COMPOSITE CONCRETE-STEEL CONSTRUCTION IN TALL BUILDINGS

by

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Abstract: The construction of composite high-rise building structures is rapidly increasing in recent years due to increased advantages in terms of improved structural performance and faster construction. This results in a significant reduction in cost and other resources, especially for high-rise building projects. The recent trends in composite construction are governed by the an achievement of optimum interactive behavior between structural steel and concrete components designed to take benefit of the best load-resisting characteristics and economy of each material. This paper discusses some key issues related to the application and design of composite structural components to result in better performance of high-rise buildings against gravity and lateral loads. It presents a unified approach to determine the axial-flexural capacity of various composite and complex cross-sections. Using this approach, the analysis of all composite cross-sections can be performed in an integrated manner. The paper also discusses important considerations which should be kept in mind for an effective design of composite members (columns, shear walls, floors, link beams and transfer systems) and presents insights on the practical aspects of composite concrete-steel construction in tall buildings.

Keywords: Composite structures, high-rise buildings, concrete-steel construction, design philosophy

1 BACKGROUND

The composite structures are generally defined as the structures with members having composite cross-sections. In such cross-sections, more than one material (generally reinforced concrete and steel sections) are bound to act together to get optimum benefit and capacity utilization of each material. The steel reinforcing bars are generally considered as a component of traditional RC construction, while the steel sections are hot-rolled or built-up sections welded, riveted or bolted with steel plates.

Historically, the design of building structures against gravity load is mainly concerned with the provision and support of load-bearing horizontal surfaces (floors and decks). Except in some long-span structures, these floors or decks were usually made of reinforced concrete, as no other material provides a better combination of low cost, high strength, and resistance to corrosion, abrasion and fire (Johnson, 2004). For relatively longer spans, it is generally cheaper to support the slab on beams, ribs or walls than to thicken it. Where the beams or ribs are also of concrete, the monolithic nature of the construction makes it possible for a substantial breadth of slab to act as the top flange of the beam that supports it. With growing complexity of structural forms and increasing requirements of higher span lengths, it was realized that steel beams often become a cheaper option than concrete beams. It was at first customary to design the steelwork to carry the whole weight of the concrete slab and its loading; but by about 1950, the development of shear connectors had made it possible to connect the slab to the beam, and so to obtain the “composite” T-beam action that had long been used in traditional concrete construction (Johnson, 2004).

The economic return from a construction project is also a major parameter governing the construction techniques and applied technology. No income is received from money invested in construction of a high-rise building until the building is occupied. The construction time is strongly influenced by the time taken to construct a typical floor of the building. It was soon realized that a significant amount of time can be saved if the floor slabs are cast on permanent steel formwork, which acts first as a working platform and then as bottom reinforcement for the slab. The use of this formwork, known as profiled steel sheeting is currently widely used in Europe. These floors span in one direction only and are known as composite slabs. Where the steel sheet is flat, so that two-way spanning occurs, the structure is known as a composite plate. Steel profiled sheeting and partial-thickness precast concrete slabs are known as structurally participating formwork (Johnson, 2004).

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 (Peng, 2014). Similarly, full or partial encasement in concrete is an economical method for steel columns, since the casing makes the columns much stronger resulting in improved overall structural performance of the building.

The choice between steel, concrete and composite construction for a particular structure and project therefore depends on several factors. Composite construction is particularly competitive for

- medium- or long-span structures where a concrete slab or deck is needed for other reasons,
- where there is a premium for rapid construction, and
- where a low or medium level of fire protection to steelwork is sufficient. The degree of fire protection that must be provided is another factor that has historically governed the choice between concrete, steel and composite structures (Johnson, 2004).

This paper focusses on some important and practical aspects related to the application and design of composite structural components to result in better performance of high-rise buildings against gravity and lateral loads. After discussing some key advantages of concrete-steel composites in tall buildings, it presents a unified approach to determine the axial-flexural capacity of various composite and complex cross-sections. Using the presented approach, the analysis of all composite cross-sections can be performed in an integrated manner.

2 ADVANTAGES OF CONCRETE STEEL COMPOSITES IN TALL BUILDINGS

Composite construction is almost a perfect solution to satisfy the increasing requirements of high-rise building construction in terms of complex structural forms, growing needs of improved structural performance and the use of innovative structural and nonstructural systems. The steel section, with a continuous distribution of steel material, provides a stable high strength in axial and shear resistance in composite sections. Also, the buckling of steel plates becomes much less important in this case than that in steel construction. If concrete is poured in the steel box or tube, the confinement effect would increase the strength and ductility of the concrete. For steel reinforced concrete or SRC sections, the fire protection is either unnecessary or much less applied because of the thermal mass of the concrete.

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 requirements in modem tall building structures and therefore becomes the main trends in recent buildings. For example, the use of concrete columns confined by steel tubes can significantly enhance the performance of overall structural system. The steel at outer perimeter performs most effectively in tension and in resisting bending moments. The greater modulus of elasticity of steel situated furthest from centroid makes significant contribution to the moment of inertia resulting in a significant increase in flexural stiffness (Shah and Pajgade, 2013). The brittle nature of high-strength concrete is partially mitigated by confinement from steel tube. On the other hand, concrete core withstands compressive loading and delays (or prevents) the local buckling of steel. This results in increased compressive strength as well as enhanced ductility of the cross-section. The use of such composite cross-sections also minimises the congestion of reinforcement in connection regions.

The use of composite cross-sections also results in several economic benefits. For example, in case of concrete sections confines by steel tubes, the tube can acts as formwork, resulting in a decreased cost of labour and material. Also, the steel can precede concrete by several stories resulting in quicker construction. Such construction is typically, cheaper than steel and is equivalent or superior to traditional RC construction in terms of strength/cost ratio.

3 INTEGRATED AXIAL-FLEXURAL THEORY FOR RC AND COMPOSITE SECTIONS

3.1 The Need for an Integrated Axial-flexural Theory

Generally, the design of structural members can be divided and categorized in many ways based on type of member, type of material, type of applied action, type of cross-section shape, design code, and design method. Often each of these types and their combinations are treated separately and differently for the purpose of determining design strength of members, which is largely derived from the strength and capacity of its cross-section. Table 1 below shows the wide spectrum and diversity of a concrete cross-section design problem (Anwar and Najam, 2016).

Traditionally, each category of cross-section is treated separately with different theoretical treatment or design procedures. However, the boundaries between these classifications are often arbitrary and transitional. For example, an un-reinforced section can be a special case of reinforced section with "zero" reinforcement. Similarly, a reinforced concrete section with round bars and composite section with steel shapes is essentially similar as-far-as the strength/capacity is concerned. A rectangular section or a tee/flanged section is a special case of a general polygon shape, and singly or doubly reinforced sections are special cases of arbitrary reinforcement layout. It would therefore, be advantageous to develop an integrated and unified treatment of all classes of cross-sections. This will not only provide better understanding of the intrinsic behavior but also yield in numerical formulations suitable for implementation into general-purpose computer programs.

With some critical thinking, it is possible to unify various classifications of the cross-sections, to develop a unified set of governing equations for determining the axial-flexural response. Such unified approach is specifically useful for application to computer-based solutions and implementation.

Table 1: The diversity of concrete cross-section design problem

Types of Materials and their Combinations	Types of Actions	Location of Reinforcement	Stress-Strain Curve	Cross-section Shape	Design Approach and Method
Un-reinforced Concrete Reinforced Concrete Partially Pre-stressed Concrete Fully Pre-stressed Concrete Fiber Reinforced Concrete Steel-Concrete Composite	Uniaxial Bending, M_x or M_y only Uniaxial Bending and Axial Force, M_x or M_y and P Biaxial Bending, M_x and M_y Biaxial Bending and Axial Force, M_x and M_y and P	Singly Reinforced Doubly Reinforced Arbitrarily Reinforced	Simplified Rectangular Block Semi-Parabolic and Full Parabolic Curves Curves for Confined and Unconfined Concrete Linear Elastic Bilinear Elasto-Plastic Elastic, Post Elastic, Strain Hardening	Rectangular Circular Flanged General Polygonal Multi Cell Sections	Allowable Stress Design (ASD) Ultimate Strength Design (USD) Load Resistance Factor Design (LRFD) Performance Based Design (PBD)

3.2 The Unification of Cross-section Materials

Consider a concrete section with some normal reinforcement, some pre-stressing strands and a steel section placed inside. When this section is subjected to biaxial moment and axial load, we have a very general case of partially pre-stressed, composite beam-column. Let's also consider that the strain vs. depth relationship for each material is known. Similarly, let's assume that the stress-strain relationship for each material is also available. This relationship can be represented by a set of discrete points, or a continuous function, and will enable us to handle arbitrary stress-strain curves of concrete, as well as steel. Developing the stress resultant equation for this case will greatly help in practical handling of any case of cross-section analysis and design. This will cover concrete sections that are completely un-reinforced to fully pre-stressed to composite sections, either made up of concrete and steel, or from concrete of different strengths or different stress-strain characteristics.

3.3 The Unification of Cross-section Shapes and Configurations

Similarly, almost every cross-section can be defined by using multiple shapes and points and almost all shapes can be represented by polygons. The general polygons can be further sub-divided into simple quadrilaterals, and ultimately into triangles. Therefore, we can develop the equations for a general cross-section made up of several polygons and points having different properties. This will cover practically any cross-section, and there will be no need to separately handle rectangular, tee or circular sections as specific cases. Points representing rebars and pre-stressing strands with arbitrary location, area, and stress-strain curve will enable to handle all cases of reinforcement, from singly reinforced to arbitrarily reinforced and pre-stressed sections.

3.4 The Unification of Line-type Structural Members

The differentiation between a beam and a column can't be based on orientation alone. In general, a frame member is subjected to axial load and two moments. Therefore, it is obvious that the axial-flexural theory should be developed for the general beam-column. When using the formulation for beams, the axial load may be neglected (or better it may always be included even small). So it is quite apparent that there is no real need to differentiate between beam and column cross-sections, or between uniaxial and biaxial loads to determine stress resultants. In fact, the general stress resultants, are independent of the applied actions, and are an intrinsic property of the cross-section. The general case of a section undergoing bending about an arbitrary axis will cover biaxial loaded columns, as well as beams. Therefore, a cross section undergoing axial and biaxial-flexural deformations (Fig. 1) will be considered here to present the general formulation of this unified approach (Anwar and Najam, 2016).

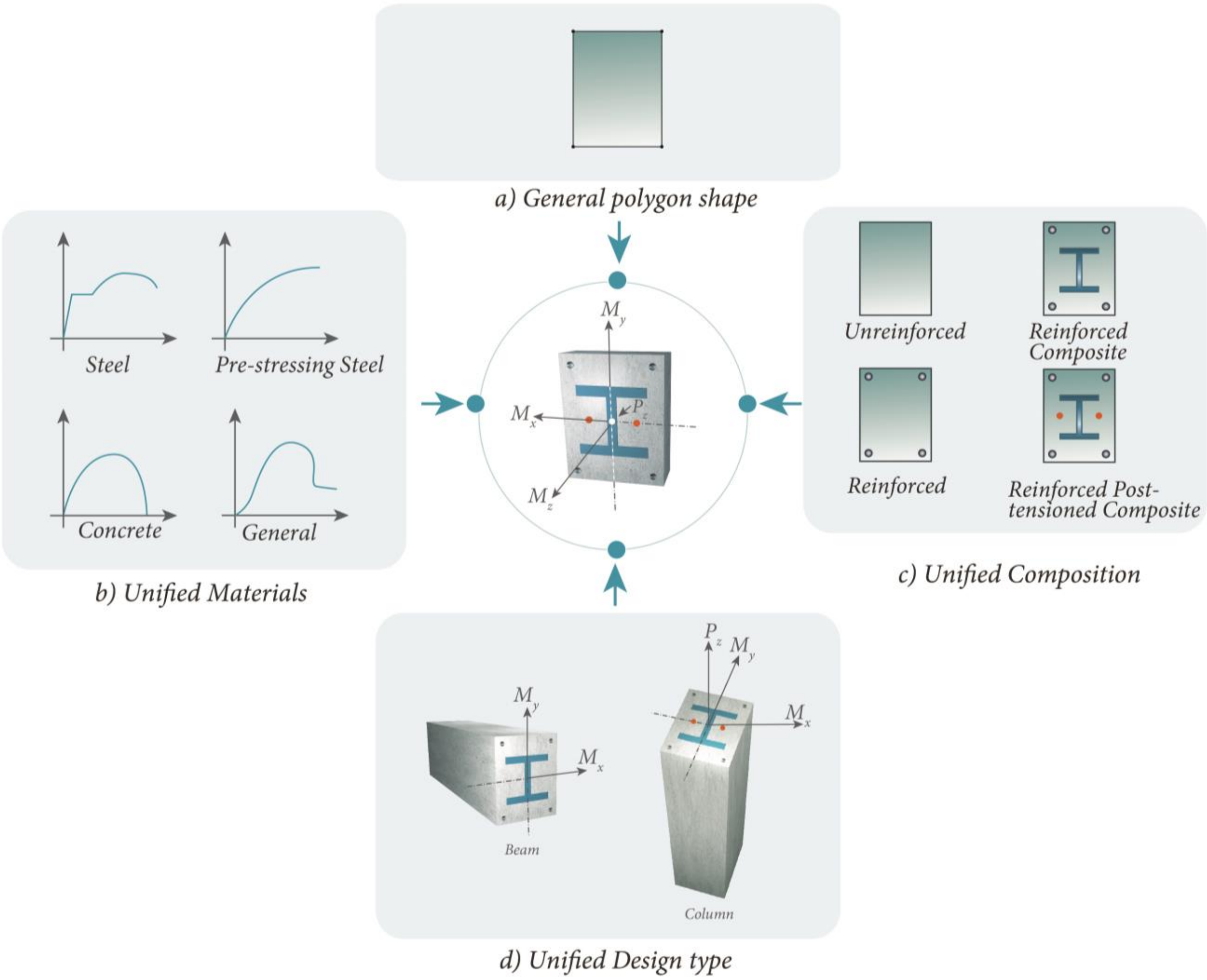

Fig. 1 A general partially pre-stressed, composite beam-column cross-section, subjected to bending about arbitrary axis

3.5 The Unification of Design Approaches and Design Codes

In general, three basic approaches are prevalent for cross-section design in different design codes and guidelines:

- The Working Strength Design (WSD)
- The Ultimate Strength Design (USD)
- The Performance-Based Design (PBD)

The key difference between the WSD and USD, as far as the determination of axial-flexural stress resultants is concerned, is the way the stress distribution is determined. In WSD, the stress profile is specified directly, is often linear and is a fraction of the material strength (called the allowable stress or the working stress). In USD, the strain profile is specified directly, from which the stress profile is determined based on the material stress-strain relationship. In Performance-based Design (PBD), the expected material properties, often without the use of arbitrary capacity reduction factors for various levels of risk, are used to determine cross-section deformations, strength, and seismic response. However, a general set of equations based on equilibrium conditions will satisfy the requirements of the WSD, USD, and consequently PBD.

In summary, it is possible and convenient to deal with the problem of flexural capacity of any complex cross-section in a general and unified manner. The next sub-section presents the development of a set of general equations to determine the axial-flexural stress resultants for any composite cross-section.

3.6 The General Stress Resultant Equations

Consider a cross-section (Fig. 2) made up of a single shape of a single material under flexural rotation about an inclined axis due to biaxial bending, and a known location of neutral axis, NA. Let's also assume that a strain distribution across the section is defined, and the stress is defined in terms of strain. The strain ϵ and stress σ can therefore be expressed as a function of x and y.

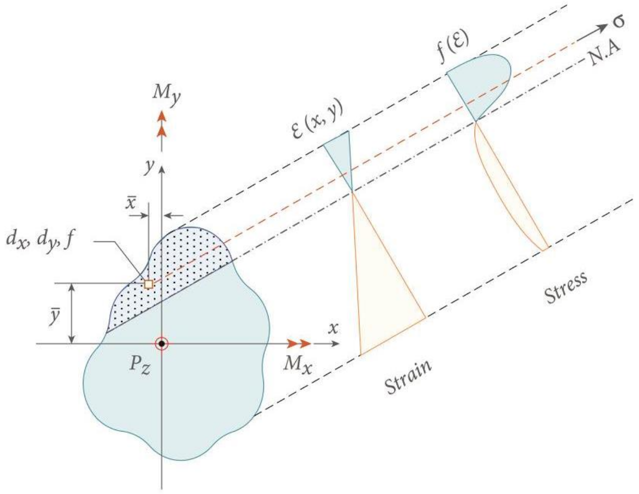

Fig. 2 Strain and stress on a cross-section made up of a single shape and material, subjected to bending about an arbitrary axis

A summation of this stress across this general, two-dimensional cross-section area will give us the required axial-flexural stress resultants for the particular strain distribution as:

$$P_z = \int_x \int_y \sigma(x,y)\,dx\,dy \quad (1a)$$

$$M_x = \int_x \int_y \sigma(x,y)\,dx\,dy \, . \, \bar{y} \quad (1b)$$

$$M_y = \int_x \int_y \sigma(x,y)\,dx\,dy \, . \, \bar{x} \quad (1c)$$

It can be seen that these stress resultants are a function of stresses that in turn, are a function of strains. The strain itself is a function of location on the cross-section. Therefore, these equations are a generalized expression to find the force, generated by a certain stress, in a plane. This plane may be steel, concrete, timber, or any other arbitrary material with an assumed or known stress-strain relationship.

These general equations are valid for any shape, composition, material or strain distribution on the continuum. It is basically dependent on the final stress distribution, including the effect of stresses induced due to applied load deformation, pre-stress, pre-strain, time dependent stress, and time dependent strain. It is, however, not practical to determine this stress distribution, and to evaluate these integrals directly for a general cross-section with arbitrary stress distribution.

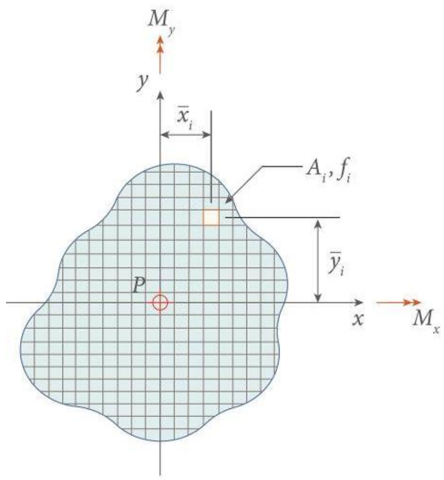

Fig. 3 Stress resultants for a 2-D stress field using stress fibers

If the cross-section is discretized into small fibers, as shown in Fig. 3, then the above equations can be converted into a simple summation form as follows:

$$N = \sum_{i=1}^{n} \sigma_i(x,y) A_i \quad (2a)$$

$$M_x = \sum_{i=1}^{n} \sigma_i(x,y) A_i \bar{y}_i \quad (2b)$$

$$M_y = \sum_{i=1}^{n} \sigma_i(x,y) A_i \bar{x}_i \quad (2c)$$

This form of equations is suitable for computer-aided determination of stress resultants. To use the above equations, the cross-section must first be divided into very small fibers (or mesh elements) and then the stress must be determined at the center of each fiber. The accuracy of the stress resultants determined in this manner would depend on the size of mesh and on the shape, size and composition of the cross-section. This approach offers unique solutions to determine the axial-flexural stress resultants and the complete capacity surface of general cross-sections made up of different materials. This simple formulation addresses the case of cross-sections subjected to a particular level of induced strain, such as from external loads and moments only. The two-step process consists of,

a) Dividing a general cross-section into appropriate fibers or mesh elements and;
b) Determining stress in each fiber considering all load and material characteristics.

If some points are added on the section (each with a specified area and a stress function related to the strain at that point) in the same way as for the shape above, then the total stress resultants from two components will become as shown in equation 3. The second half of the equation expresses the force generated in a point. This point may be an ordinary reinforcing bar or a pre-stressed strand. The force generated in these points is simply a summation of the force generated in the individual point. It may be noted that different points will have different contribution to the total force. This will depend on the points, locations and stress-strain relation, defined for it.

$$P_z = \int_x \int_y \sigma\,(x, y)\,dx\,dy + \sum_{i=1}^{n} A_{Pi}\sigma_{Pi}(x, y) \quad (3a)$$

$$M_x = \int_x \int_y \sigma(x, y)\,dx\,dy.\bar{y} + \sum_{i=1}^{n} A_{Pi}\sigma_{Pi}(x, y)\; y_{Pi} \quad (3b)$$

$$M_y = \int_x \int_y \sigma(x, y)\,dx\,dy.\bar{x} + + \sum_{i=1}^{n} A_{Pi}\sigma_{Pi}(x, y)\; x_{Pi} \quad (3c)$$

The above concept can be extended to determine the stress-resultants for cross-sections made up from several shapes and points of different materials (see equation 5). This can cover plain concrete, reinforced concrete, pre-stressed concrete, and composite concrete sections (Fig. 4). This method to determine the stress resultants is also the basic principle behind the method referred to as the "fiber model" of the cross-section analysis, in which each fiber or part of the section is treated independently to determine the total stress resultant, and these fibers extend to nearby sections for determining strain profiles.

3.7 Integrating Design Codes

The general stress resultant equations represent the theoretical stress resultant values and need to be modified by appropriate capacity reduction factors before using these for design purposes. The capacity reduction factors are generally specified by the design codes. Two types of capacity reduction factors are in use at the cross-section level. The first is applied to the total value of the stress resultant, such as the "ϕ" factors used in the ACI and many other design codes. The second is applied to each material stress separately, such as the "γ_m" factors in the British Standards and other limit state design procedures. The above equations can therefore be modified to include both types of factors. The modified equations thus become universal and can be adapted for several design codes. For example, while using for ACI codes, all γ_m factors can be set to 1, whereas use the appropriate ϕ factors for axial and bending components depending on the strain value. For use in BS code, the ϕ factors will be 1 while appropriate values of γ_m will be used for concrete and steel components.

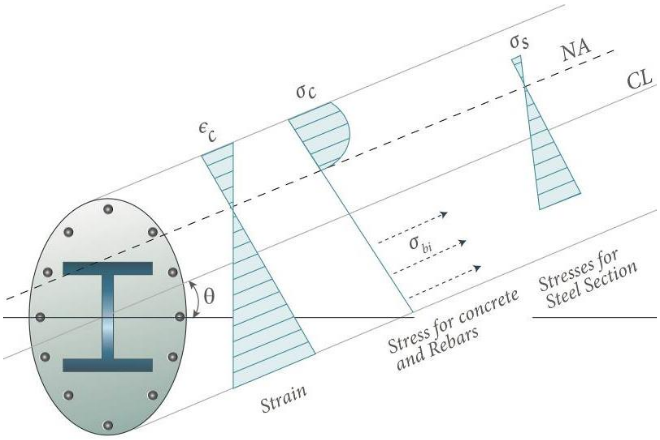

Fig. 4 The stress resultants for a general cross-section made from several materials can be computed for a particular neutral axis angle direction and depth by first using assuming a strain profile, then computing stresses in each material at various location and then summing them

$$N_z = \phi_1\left[\frac{1}{\gamma_1}\int_x \int_y f(x, y)dxdy + \frac{1}{\gamma_2}\sum_{i=1}^{n} A_i f_i(x, y)\right] \quad (4a)$$

$$M_x = \phi_2\left[\frac{1}{\gamma_1}\int_x \int_y f(x, y)dxdy.\bar{y} + \frac{1}{\gamma_2}\sum_{i=1}^{n} A_i f_i(x, y)\; y_i\right] \quad (4b)$$

$$M_y = \phi_3\left[\frac{1}{\gamma_1}\int_x \int_y f(x, y)dxdy.\bar{x} + + \frac{1}{\gamma_2}\sum_{i=1}^{n} A_i f_i(x, y)\; x_i\right] \quad (4c)$$

3.8 Analysis of a Generalized Composite Cross-section

The analysis of a completely general cross-section consisting of a combination of shapes of different materials, including concrete and steel can be performed using the generalized stress relationships. The cross-section may also contain holes, reinforcements and pre-stressing strands at any arbitrary locations. The shapes in the section may partially or fully overlap each other or may be completely inside or outside each other's boundaries. Also consider that all parts of the section have not been built at the same time and that the cross-section has been loaded incrementally. This means that at any given time and loading state the strains in adjacent materials at the same location may not be the same. A generalized representation of such a cross-section is shown in Fig.5.

Such complex cross-sections can be represented by a combination of two basic entities, the polygons and the points. The polygons are used to represent solid shapes and holes, and the points represent the conventional reinforcing bars and pre-stressed strands. Curved shapes and boundaries are modeled by several straight edges. If required, even the large reinforcing bars or pre-stressing strands can be represented by n-sided polygons to achieve greater accuracy. Each different material or same material with different properties or loading history is represented by a separate entity.

The materials used in a cross-section are defined separately. For each material the following five relationships can be defined.

a) The basic stress-strain relationship, used to obtain basic stress for a given strain;
b) The time dependent stress modification relationship, used to model change in concrete strength and modulus of elasticity with time;
c) The stress modification relationship, used to model pre-stress conditions, such as residual stresses or other non-strain dependent stresses;
d) The time dependent strain relationship, used to model creep, shrinkage and relaxation;
e) The strain modification relationship, used to model pre-strain, slippage, local buckling, non-linear strain distribution, cross-section warping, strain due to temperature gradient.

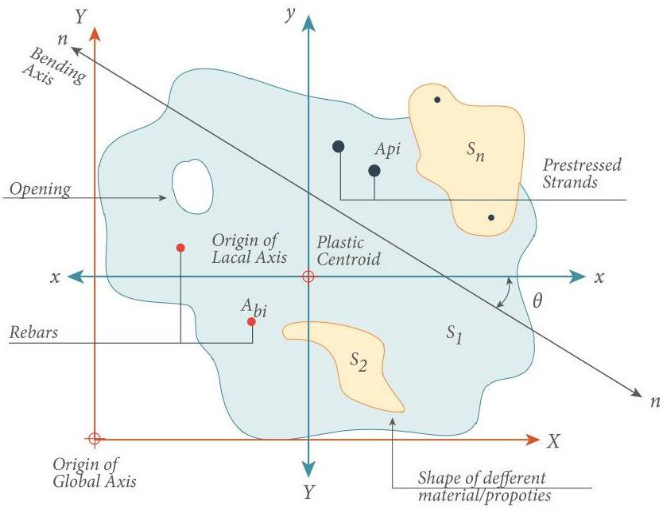

Fig. 5 A generalized representation of cross-section having several shapes and materials

Once the materials are defined, they are assigned to corresponding entities on the cross-section and the stress resultants are determined as follows.

$$P_z = \int_x \int_y \sigma_C(x,y)\,dx\,dy + \sum_{i=1}^{n} A_{Pi}\sigma_{Pi}(x,y) + \sum_{i=1}^{n} A_{Si}\sigma_{Si}(x,y) \tag{4a}$$

$$M_x = \int_x \int_y \sigma_C(x,y)\,dx\,dy.\bar{y} + \sum_{i=1}^{n} A_{Pi}\sigma_{Pi}(x,y)\ y_{Pi} + \sum_{i=1}^{n} A_{Si}\sigma_{Si}(x,y)\ y_{Pi} \tag{4b}$$

$$M_y = \int_x \int_y \sigma_C(x,y)\,dx\,dy.\bar{x} + \sum_{i=1}^{n} A_{Pi}\sigma_{Pi}(x,y)\ x_{Pi} + \sum_{i=1}^{n} A_{Si}\sigma_{Si}(x,y)\ x_{Pi} \tag{4c}$$

It is important to note that each of these relationships can be assigned to different entities in the section independently. In summary, any combination of basic stress-strain relationships, time dependent stress variations, time dependent strain variation and pre-strain conditions can be used for the same entity within the cross-section.

4 AXIAL-FLEXURAL ANALYSIS OF CONCRETE-FILLED STEEL TUBES – AN EXAMPLE

The most effective and efficient way of utilizing the strength of steel in a column under biaxial bending and load is to place the steel at the extremities of the cross-section. This is best achieved by placing concrete inside steel tubing. Composite columns consisting of concrete-filled steel tubes have become increasingly popular in structural applications around the world. By using composite columns consisting of concrete-filled steel tubes instead of traditional reinforced concrete columns, the problem of concrete cover spalling can be avoided. Furthermore, inward buckling of the steel tube is prevented by the concrete core, thus increasing the stability and the strength of the column system. The shape of the composite may vary, depending on the specific requirements for the particular case. Though effective, the use of concrete-filled steel tubes has been limited in the past, owing to the difficulty in analyzing the true behavior of the cross-section.

In a normal RC section, the individual stress-strain relationships of concrete and steel reinforcement are generally considered to be independent of each other. However, in the case of steel tubes filled with concrete, the stress strain curve for concrete is dependent on both the geometric and material properties of the steel tubes, due to the confining effect. The failure of concrete in compression is dependent on the failure of steel tubes in hoop tension due to the transverse strain produced in concrete. This is similar to the confinement effect of hoop reinforcement (ties or/and spiral), but is more significant, particularly when tubes of large thicknesses are used. It is obvious that circular steel tubing will have the greatest confining effect as compared to other shapes. This is because circular sections are placed in hoop tension as the concrete expands under uniaxial compression, which provides a continuous confining line load around the circumference of the enclosed concrete. On the other hand, rectangular tubes are only fully effective near the corners. Flexural deformation is prominent in rectangular steel tubes away from the corners as compared to axial deformation in circular tubes, resulting in lower stiffness and hence, less significant confinement.

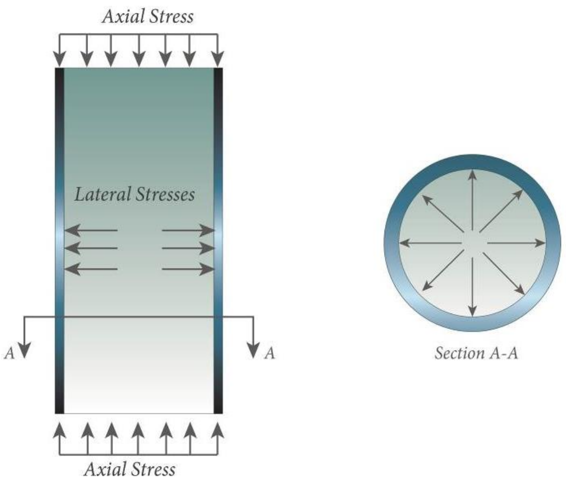

Fig. 6 The development of lateral stresses in a concrete filled steel tube

Concrete filling has a significant effect on the axial load carrying capacity of composite tubes. It does not, however, have a very considerable contribution towards the moment capacity of the section. Furthermore, inward buckling of the steel tube is prevented by the concrete core, which acts as a stiffener for the tube, thus increasing the stability and strength of the column. The presence of steel tube alters the performance of concrete significantly. In addition to increased earthquake resistant properties, such as high strength and high ductility, the ease of construction of such columns is appreciable. The steel tubing acts both as a reinforcement and formwork for the concrete core. In modern construction, the use of high strength concrete has led to the emergence of tall buildings consisting of thin slender columns. This raises the question of brittle failure in such columns. To prevent any such failure, closely spaced strips are often used, increasing the risk of premature spalling of concrete cover. These problems are totally eradicated by the use of steel tubes as reinforcement, thus giving greater effective concrete area. Due to the presence of the confining steel tube, concrete is able to undergo large strains. The peak axial compressive stress that concrete can sustain is also increased with increase in confinement (and so is the strain at which this stress is reached). Experiments have shown that a small confining pressure of about 10 percent of the uniaxial cylinder compressive strength was sufficient to increase the load-bearing capacity of the specimen by as much as 50 percent. On the other hand, a small lateral tensile stress of about 5 percent of the uniaxial compressive strength was sufficient to reduce the capacity by the same amount. An efficient bonding between steel tubes and concrete core can be achieved by exploiting any of the following factor:

- Presence of mechanical connectors
- Interlocking at the interface of concrete and steel due to irregularities of surfaces
- Friction between the material due to normal forces
- Adhesion due to chemical reaction
- Creep in concrete

The method of loading also has a very significant effect on the behavior and performance of concrete-filled steel tubes. These composites can be visualized as a system acting together and interacting with each other. As load is applied to the concrete uniaxially, it tends to expand outwards and is constrained due to the presence of steel tubing. This does not only produce confinement to concrete, but also induces hoop stresses in the steel tube. Appling load only to the outer steel tubing will force it to behave like an empty tube except for the fact that the concrete filling restraints the tube from bucking inwards and thus prevents stability failure. It is, therefore, important to ensure that the load transfer to the column is effectively being distributed on/to the entire section and not only to the steel tube, in which case the capacity of the section will be under-utilized.

The capacity of concrete-filled tubes can be further enhanced by addition of reinforcement bars and/or additional steel shapes/sections (Fig. 7). Reinforced concrete-filled tubes can be used to carry various levels of axial load and moment while keeping the overall dimension and tube sizes constant.

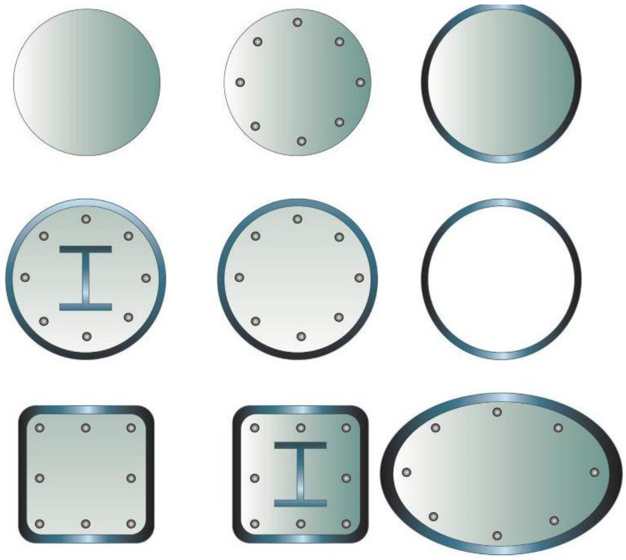

Fig. 7 Various forms of concrete-filled steel tubes

The determination of the axial-flexural stress-resultants for the purpose of capacity estimation depends on the stress-strain relationships of both concrete and steel tube, including the effect of confinement. However, the maximum strain is generally limited to a pre-defined maximum strain value corresponding to the failure criteria. On the other hand, the determination of the moment-curvature or axial load-deformation relationship requires the evaluation of stress resultants far beyond the elastic stress level and pre-defined strain limits. The entire stress-strain curve, up to failure must be considered in this case. For ordinary reinforced or composite sections, the stress-strain curve for concrete is only considered up to the assumed maximum strain capacity (0.003 or 0.0035).

Due to the confining effect of steel tube on concrete, the concrete itself possesses significant ductility which should be modeled using the appropriate stress-strain model. The primary ductility is provided by the stress plateau and the strain hardening in steel. In the conventional determination of the capacity of a cross-section, where independent stress-strain curves are used for concrete as well as steel, the shape of the steel tube will not affect the total compressive load-carrying capacity as long as the area of concrete and steel are equal. In reality, the stress-stain curve of concrete is modified by the hoop tension capacity of the steel tube. It is obvious that the circular or nearly circular tubes will have the highest confinement effect and the least deformation in the transverse direction.

A comparative study is carried out to analyze the effect of the type of stress-strain relationship used for concrete on the overall capacity of the section. For this purpose, two stress-strain relationships for concrete were considered, the ACI Whitney Rectangle and the Modified Mander Confined

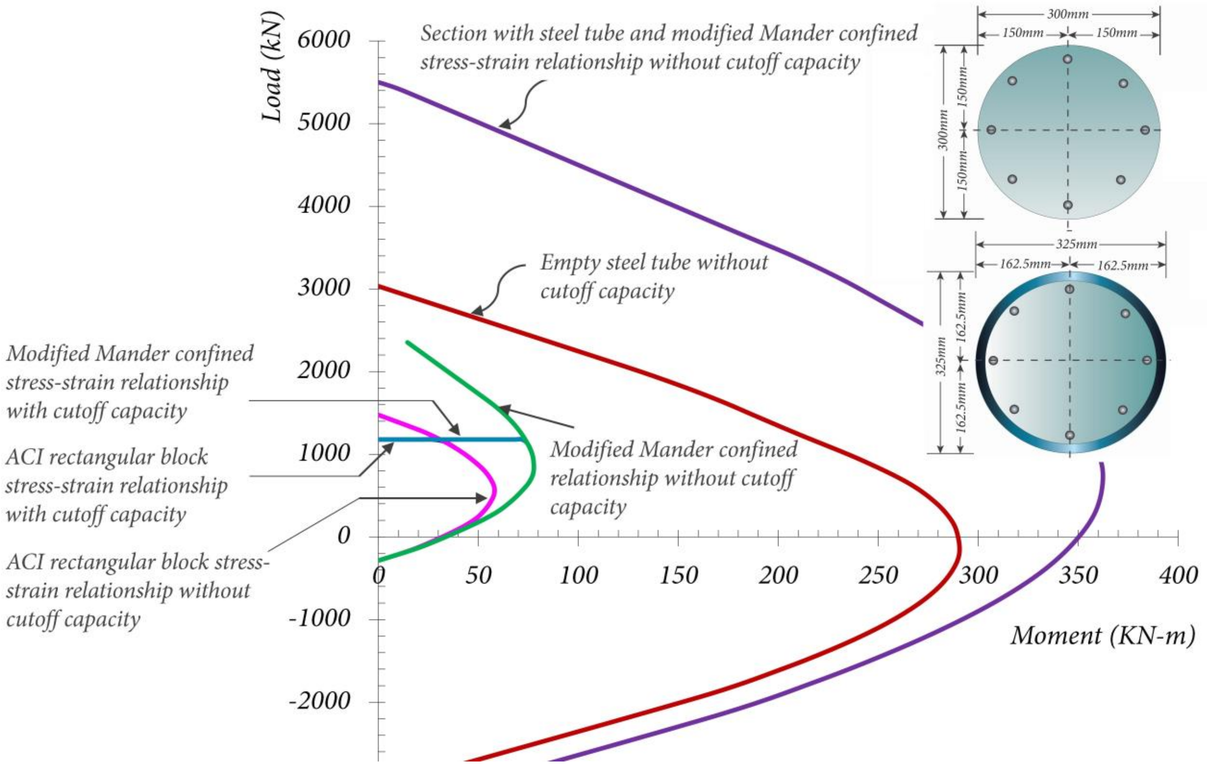

Fig. 8 The effect of stress-strain relationship and confinement of concrete on the capacity of concrete filled tubes

stress-strain curve. A circular concrete section of diameter 300 mm, reinforced with 8#4 bars was considered as shown in Fig. 8. A 12.5 mm thick steel tube is used to confine the circular concrete section (Fig. 8).

The axial load-moment interaction curves for different cases of confinement model can be seen in Fig. 8. It can be observed that ACI Whitney's rectangular stress block is representing only the unconfined concrete and thus resulting in low axial-flexural capacity. The confinement effect included using Mander's stress-strain model resulted in enhanced moment carrying capacity of the section. Similarly, the P-M interaction diagrams for the section with steel tubing around the concrete resulted in a remarkable increase in both the moment and the axial load (both tensile and compressive) carrying capacities.

5 RECENT TRENDS IN COMPOSITE CONSTRUCTION

5.1 Concrete-filled Composite Plate Shear Wall System

Recently, a new composite assembly referred to as the "concrete-filled composite plate shear wall (CF-CPSW) core system (also commonly referred to as sandwich panel wall system) is proposed (Morgen et al., 2018). This system includes prefabricated wall panels and boundary elements comprised of steel face plates, typically 12.5 mm thick, separated by 25 mm-diameter cross-connecting tie rods spaced 200 mm on center, both horizontally and vertically. These panels, which include integrally detailed composite (concrete-filled) coupling beams, are rapidly erected at the same pace as the balance of the steel erection. They are designed with adequate strength and stability to support up to four floors of steel floor beams and metal decking prior to being filled with concrete, where the face plates serve as permanent formwork for the infill concrete. The role of the cross-connecting tie rods is critical to the overall performance of the system. The rods provide strength and stability of the un-concreted wall panel to support erection loads as well as the lateral resistance and face plate bracing during the concrete infill operation. Once the panels are erected and the panel-to-panel connections are made, a self-consolidating concrete mix is placed in the space between the two plates. The concrete, combined with the steel plates, provides the ultimate strength and stiffness for the core wall assembly as a composite section (Morgen et al., 2018).

5.2 Composite Beams and Link Beams

The use of composite beams and their different configurations is currently an important part of composite construction. The following three types of composite beams are recognized in the AISC specifications.

a) Fully encased steel beams
b) Concrete-filled HSS, and
c) Steel beams with mechanical anchorage to slab

Composite beam sections have greater stiffness than the summation of the individual stiffness of slab and beam and, therefore, can carry larger loads or similar loads with appreciably smaller deflection and are less prone to transient vibrations. Composite action results in an overall reduction of floor depth, and for high-rise buildings, the cumulative savings in curtain walls, electrical wiring, mechanical ductwork, interior walls, plumbing, etc., can be considerable. Composite beams can be designed either for shored or unshored construction. For shored construction, the cost of shoring should be evaluated in relation to the savings achieved by the use of lighter beams. For unshored construction, steel is designed to support by itself and the wet weight of concrete and construction loads. The steel section, therefore, is heavier than in shored construction (Taranath, 2016).

5.3 Composite Floors and Decks

In composite floor construction, because top flange of steel beam is attached to concrete by the use of shear connectors, the slab becomes part of the compression flange. As a result, the neutral axis of the section shifts upward, making the bottom flange of the beam more effective in tension. Since concrete is required to serve as floor system, the only additional cost is that of the shear connectors. In addition to transmitting horizontal shear forces from the slab into the beam, the shear connector prevents any tendency for the slab to rotate independently of the beam. The stud shear connector is a short length of round steel bar welded to the steel beam at one end and having an anchorage provided in the form of a round head at the other end. The studs are normally welded to the beam with an automatic welding gun, and when properly executed, the welds are stronger than the steel studs. Studs located on the side of the trough toward the beam support are more effective than studs located toward the beam centerline. The larger volume of concrete between the stud and the pushing side of the trough helps in the development of a larger failure cone in concrete, thus increasing its horizontal shear resistance (Taranath, 2016).

Steel decks for composite construction are generally available in in three depths, 37.7 mm, 50 mm, and 75 mm. The earlier types of steel deck did not have embossments, and the interlocking between concrete and steel deck was achieved by welding reinforcement transverse to the beam. Later developments of steel deck introduced embossments to engage concrete and steel deck and dispensed with the transverse welded reinforcement.

Composite floors using joists and trusses typically involve simply supported members. The joists and trusses are linked by shear connectors to the concrete slab to form an effective T-beam to resist gravity loads. The versatility of the system results from the inherent strength of the concrete floor component in compression and the ability of the joists and trusses to span long distances. Composite floor systems are advantageous in reducing material cost, on-site labor, and construction time. They also result in reduced structural depth (Taranath, 2016).

6 CONCLUDING REMARKS

Steel–concrete composite structures have become a common and economical form of construction all across the globe. The construction of composite high-rise building structures is rapidly increasing in recent years due to increased advantages in terms of improved structural performance and faster construction. This paper presented an overview of some practical aspects of the use of composite sections in high-rise buildings. A unified and integrated approach to determine the axial-flexural capacity of complex cross-sections made of any combination of materials (reinforced concrete, concrete-steel composites, pre-stressed concrete, fiber-reinforced concrete, hot-rolled and cold-formed steel) is presented. Using this approach, the analysis of all composite cross-sections can be performed in an integrated manner. The paper also discusses some recent trends and important considerations which should be kept in mind for an effective design of composite members (composite columns, shear walls, floors) and presents an overview of some of the practical aspects of composite concrete-steel construction in tall buildings.

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