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Structural System Selection and Highlights of Changsha IFC T1 Tower

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Abstract

This paper presents the determination of the structural system of the Changsha IFC T1 tower with 452 m in architectural height and 440.45 m in structural height. Sensitivity analyses are carried out by varying the location of belt trusses and outriggers. The enhancement of seismic capacity of the outer frame by reasonably adjusting the column size is confirmed based on parametric studies. The results from construction simulation including the non-load effect of structures demonstrate that the deformation of vertical members has little effect on the load-bearing capacity of belt trusses and outriggers. The elastoplastic time-history analysis shows that the overall structure under rare earthquake load remains in an elastic state. The influence of the frame shear ratio and frame overturning moment ratio on the proposed model and equivalent mega column model is investigated. It is found that the frame overturning moment ratio is more applicable for judging the resistance of the outer frame against lateral loads. Comparison is made on the variation of these two effects between a classical frame-core tube-outrigger structure and a structure with diagonal braces between super columns under rare earthquakes. The results indicate that plasticity development of the top core cube of the braced structure may be significantly improved.

Keywords: Super high-rise structural system, Belt truss and outriggers, Sensitivity analysis, Outer frame, Plasticity development

1. General Information

The Changsha IFC project is located in Changsha CBD. This project consists of the T1 tower, T2 tower, annex and underground garage. The total construction area of the project is over 1 million meter squares.

The architectural height of the Changsha IFC T1 tower is 452 m, while its structural height is 440.45 m, with 92 storeys above the ground level. The architectural rendering is shown in Fig. 1.

2. Structural System

2.1. Lateral resistant system of tower

The lateral resistant system of T1 tower is mega column frame-core tube-outriggers-belt truss system where the core tube is the primary lateral force resisting system, while the mega column frame, belt truss and outrigger truss act as secondary (HalisGunel and EmreIlgin, 2007). Steel reinforced concrete columns were adopted for the external frame. The frame was connected with the core tube by outriggers. This may enhance the contribution of the outer frame column on the lateral resistance of the whole structure.

There are five belt trusses and two outriggers arranged in the tower, as shown in Figs. 2 and 3.

2.2 Gravity system of tower

A structural system of cast-in-situ reinforced concrete beam-slab was applied for the core tube of tower. Steel beams and composite slabs were used to connect the core tube with the outer frame. The typical floor thickness for offices and hotels was taken as 120 mm.

Typical floors of lower and higher zone of the tower are

Figure 1. Architectural rendering of the Changsha IFC.

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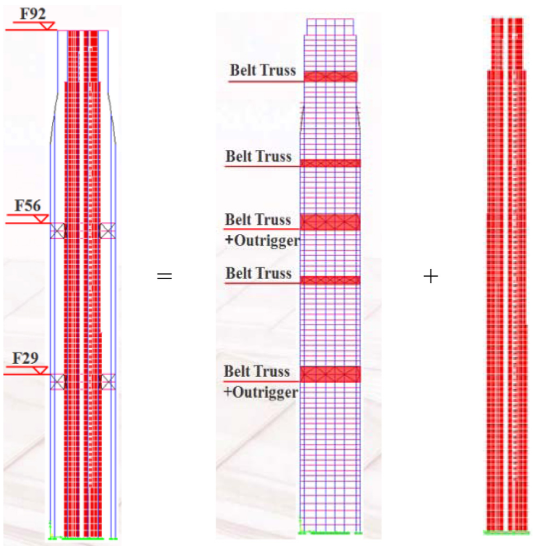


Figure 2. Lateral Resistant System.

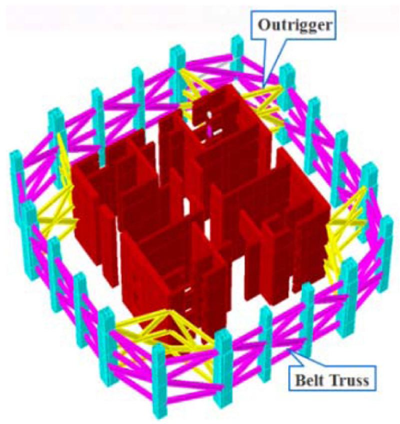


Figure 3. Typical storey with belt trusses and outriggers.

depicted in Fig. 4.

2.3 Sensitivity analysis of belt trusses and outriggers

In order to determine the location of belt trusses and outriggers of the T1 tower, the sensitivity analysis was performed based on the stiffness of the tower. The structural period, shear-weight ratio, stiffness-gravity ratio and

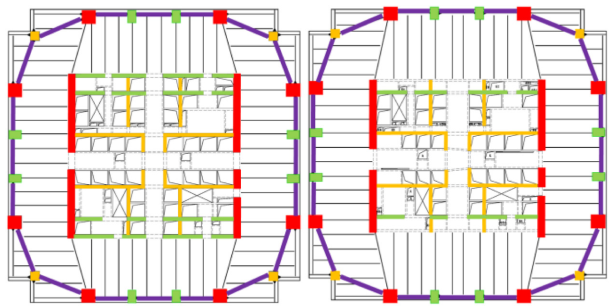


Figure 4. Typical floors of lower higher zone of the tower.

storey drift ratio are among the main influencing factors. Comparison is made based on frequent earthquakes.

Table 1 lists the comparison of main influencing factors for the above 7 schemes.

From Table 1 it can seen that the structural stiffness and factors are very close for scheme 1 and scheme 2, which meet the requirements of design code.

The core wall becomes thin at higher zones, which makes it difficult to connect outrigger members with the core wall. Considering that the distance between the mega column and core tube becomes small at higher zones, the efficiency of outriggers becomes low. It is also found that the two outriggers at lower zones make more contribution to the stiffness of the structure, shear-weight ratio and stiffness-gravity ratio.

According to the analysis, belt trusses can reduce structural displacement significantly. The floor thickness is extended to 200 mm at the belt truss floor, which makes the whole floor act as a virtual outrigger and thereby enhance the structural integrity. Belt trusses connecting the mega column, corner column and common column are to strengthen the integrity of the frame column. Therefore, the model with 5 belt trusses was adopted for the final scheme.

Taking reasonability of structural arrangement, construction convenience and economic advantages into account, the scheme 2 was taken as the final arrangement for belt trusses and outriggers.

2.4 Reasonable adjustment of column size

For the same concrete and steel consumption of outer

Table 1. Sensitivity analysis of belt trusses and outriggers

Scheme	1	2	3	4	5	6	7
Shear-weight ratio 1st floor X-direction	0.52	0.52	0.51	0.52	0.52	0.52	0.52
Shear-weight ratio 1st floor Y-direction	0.50	0.50	0.49	0.49	0.50	0.49	0.49
Stiffness-gravity ratio x-direction	1.86	1.81	1.73	1.79	1.79	1.72	1.71
Stiffness-gravity ratio y-direction	1.55	1.48	1.40	1.47	1.47	1.41	1.40
Storey drift ratio x-direction earthquake	1/1787	1/1705	1/1591	1/1675	1/1703	1/1631	1/1671
Storey drift ratio y-direction earthquake	1/1539	1/1454	1/1330	1/1413	1/1452	1/1396	1/1431
Periods T1/T2/T3	7.86/7.45/ 3.42	7.93/7.49/ 3.42	7.99/7.53/ 3.41	7.95/7.51/ 3.43	8.00/7.55/ 3.46	8.12/7.68/ 3.43	8.17/7.70/ 3.43

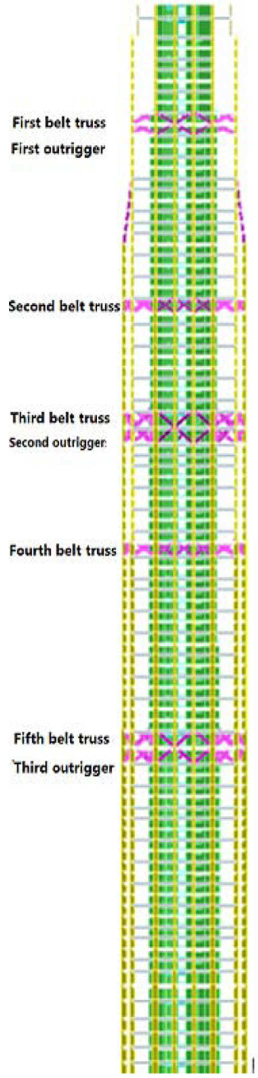
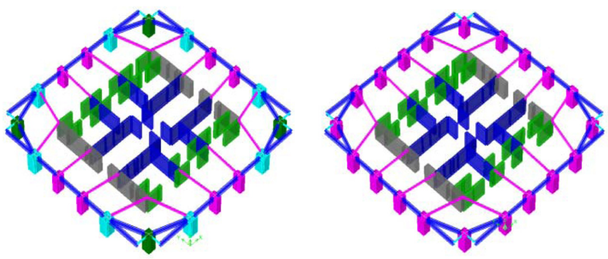


Figure 5. Scheme 1.



(a) Original model

(b) Equivalent model with equal column size

Figure 6. Original model and equivalent model with equal columns (same material consumption).

frame column, two models are compared:

Model 1: Enhanced corner columns and mega columns connected with outrigger trusses (Fig. 6(a));

Model 2: Equal size for all columns at one storey (Fig. 6(b))

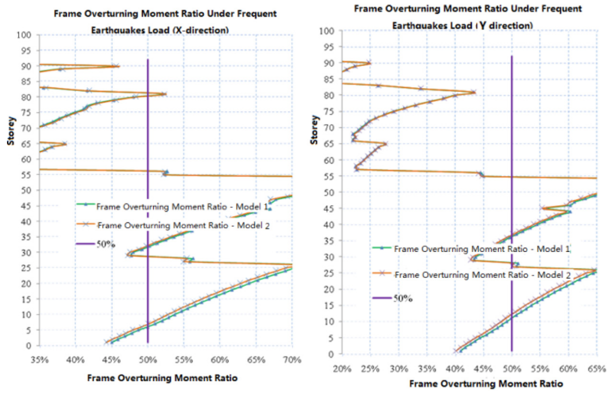


Figure 7. Comparison of the frame overturning moment ratio for Model 1and Model 2.

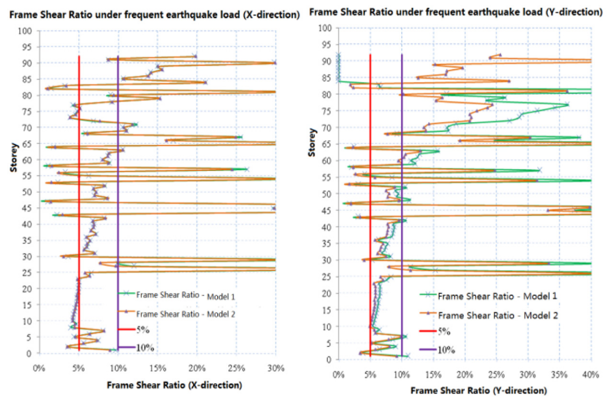


Figure 8. Comparison of the frame shear ratio for Model 1 and Model 2.

Table 2. Comparison of base shear force and overturning moment in wind tunnel test and Loading code

	V_x (kN)	M_y (kN.m)	V_y (kN)	M_x (kN.m)
2011 Load Code	41600	1.11E7	43600	1.19E7
Wind tunnel test	40220	1.01E7	43550	1.11E7

Figs. 7 and 8 show the variation of the frame overturning ratio and frame shear ratio, respectively.

The above diagrams illustrate that Model 1 has higher frame overturning moment ratio and frame shear ratio compared to Model 2. As the secondary defence in seismic design, the bearing capacity of the outer frame has been strengthened. Therefore Model 1 was accepted for columns.

3. Lateral Loads

3.1. Wind load

According to the suggestion of seismic review experts, the design of wind loads should be on the basis of wind tunnel tests.

3.2. Earthquake action

It is suggested that the maximum acceleration from seismic hazard study report (SHSR) should be taken for frequent, medium, and rare earthquakes, respectively. The seismic amplification coefficient was taken as 2.25. The response spectrum shape parameters were taken from the design code.

Taking frequent earthquakes for example, the response spectrum curves for design code, SHSR and seismic review experts recommended are shown in Fig. 9. (All of them have been converted to a damping ratio of 4%)

4. Elastic Analysis of T1 Tower

4.1. Main indices for elastic analysis

Results of elastic analyses are mainly shown in Table 3 (Malekinejad and Rahgozar, 2012).

5. Construction Simulation Considering Non-load Effects

The construction sequence was based on the tower construction progress plan and standard assumption of high-rise building construction sequence (Wang et al., 2013). CEB-FIP model in Eurocode was used to simulate concrete shrinkage and creep.

Relative compressive deformations between mega columns and the core tube at different phases are shown in Fig. 10.

Fig. 10 illustrates that the design of outriggers considering construction sequence and long-term load effect satisfies requirements of design stress ratio. Fig. 11 shows the differences of vertical deformations between mega columns and corner columns. Due to the uniformity in axial compression ratio, column sizes and ultimate strength between mega columns and corner columns, long-term compressive deformation may have little impact on the

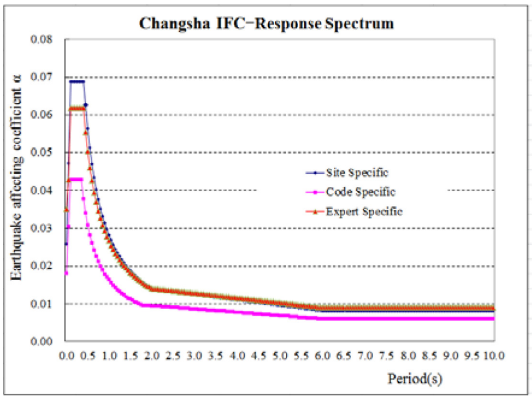


Figure 9. Comparison of response spectrum curves in different specifics.

Table 3. Main indices of elastic analysis

Items		Result	Notes/limits
Seismic mass (t)		519600	1.8t/m^2
period (s)	T1	7.58	Y-direction
	T2	7.18	X-direction
	T3	3.62	torsion
Wind load	X-direction	1/1069	1/500
	Y-direction	1/886	
Seismic action	X-direction	1/1183	
	Y-direction	1/1041	
Shear-weight ratio	X-direction	0.776%	0.737%
	Y-direction	0.728%	
stiffness-gravity ratio	X-direction	1.68	Satisfy requirement of 1.4, P-delta effect should be considered
	Y-direction	1.68	

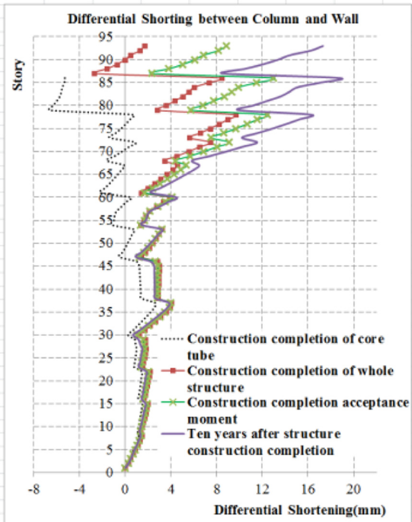


Figure 10. differential shortening between mega column and core tube at different phases.

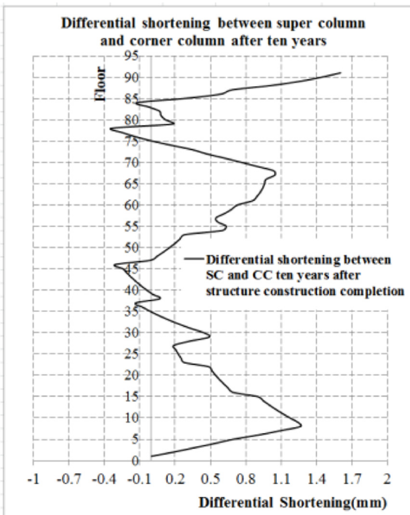


Figure 11. differential shortening between mega column and corner column after 10 years.

Table 4. Storey drift ratio under rare earthquake load

Elastoplastic storey drift ratio	X-direction storey drift ratio	Y-direction storey drift ratio	limit
maximum value	1/114	1/103	1/100
average value	1/172	1/166	1/100

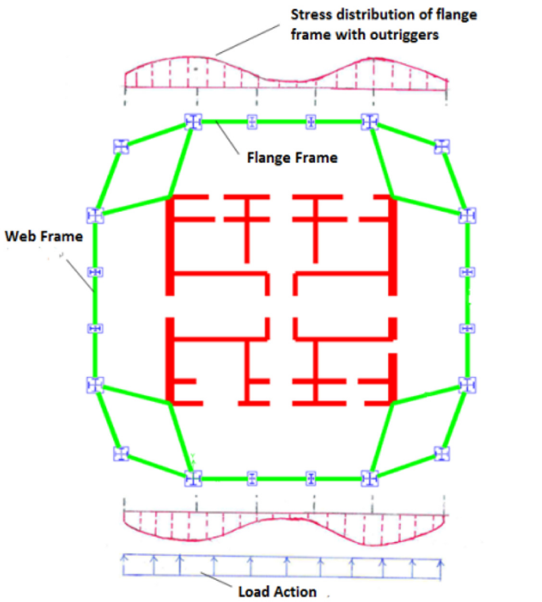


Figure 12. Phenomenon of "shear lag" of outer columns.

belt truss.

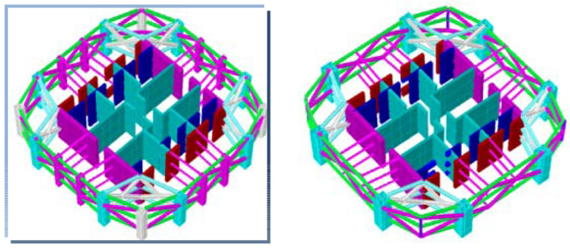
6. Dynamic Elastoplastic Time History Analysis

Through the elastoplastic time history analysis of structures under 7 groups of rare earthquake record with peak acceleration of 157 gal in 3 directions, the maximum story drift ratio is shown in Table 4 which agree well with requirements of the design code.

7. Discussion on Frame Shear Ratio and Frame Overturning Moment Ratio for Frame-core Tube Structure

Outriggers can reduce horizontal displacements of structures. This is because the outriggers and mega columns can prevent the rotation of the core tube. Therefore, the tension and compressive stiffness of columns at the two sides of outrigger are not fully used due to non-uniform distribution of axial forces acting on frame columns, shown in Fig. 12.

Keeping the same concrete and steel consumption of outer frame column, a new model was established to replace 20 frame columns of the original model by 8 mega columns connected directly by outrigger trusses, as shown in Fig. 13.



（a）original model （b）mega column model

Figure 13. The original model versus the mega column model.

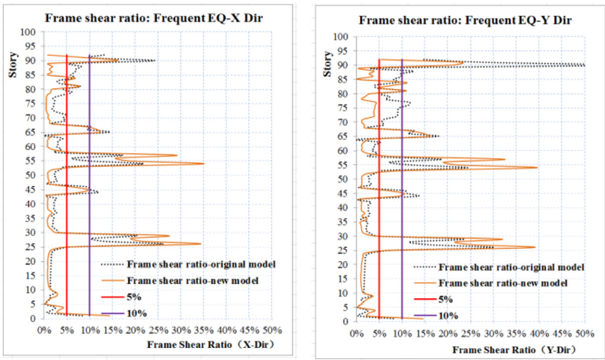


Figure 14. Frame shear ratio in two directions for both the original model and mega column model.

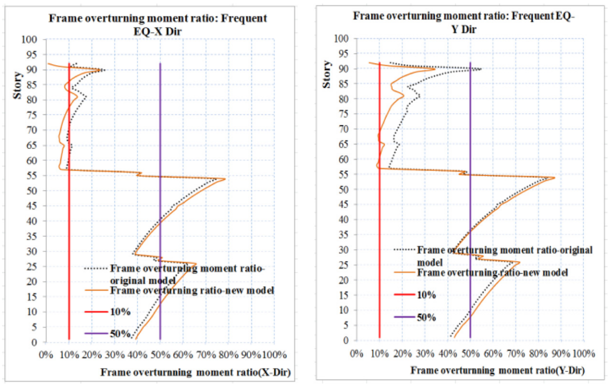


Figure 15. Frame overturning ratio in two directions for both the original model and mega column model.

The comparison of the frame shear ratio and frame overturning ratio in two directions between the two models are shown in Figs. 14 and 15, respectively. Periods of the two models are shown in Table 5.

According to the Table 5, after the replacement of 20 outer columns with 8 equivalent mega columns, the frame shear ratio is slightly reduced, but the frame overturning moment ratio is increased at lower zones of tower.

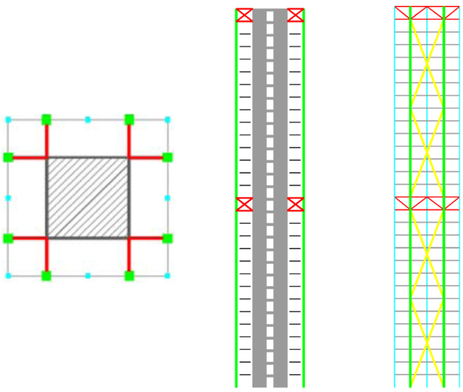
Therefore, the variation of the frame overturning moment ratio indicates the improvement of lateral resistant

Table 5. Periods of two models

		original model		mega column model		(2)/(1)-1
		period	Vibration mode	period	Vibration mode	
Period (s)	T1	7.97	Y- Direction	7.86	Y- Direction	-1.3%
	T2	7.46	X- Direction	7.33	X- Direction	-1.7%
	T3	3.69	Torsion	3.71	Torsion	0.5%

Table 6. Basic structural information for a typical mega frame - core tube - outrigger structure

Design intensity	Degree 8 (0.30g)	peak acceleration of rare earthquake	510 gal
Structural height	283 m	Height-width ratio	5.5
height-width ratio of core	13	Wall thickness of ground floor	1100 mm



(a) typical plane (b) model 1 elevation (c) model 2 elevation

Figure 16. Plane and elevation of model1 & model 2.

Table 7. Period of two models

	Model 1	Model 2	difference
T1(s)	6.17	5.75	-7%
T2(s)	5.88	5.45	-7%

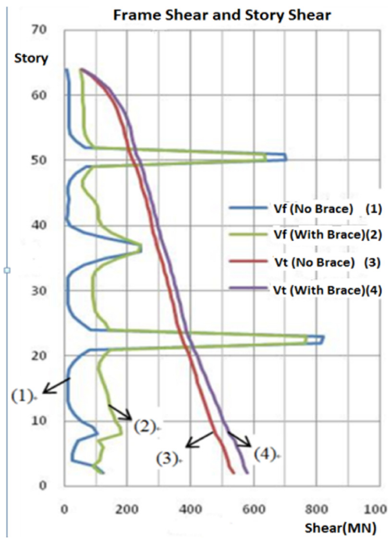


Figure 17. Frame shear (V_f) and story shear (V_t) of the two models.

efficiency for the mega column frame model due to shear lag phenomenon of outer frame.

After the replacement of outer columns, the frame shear ratio and frame overturning ratio changes slightly. This is because the original model has weakened "shear lag" due to the arranged 5 belt trusses working together with outer frame.

8. Correlation of Frame Shear Ratio, Overturning Moment Ratio and Degree of Damage of Core Tube

8.1. Parameters assumption

In order to study the relationship of the frame shear ratio, overturning moment ratio and degree of damage of the core tube, two models have been established:

Model 1: typical mega frame-core tube-outrigger structure system with basic structural information referring to Table 6.

Model 2: Base on the model 1, cross braces are arranged on four elevations between mega columns.

The period of two models are shown in the Table 7. The stiffness of structures increases due to the application of braces.

8.2 Storey internal stress analysis

The frame shear and storey shear are shown in Fig. 17.

The comparison of the frame shear ratio and frame overturning ratio of the two models are shown in Figs. 18 and 19, respectively.

The following conclusions can be drawn from the above diagrams:

As structural stiffness increases, the total story shear force increases slightly.

By using braces, the frame shear ratio is increased from 2~4% (Model 1) to 15~20% (Model 2)

The frame overturning ratio does not increase significantly, except the story above the upper outrigger truss.

8.3. Performance analysis of core tube under rare earthquakes

Plastic development of the core tube of Model 1 and

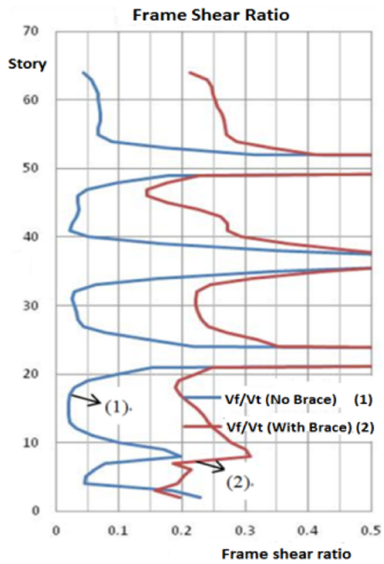


Figure 18. Frame shear ratio.

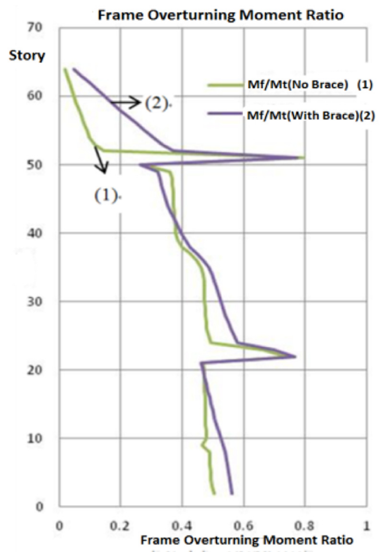
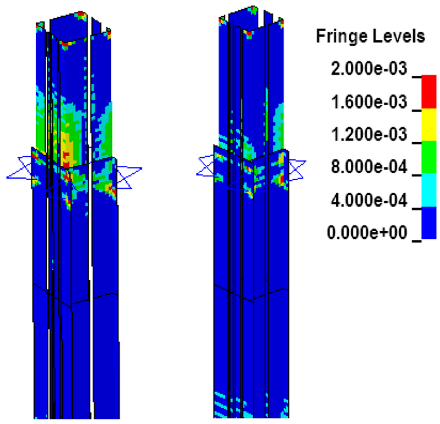


Figure 19. Frame overturning moment ratio.



(a) Model 1 (b) Model 2

Figure 20. Plastic development of the core tube for model 1 and model 2 under rare earthquakes.

Model 2 under rare earthquakes is compared in Fig. 20.

Under rare earthquakes, the tension and compressive strain changes slightly at the bottom of the core tube. By using braces, the tension strains of the core tube at the story above outrigger declines largely. The frame overturning moment at the top increases, whilst the core-tube overturning moment reduces significantly. The stiffness of the structure increases due to the application of braces. The increasing frame overturning moment ratio indicates the reducing influence of high vibration modes.

9. Conclusions

The Changsha IFC T1 tower is a super high-rise structure with a lateral resisting system of mega column frame-core tube-belt truss-outrigger system. The conclusions can be drawn as follows:

(1) Considering the efficiency and construction convenience of belt trusses and outriggers, five belt trusses and two outriggers are arranged on mechanical floors. In this way the floor slab with both upper and lower chords of trusses is strengthened.

(2) Based on the same material consumption of outer frame column, two models have been compared: one with equal cross-section frame columns and the other with enhanced corner columns and mega columns connected with the outrigger truss. It is found that the mega column model has higher frame overturning moment ratio and frame shear ratio, thus is selected for the scheme of columns.

(3) The construction simulation considering non-load effect indicates that the vertical deformations of frame columns and the core tube slightly influence belt trusses and outriggers.

(4) The dynamic elastoplastic analysis of structures manifests that, under rare earthquakes, the overall structure is in an elastic state and the displacements of the structure meet the requirement prescribed in design codes.

(5) Based on the same material consumption of outer frame columns, 20 frame columns in the original model are replaced by mega columns connected directly with outrigger trusses. For this new model, the frame overturning moment ratio is preferred to reflect the efficiency of the outer frame against horizontal loads compared to the frame shear ratio.

(6) By applying diagonal braces between mega columns in the outer frame of the frame-core tube-outrigger structure, the structural stiffness and frame shear ratio increases significantly; while the frame overturning moment changes slightly except the story above the first outrigger. The analysis of structures under rare earthquakes demonstrates that plasticity of at the top of the core tube is obviously

improved compared with the bottom core tube.

References

HalisGunel, M. and EmreIlgin, H. (2007). A proposal for the classification of structural systems of tall buildings. *Building and Environment*, 42(7), pp. 2667~2675.

Li, T., Chen, Y., and Xiao, F. (2012). Super Frame and Frame-core tube Composite Structural System Design. *Building Structure*, 42(12), pp. 19~25.

Jijun. (2013). Wind Tunnel Simulation of typical super high structure is influenced by adjacent building. *Computer Assistant Project*, 22(5), pp. 74~78.

Malekinejad, M. and Rahgozar, R. (2012). A simple analytic method for computing the natural frequencies and mode shapes of tall buildings. *Applied Mathematical Modelling*, 36(8), pp. 3419~3432.

El-Sokkary, H. and Galal, K. (2009). Analytical investigation of the seismic performance of RC frames rehabilitated using different rehabilitation technique. *Engineering Structures*, 31(9), pp. 1955~1966.

Wang, H., Fan, F., and Zhi, X. (2013). Change rule of vertical deformation of super-high structure construction and research of pre-deformation control. *Engineering Mechanics*, 30(2), pp. 298~300.