overall section as assumed in the modeling. Otherwise the deformation does not satisfy plan-section-remain-plan assumption and the strength shall be discounted.

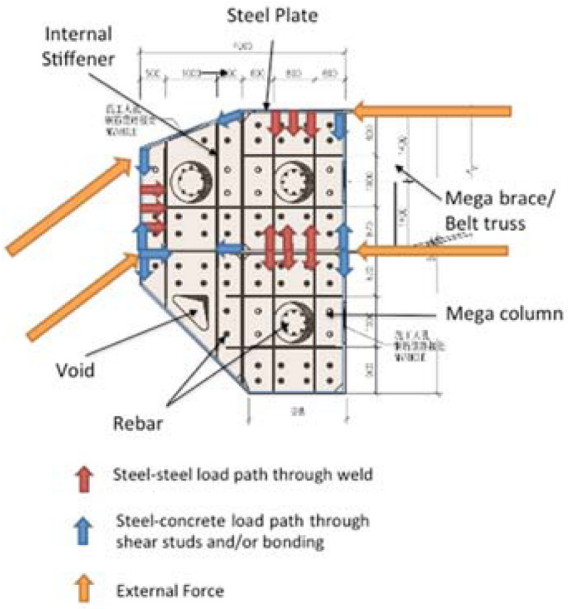


Figure 9. The load paths within composite mega column (indicative).

Traditionally the individual steel stanchions were installed separately in SRC mega columns. The longitudinal shear force between the steel stanchions and concrete was checked and shear studs were distributed all around the surface of the steel stanchions. For columns subject to large axial and bending moment in seismic design, the longitudinal shear capacity of the shear studs may not be sufficient. Fig. 10 shows the results of a test in which the longitudinal through-out cracking of a L shape composite column where the two parts of the steel section are connected by batten plates only. Therefore it is generally required the steel plates to be continuously distributed in the SRC section. For mega columns which are mainly subject to axial force, it is arguable to to distribute steel stanchions separately since the requirement for longitudinal shear is small. However to maximize the section strength as a composite construction in seismic design, continuous configuration of steel stanchions are generally required for SRC sections in the tall building structures in Mainland China.

On the other hand, the CFT section gradually gets more usage in mega columns of recent super tall buildings (Figs. 8 and 9). Examples include Shenzhen Kingkey 100 tower, Tianjin Goldin 117 tower, Guangzhou East Tower and Beijing China Zun Tower. For very large mega columns,

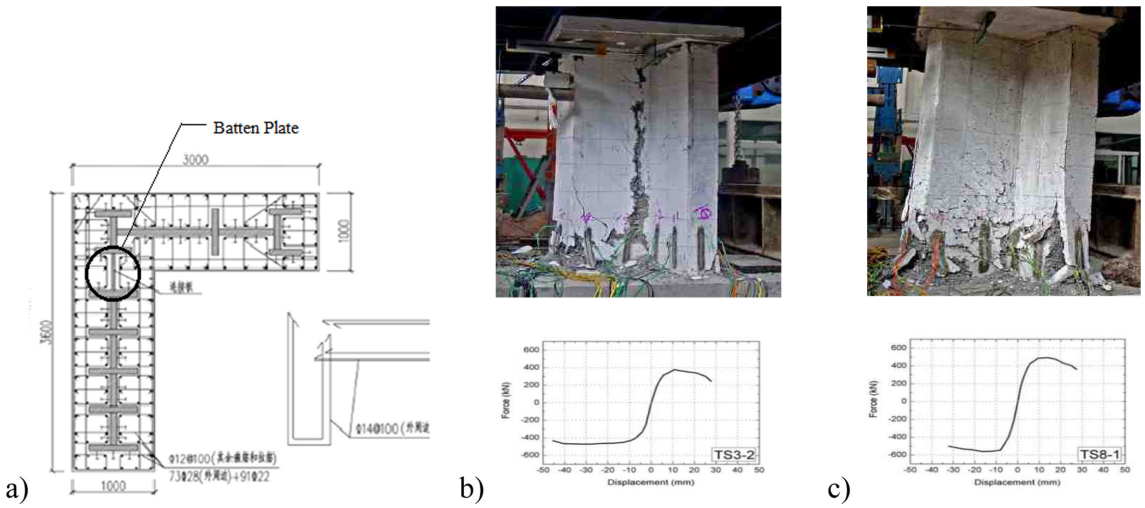


Figure 10. The continuity of steel section in composite column: a) the section; b) the longitudinal shear failure at the location of batten plate; c) no failure when steel sections are continuously connected.

multiple CFT sections are bundled together to form a "multi-cell" configuration, and concrete fills the cells formed by steel plates welded together. This configuration features continuous and interconnected steel plates on which stiffen plates may be added to prevent local buckling of the plates when concrete is poured. Self-compact concrete is used as the in-filled concrete to prevent bubbles or voids. However it is still highly dependent on the concrete mix and the workmanship. The method statement for the CFT construction should be carefully verified by trials and mock-ups. For large dimension CFT sections, rebar or rebar cages has been proven useful to improve the ductile property of the section. For the mega column of the Tianjin Goldin 117 tower shown in Fig. 8, the two box shapes of the hexagon mega column simplify the connection to mega braces and belt trusses. The "cells" were fabricated to the size allowable by the transportation and lift capacity, and then welded together on the sky (Fig. 11). Due to the size and the large thermal mass of the infilled concrete, the thickness of the fire protection layer to the perimeter steel plates may be reduced significantly for the same fire proofing period, justified by fire engineering analysis.

3.3. The longitudinal shear design of composite columns

The longitudinal shear force transfer for the composite column is a subject lack of in-depth study, compared to that for a composite beam. For a composite column in a specific story of a tall building, the new forces to be distributed between the steel and the concrete include the axial force from the beams under gravity load, and the axial and bending moment due to the frame action under gravity load and lateral load. The combination of axial force and bending moment makes the analysis and determination of the composite mechanism complicated. The various configurations



Figure 11. The site photo of mega CFT column in Tianjin Goldin 117 Tower.

of composite sections further complicate the issue. A conservative way, as shown in Fig. 12, is to assume the com-

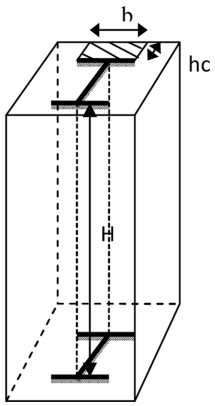


Figure 12. The longitudinal shear calculation of a SRC column.

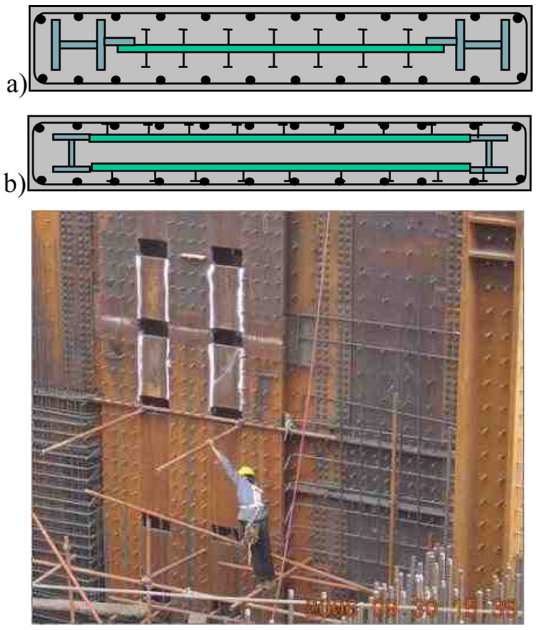


Figure 13. The composite shear wall a) with single steel plate; and b) with double steel plates; c) site photo.

pression strength of the shaded concrete area is transferred by the longitudinal shear developed in the surface of steel flange and concrete. This becomes more necessary if the width of the steel flange is considerably larger than the width of the concrete on both sides.

3.4. Composite shear wall

The concrete shear wall provides large lateral stiffness and also serves as a natural partition for the vertical transportations. However it demonstrates brittle failure in hysteretic loading thus its application in seismic zone is limited. For super tall buildings in which the shear walls are under large axial stress the strength of the shear wall therefore drops significantly. The composite shear wall is to embed one or two steel plates in the middle of the concrete shear wall (Fig. 13). The steel plate is confined by the concrete from any buckling and thus is able to perform shear strength of the full steel area, which is much larger than a normal concrete wall. The steel plate takes axial force also which in turn helps reduce the concrete wall thickness. The edge of the steel plate is normally surrounded by the steel stanchions and steel beams serving as the boundary elements. These steel stanchions are also part of the hidden columns to resist the axial-flexural force of the shear wall.

Composite shear wall with double steel plates is an alternative when the steel plate is too thick to be weld on site without bringing in large welding stress. The two steel plates may be fabricated as a series of shallow steel boxes to be connected on site. In this case no rebar is needed between the two steel plates. When the steel sections installed, reinforced concrete construction are then carried on the both sides of the steel plates. When completed, it looks no difference from a normal concrete wall.

This configuration of composite shear wall was firstly applied in the China World Trade Center Phase 3A China World Tower which was completed in 2009. Afterwards it is used broadly in many super tall buildings. The concrete core with local composite construction becomes the most cost-effective solution. It is different from its origin in United States, which intends to use concrete wall to prevent steel plate wall in a steel construction.[2]

3.5. Composite connections

The connection in a composite construction is critical to the structural behaviour. However the construction quality is quite often not satisfying because of many reasons. There is always a gap between the designer and the contractor - because the former only gives typical or standard details not sufficient to cover all scenarios and the latter also suffers from the fact that the fabrication/construction of concrete and steel are mostly technically controlled by separate teams. The specific aspects of the design of the composite connections include

- A detailed consideration of the relationship between steel sections and rebars;
- How to ensure the quality of concrete pouring when the sections are congested with steel plates and stiffening plates etc;

Fig. 14 shows several types of rebar anchorage in a composite connection.

4. The Composite/Mixture Index

By mixing the construction types, the percentage of composite construction in the whole structure may vary very much. The current code classifies concrete structure, steel structure and mixed/composite structure, and requirements differ largely. The actual design may be any point between a pure concrete structure and a pure steel structure. Such a “Composition/Mixture Benchmark” provides

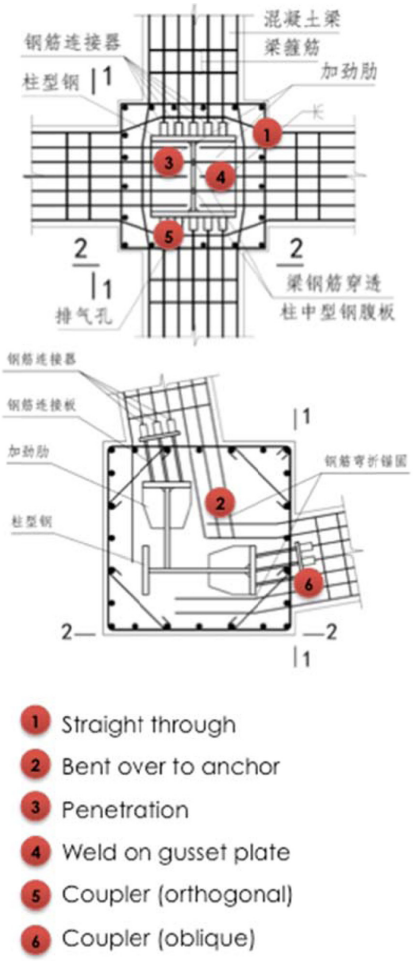


Figure 14. Various types of rebar anchorage in a composite connection.

a unified base to the essential attribute of the structure and thus help a more accurate code limit definition. Virtual strain energy for a specific displacement can be calculated as the sum of contribution of each member and thus can be considered as such an "index". For the composite section, the steel and concrete portion are all meshed into a fiber model so that the strain energy contribution of steel and concrete are distinguished (Fig. 15).

Table 2 shows the "index" of concrete and steel in terms of each material's percentage in strain energy under lateral loads of two directions and gravity load direction. A tower consisted of a concrete core and a composite perimeter frame of CFT column and steel beam is used. This contribution "index" can also be found for the perimeter structure and the core respectively.

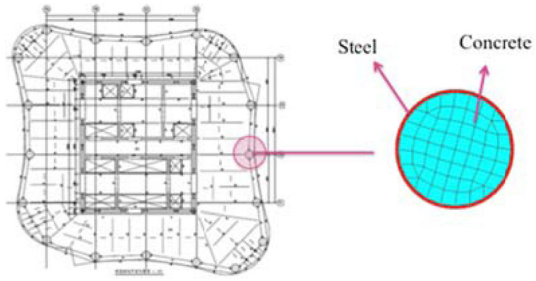


Figure 15. Fiber model to be used for strain energy calculation.

Table 2. Strain energy distribution

	Concrete	Steel
X-dir wind	69%	31%
Y-dir wind	77%	23%
Gravity	65%	35%
	Perimeter	Core
X-dir wind	21%	79%
Y-dir wind	20%	80%
Gravity	54%	46%

5. The Future of Composite Construction

The composite construction will obviously be used in a broader range and smarter way in tall buildings. Using it strategically with the concrete and steel construction, the mixed structure becomes the main stream in modern tall building structures. However it has put higher requirements on the design and construction. Many further studies are necessary and interesting for its better use in the future:

- The composite mechanism and relevant design and detailing methods especially for those new composite types lack of study;
- The "composite index" and "mixture index" of a mixed structure with composite construction to benchmark its behavior.

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