Modelos conceptuales refinados de cálculo para el análisis global de edificios de hormigón de gran altura

Refined conceptual models for global analysis of supertall concrete buildings

Rabee Kafina[a], **Juan Sagaseta**[*, b]

[a] Chartered Engineer MIStructE. Senior Structural Engineer. Xavier Knight Consulting Engineers. E-mail: rkafina@hotmail.com

[*,b] Dr. Department of Civil and Environmental Engineering. Senior Lecturer. University of Surrey. E-mail: j.sagaseta@surrey.ac.uk

RESUMEN

En el presente artículo se presentan varios ejemplos de cálculo de edificios de gran altura (300 m de altura o más) con núcleo central y vigas transversales "outriggers" usando un modelo conceptual refinado propuesto previamente por los autores. El modelo se utiliza para los casos frecuentes de carga lateral y asiento diferencial entre las columnas perimetrales y el núcleo central. El presente estudio confirma que los modelos conceptuales siguen teniendo una utilidad práctica en la fase conceptual de diseño (concepción del esquema estructural y optimización de los elementos estructurales) y para la verificación de los resultados obtenidos mediante modelos numéricos más avanzados.

ABSTRACT

In this paper the refined conceptual model proposed by the authors for the lateral analysis of supertall concrete buildings (beyond 300 m height) is applied to different case studies showing reasonable predictions of deflections and moments for the core-supported-with-outrigger system. A novel simplified formula is proposed based on the conceptual model to solve gravity induced differential settlement between the core and the outrigger. This work shows that the use of simple conceptual models are still useful in the conceptual design of structural schemes (i.e. type of outrigger-bracing, optimal design of structural elements) and for the verification of results from advanced computational models.

PALABRAS CLAVE: edificios de gran altura, núcleo central y apoyos perimetrales, viga transversal.
KEYWORDS: supertall buildings, core-outrigger lateral bracing system, outriggers.

1. Introduction

A significant increase in the demand of tall or supertall concrete buildings (up to and beyond 300 m height respectively) has taken place over the last two decades for commercial and residential purposes in highly urbanized areas [1]. The design of such structures is generally governed by lateral loading leading to the implementation of complex lateral bracing systems. An efficient bracing system is the core-outrigger system in which the lateral sway is reduced by rigidly linking the central core to the external columns as shown in Figure 1. The global analysis of such structures is generally carried out in practice by means of 3D computational models (Figure 2) which need to be verified although this task is not straightforward. Classical conceptual analytical models developed in the 1980s, for example in

[2-3], are sometimes used for verification purposes or to obtain preliminary results in design although they cannot be used for all bracing systems and they often give rather conservative predictions of the deflections [4].

In this paper the refined model proposed by the authors for lateral analisis in [4] is applied to different case studies showing reasonable predictions of deflections and moments for the core-supported-with-outrigger system. In addition, a novel simplified formula is proposed based on the conceptual model to solve gravity induced differential settlement between the core and the outrigger.

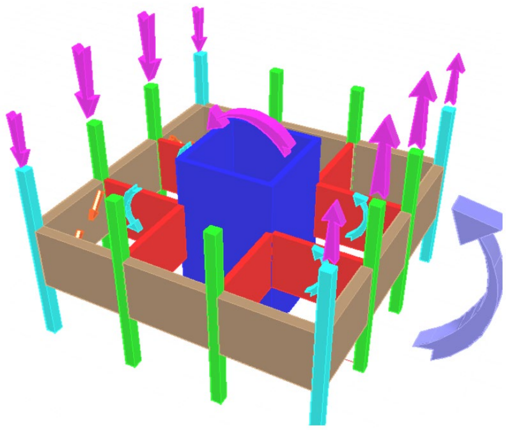


Figure 1. Load transfer in core-outrigger systems [5].

2. Proposed refined conceptual model

The classical conceptual model for core-outrigger bracing proposed by Smith and Salim in 1981 in [2] shown in Figure 2 neglects the outrigger's reverse rotation due to the propping of the peripheral columns. This can result in the overprediction of lateral deflections and underestimation of the moments in the outriggers.

This limitation was addressed by the refined model proposed by the authors in [4] shown in Figure 3 and equation (1). The model was developed for direct outriggers without openings, neglecting P-Δ effects, floors acting as rigid diaphragms and stiffness ratio ω as defined in [3] between the core and outrigger less than 1.

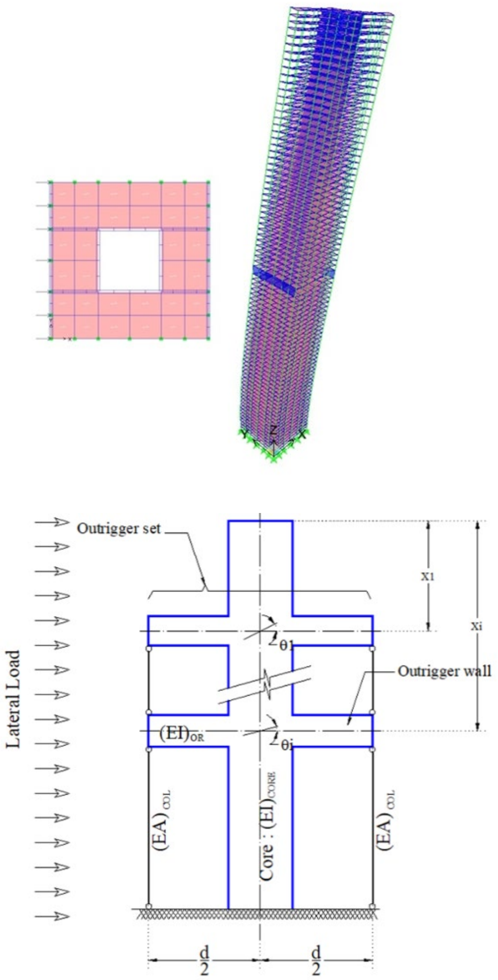


Figure 2. Global analysis of supertall buildings: (top) typical 3D FE analysis [4] and (bottom) classical conceptual model for lateral bracing [2].

The refined model proposed in [4] considers that the outrigger rotation has three components, one due to the rotation of the core, other due to the shortening of the columns and another due to reverse bending of the outrigger.

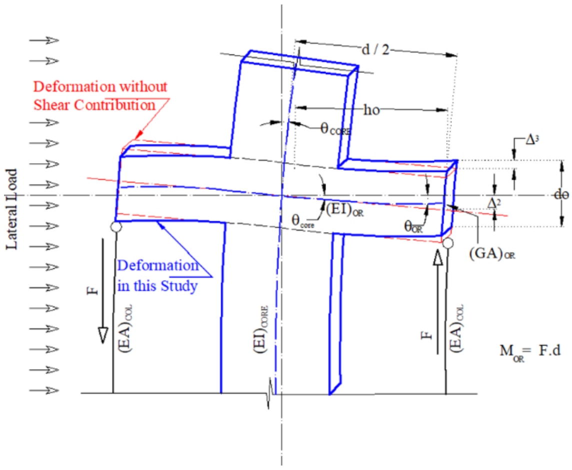


Figure 3. Refined conceptual model accounting for the outrigger's reverse rotation [4].

$$\frac{w}{6(EI)_{\mathrm{CORE}}}\begin{bmatrix}H^3-x_1^3\\ H^3-x_2^3\\ \vdots\\ H^3-x_n^3\end{bmatrix} = \begin{bmatrix} S_2+S(H-x_1) & S(H-x_2) & \dots & S(H-x_n)\\ S(H-x_2) & S_2+S(H-x_2) & \dots & S(H-x_n)\\ \vdots & \dots & \ddots & S(H-x_n)\\ S(H-x_n) & S(H-x_n) & \dots & S_2+S(H-x_n)\end{bmatrix}\times\begin{bmatrix}M_{\mathrm{OR1}}\\ M_{\mathrm{OR2}}\\ \vdots\\ M_{\mathrm{OR}n}\end{bmatrix} \qquad \textbf{(1)}$$

2.1 Refined general solution for the outrigger moments and deflection

Equation (1) gives the modified expression for the moments transferred by the n outrigger which was derived in [4] from compatibility conditions similarly as in the classical model from Smith and Salim [2]. Equation (1) is identical to that proposed in [1] except for the new term S_2 obtained as $S_2 = S_1 - \frac{2h_o^3}{3d^2(EI)_{\mathrm{OR}}} - \frac{2.4h_o}{d^2(GA)_{\mathrm{OR}}}$, where w is the uniformly distributed load, H and d are the total height and width of the building respectively, x_i is the distance of the outrigger from the top of the building, h_0 is the effective span of the outrigger and $(EI)_{OR}$, $(EI)_{CORE}$ are the flexural stiffness of the outrigger and the core respectively. Equation (2) gives the horizontal deflection at the top Δ from a cantiliver model using the outrigger moments calculated from proposed equation (1).

$$\Delta = \Delta_1 + \Delta_2 \qquad \textbf{(2)}$$

where $\Delta_1 = \frac{wH^4}{8(EI)_{\mathrm{CORE}}}$

and $\Delta_2 = \frac{1}{2(EI)_{\mathrm{CORE}}}\sum_{i=1}^{n} M_{\mathrm{OR}i}(H^2 - x_i^2)$

3. Verification against FE models

The proposed method was validated in [4] against numerical predictions of the lateral displacements obtained from FE analyses as well as predictions using classical approach in [2]. The basic geometry used, shown schematically in Figure 2 represents a large number of tall and supertall buildings for residential use, see examples in [1]. The building heights considered varied between 200 m - 400 m with an aspect ratio between 4 – 8, the building width was 50 m. Further details can be found in [4].

Figure 4 shows the comparison of the moments predicted using equation (1) and Smith and Coull approach in [3] compared to FE results for the case of buildings with one outrigger. The analysis showed that classical formulae provided significantly larger lateral deflections and smaller moments in the outriggers compared to FE models and the proposed approach given by equation (1). This is true except in the second outrigger from the top (in buildings with more than one outrigger) where the moments were higher. In general, the differences between the existing methods and equation (1) were larger for increasing values of the stiffness ratio ω between the core and the outrigger system (i.e. higher value of ω in cases with shortest buildings and lowest aspect ratio).

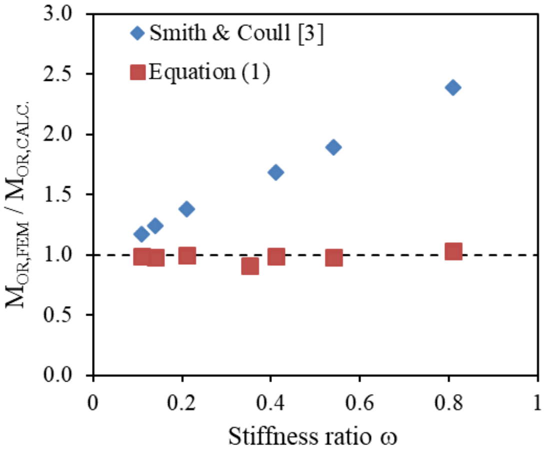


Figure 4. Moments in outrigger from existing approach in [3], equation (1) and FE results [4].

4. Axial shortening effects

For supertall buildings the effects of differential axial shortening of core and columns must be considered in design and analysis [1]. Differential axial shortening, as shown in Figure 5, is due to the different levels of stress in the columns and the core (i.e. columns are generally highly stressed compared to the core). This problem is complex since the ratio of stresses varies during construction and it is also influenced by elastic and creep shortening.

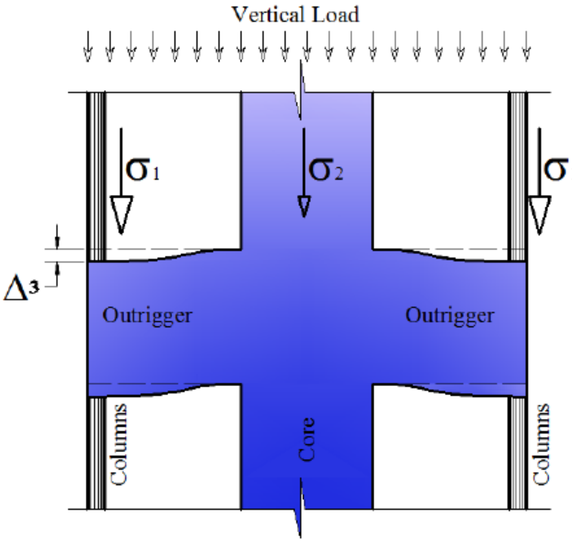


Figure 5. Differential shortening between core and columns [5].

4.1 Approximate formula for gravity induced differential settlement

A simplified formula was developed in [5] to estimate the moment developed in the outrigger due to the differential settlement in the core with respect to the external columns. The formula is derived based on a simple spring-propped cantilever beam. The conceptual model shown in Figure 6 considers the axial stiffness of the lower columns and core and the shear stiffness of the outrigger.

The total load under the outrigger is given by equation (3) which was derived adding the contribution of the vertical deflection of the outrigger due to load N_1 from the top, the deflection of the columns below the outrigger as well as at lower levels and the vertical deflection of the core. In equation (3), N_{col} and N_{core} are the column and core axial loading at typical floors, n is the level of the outrigger counting from the base and h is the typical storey height.

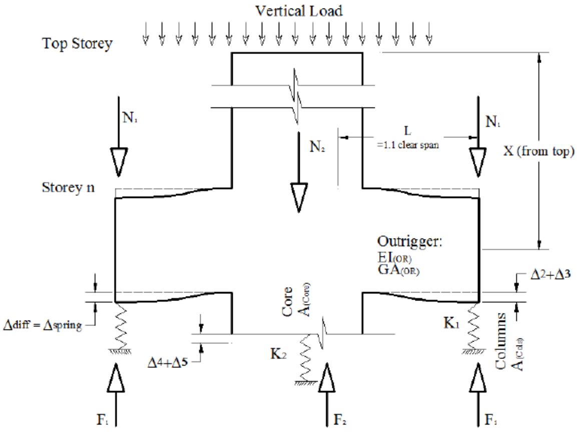


Figure 6. Conceptual model for axial shortening effects [5]

The total moment developed in the outrigger due to the differential settlement is the net force at the end of the outrigger $(N_1 - F_1)$ times the clear span. The estimated moments were verified against numerical results from FE for two case studies summarized in Table 1.

Table 1. Case studies of axial shortening.

Parameter	Case 1	Case 2
N_{col} [kN]	250	750
N_{core}[kN]	500	1500
N_1 [kN]	3000	4500
N_2 [kN]	6000	9000
$(EI)_{OR}$[kN/m^2]	800×10^6	292×10^6
$(GA)_{OR}$[kN]	81666667	58333333
L [m]	11	16.5
A_{col} [m^2]	16	2.25
A_{core} [m^2]	10	20
n	28	34
H [m]	280	200
h	7	5
x	84	30

$$F_1 = \frac{\dfrac{N_1 L^3}{3(EI)_{OR}} + \dfrac{1.2 N_1 L}{(GA)_{OR}} - h\left[\dfrac{N_{col}}{(EA)_{col}} - \dfrac{N_{core}}{(EA)_{core}}\right]\left(\dfrac{n^2+n}{2}\right) + \dfrac{(2N_1+N_2)(H-x)}{(EA)_{core}}}{\dfrac{L^3}{3(EI)_{OR}} + \dfrac{1.2L}{(GA)_{OR}} + \dfrac{(H-x)}{(EA)_{col}} + \dfrac{2(H-x)}{(EA)_{core}}} \tag{3}$$

The moments predicted in the case studies shown in Table 1 using equation (3) were slightly lower (less than 20%) than those obtained using FE models. The differential settlement in Case 1 (Table 1) predicted with FE was 2.2 mm whereas using the proposed approach it was 1.8 mm; for Case 2 (Table 1) the settlement was 20 mm with FE and 23 mm with the formula. These results confirm that the proposed approach provides reasonable results.

4. Member design of RC outriggers

The design and detailing of RC outriggers has several challenges as described in [4]. Outriggers are heavily loaded deep structures with span-to-depth ratios between 1:1 and 3:1 and therefore they are designed as "discontiuity regions" in most codes of practice [6-7]. Stress fields and strut-and-tie modelling STM are commonly adopted in such cases. In the latter, different conceptual models can be adopted for the load transfer between the core and the peripheral columns as shown in Figure 7.

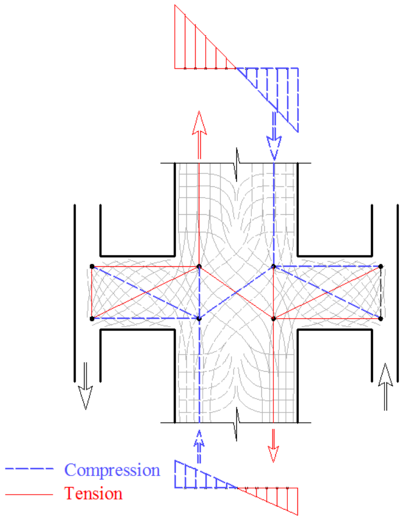
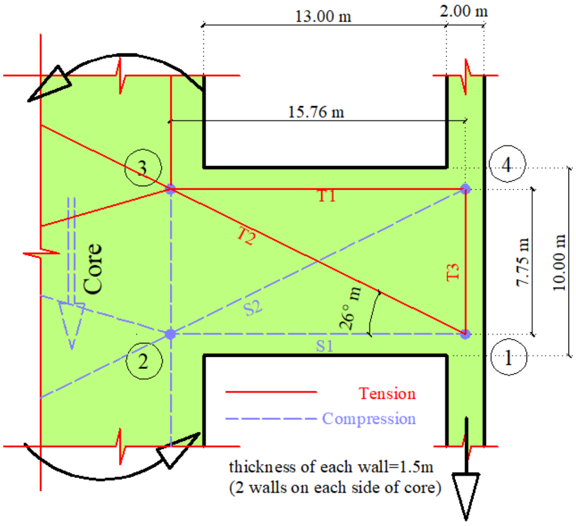


Figure 7. Stress field and STM of core-outriggers.

The strut-and-tie model shown in Figure 8 is commonly adopted in shear-dominated coupling beams in seismic design in American and European codes [6-7]. Additional reinforcement used for buildability purposes [8] can contribute towards resisting vertical loads and also towards providing additional load paths. The system is statically indeterminate (internally) and it includes two possible load paths (top and bottom loads in the cantilever beam) as shown in Figure 8. The system captures the fixity of the outrigger at the top and bottom of the floors acting as diaphrams. The fraction of the load transferred by each load path is given by the amount of vertical reinforcement designed to hang the load to the top of the cantilever. As shown in [4] the amount of reinforcement originally obtained using the STM could be optimised (around 10% reduction) using an iterative nonlinear FE approach. Stresses at the struts and nodal regions were checked against allowable limits defined in Eurocode 2 [6] as shown in Figure 9.



thickness of each wall=1.5m
(2 walls on each side of core)

Figure 8. Simplified strut-and-tie model.

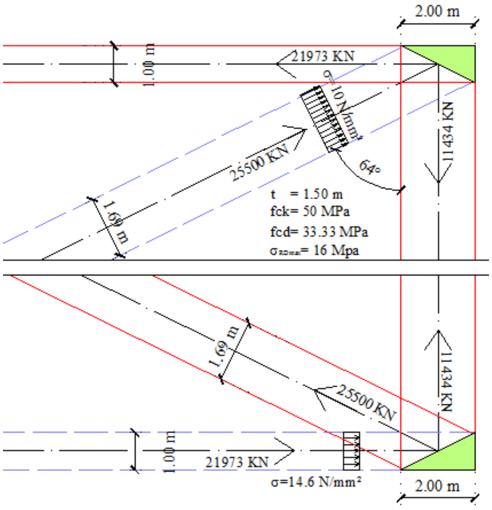
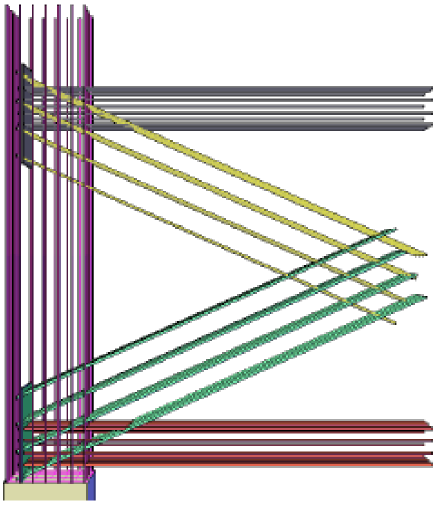


Figure 9. Nodal regions at the outter columns.

A “X” type of reinforcement cage is commonly adopted in practice, as shown in Figure 9, to prioritise strength wheras orthogonal reinforcement layouts may be considered towards optimising the stiffness. It is widely accepted that optimal strut-and-tie models use short length ties in order to minimise the strain energy and deformations. Therefore a “X” type arrangement does not seem to be the optimal solution in this case although the additional numerical FE analyses carried out by the authors [4] showed in this case that the overall shear response of the outrigger was satisfactory. The governing mode of failure of the RC outrigger was flexure with a relatively ductile behaviour.



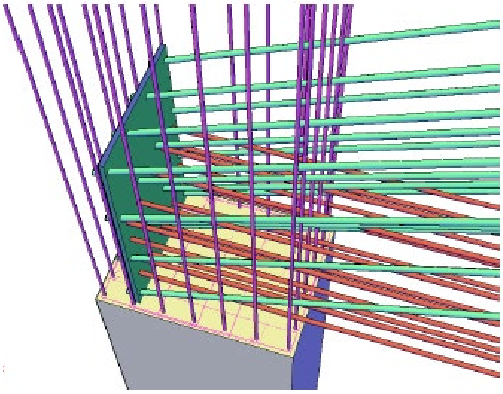


Figure 10. Detailing of concrete outrigger [5].

Traditionally outriggers consisted of structural steel trusses although reinforced concrete outriggers are also used in tall and supertall building construction. A difficulty in detailing RC outriggers is anchoring the reinforcement and finalising the column-outrigger connections due to reinforcement congestion. Different bespoke solutions can be adopted such as anchoring steel plates (Figure 10), couplers for overlapping and prefabrication of reinforcement cages [1].

5. Conclusions

The use and relevance of conceptual models for the analysis of supertall building has shifted in the last 30 years from analysis tools to verification tools. This paper shows that such models are still useful nowadays for verification purposes of advanced computational models. This is significant since international guidelines for engineering modelling are introducing as a requirement that all computer models should be verified using a conceptual model [9-10].

The following conclusions can be drawn

- The conceptual model commonly used for core-outriggers system developed by Smith and Salim in the 1980s [2] provides moments in the outrigers which are smaller than those obtained using FE models. Equally, the lateral deflections predicted using this conceptual model are larger than predicted using FE.

- The proposed model in [4] considering the reverse rotations of the outriggers provides closest predictions of the lateral displacements and moments in the outriggers to numerical results than existing classical formulae.
- A simplified model is presented to estimate the moments generated in the outriggers due to the differential settlement in the core and peripheral columns. The model based on a simple spring-propped cantilever provides comparable predictions to FE models.
- Member design and analysis of concrete outriggers can be carried out using stress field analysis and strut-and-tie modelling. Again these approaches enable the designer to use alternative conceptual models. Different STM optimization/topology techniques can be adopted depending on whether the focus is strength, stiffness or reinforcement quantity, leading to different alternative reinforcement layouts. Different challenges are highlighted regarding detailing concrete outriggers which are generally highly congested.

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