Crack formation of steel reinforced concrete structure under stress in construction period

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ABSTRACT. To obtain deformation rules of steel reinforced concrete structure under stress, this study explored the crack formation in construction period. A novel structure system – steel reinforced concrete structure with shear wall and truss at the bottom was analyzed using on-the-spot test in combination with theoretical simulation analysis with SAP2000 software. It was found that, factors influencing crack formation of steel reinforced concrete structure in construction period included construction load, creep of concrete, shrinkage of concrete, displacement of bond of section steel and concrete as well as leveling. In the construction period, the simulated results and the measured results were highly fitted under the influence of time-variant characteristics such as compressive strength, elasticity modulus, creep and shrinkage. Through processing and analyzing the measured data, we obtained the development rules of crack formation of steel reinforced concrete structure with different strength grades as well as deformation rules of time-varying structure system in construction period, figured out the reason for the difference between the simulated results and the measured results, analyzed the deformation of structural components under stress in construction period and proposed some suggestions. This work is beneficial to ensure safe and high-efficient operation of construction.

KEY WORDS: Crack; Steel reinforced concrete; Stress in construction period; Theoretical simulation analysis; SAP2000.

INTRODUCTION

With the development of economy, steel reinforced concrete structure has been applied more extensively in super high-rise building for its special advantages of high bearing capacity, large rigidity, sound anti-seismic property and convenient installation [1]. In modern construction, construction safety is especially important. Hence major factors influencing crack formation of steel reinforced concrete structure needs to be further studied [2, 3]. Large binding force between section steel and concrete is the foundation ensuring their coordination in steel reinforced concrete structure [4]. Section steel, rebar and concrete coordinate together to resist external effect, thus fully display the advantages of steel reinforced concrete structure [5]. On account of this, it is of great significance to deeply study steel reinforced concrete, explore its structure performance and apply it into engineering practice [6].
Based on the detailed cases of crack formation of steel reinforced concrete structure in actual engineering and the previous research achievements, Deierlein and Noguchi [7] obtained the distribution rule of load of steel reinforced concrete structure and the prediction model of compressive strength, shrinkage and creep of concrete, providing a theoretical basis for analysis of performance of steel reinforced concrete structure and factors influencing crack formation

under stress. Through analyzing the structure form and stress performance of the commonly used steel reinforced concrete beam-column joints as well as factors inducing crack formation, Hierro et al. [8] pointed out the defects existing in the researches carried out by Chinese scholars which concern beam-column joints of steel reinforced concrete. The study carried out by Zhao et al. [9] analyzed the distinction between one-off loading and simulated loading adopted in steel reinforced concrete structure using finite element software, which provides an important basis for the design and construction of modern high-rise building.
This study explored the crack formation of steel reinforced concrete structure, clarified the development rules of deformation of steel reinforced concrete structure in different strength grades and deformation rules of steel beam in time-varying structure system, analyzed the major reason leading to the deviation by comparing the measured results with the simulated results, and put forward some suggestions to ensure safe and high-efficient construction.

ANALYSIS ON CRACK FORMATION OF STEEL REINFORCED CONCRETE STRUCTURE UNDER STRESS

Double-tube structure of reinforced concrete

Reinforced concrete double-tube structure refers to the peripheral frame structure whose middle part is two parallel tubes and includes plain concrete structure, reinforced concrete structure and prestressed concrete structure. Fig. 1 shows the construction drawing of an office building with a reinforced concrete double-tube structure.

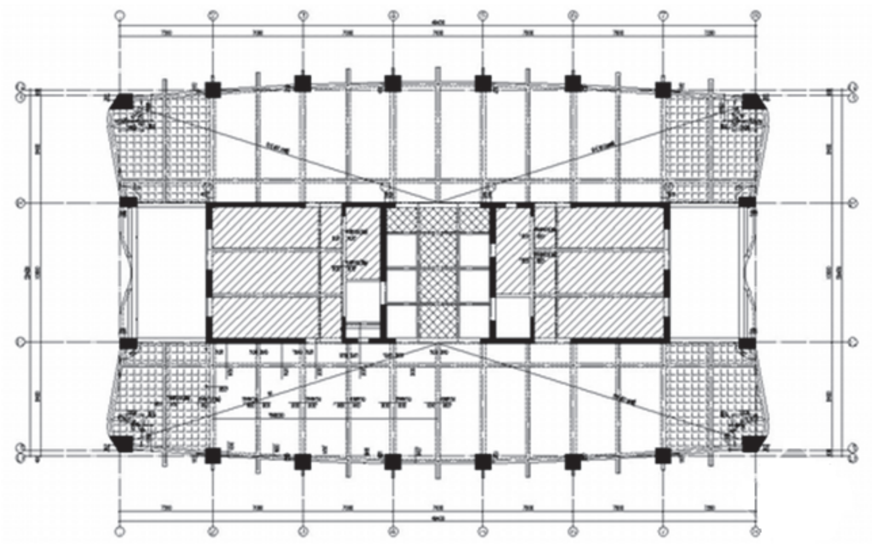

Figure 1: Reinforcement drawing of the 4th floor to the 20th floor of an office building.

Deformation of steel reinforced concrete filled double-tube structure in construction period

The first issue is the vertical deformation of steel reinforced concrete filled double-tube structure [10]. Steel reinforced concrete filled double-tube structure is a time-varying structure system. Material performance, structure rigidness, boundary condition and construction load all varies with time. Vertical deformation of components of high-rise steel reinforced concrete filled double-tube structure in construction period mainly includes instantaneous elastic deformation, creep deformation and contraction deformation. Fig. 2 shows the time-varying deformation of concrete.
For high-rise structure over 10 layers, the effect of vertical deformation needs to be given special consideration. The difference of vertical deformation would make beam or plate to generate additional bending moment and shearing force. If no measures adopt, the component is prone to crack during construction and even induce accidents and result in personal casualty.
The second issue is about the horizontal deformation of steel reinforced concrete filled double-tube structure [11]. Compared to the vertical deformation, the horizontal deformation of steel reinforced concrete filled double-tube structure is less outstanding. In construction period, some destabilizing factors may exist under horizontal load as elasticity modulus of concrete materials has not reached the designed value and moreover internal and external tubes have not formed complete coordinated lateral resistant system along with steel framework.

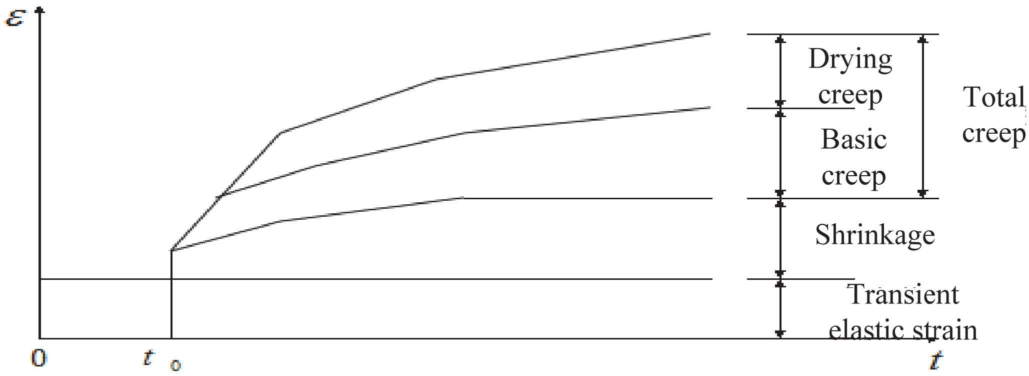

Figure 2: Vertical deformation of concrete under continuous load and drying effect.

Shear capacity of steel reinforced concrete structure

Before initial cracking, concrete in steel reinforced concrete joints plays a function of shear resistance [12]. As load increases, diagonal crack forms along the diagonal line of joints and then diagonal strut comes into being. Anti-shear capacity of concrete in steel reinforced concrete joints can be expressed as:

$$V_c = \gamma b_j h_j f_c \tag{1}$$

where f_c refers to compressive strength of axis of concrete; generally, joint section height h_j is equal to column section height h, i.e., $h_c = h_j$; b_j stands for surface width of joint core area; γ stands for an undetermined coefficient which reflects anti-shear capacity of concrete in steel reinforced concrete joints under various constraints.
To obtain the specific value of anti-shearing coefficient γ, the following formula is used.

$$\gamma = \frac{V_j^t - V_s - V_{sv}}{b_j h_j f_c} \tag{2}$$

where V_j^t stands for measured ultimate bearing capacity of joints; V_s stands for actual strength of material; V_{sv} stands for bearing capacity of section steel web and hooping of joints.

FACTORS INFLUENCING CRACK FORMATION OF STEEL REINFORCED CONCRETE STRUCTURE UNDER STRESS IN CONSTRUCTION PERIOD

Construction load

Construction load can be divided into construction dead load, construction live load and accidental load according to action time, and can be divided into vertical loading, horizontal loading, additional vertical load and special load according to action direction.

Creep of concrete

Creep of concrete refers to plastic deformation of concrete under single-axial stress effect along stress direction as time goes on [13]. Creep is composed of basic creep and drying creep. Ignoring the fact that creep deformation is larger than deformation of dried concrete under loading effect, creep is considered as a kind of deformation which has exceeded free shrinkage under loading effect (Fig. 3).
Major factors influencing creep included exerted stress, water cement ratio, curing condition, temperature, humidity, cement composite, aggregate, chemical admixture, geometrical shape of test specimen and loading age.

Shrinkage of concrete

Shrinkage of concrete which refers to volume reduction of concrete induced by factors such as changes of water content, chemical reaction and temperature decrease includes drying shrinkage, cold shrinkage, condensation shrinkage, autogenous shrinkage, carbonization shrinkage, etc.

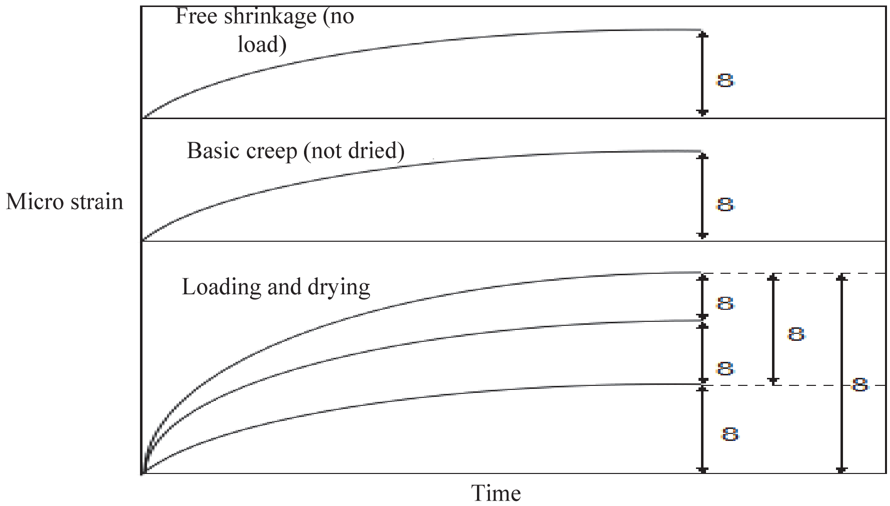

Figure 3: Creep of concrete under continuous loading and drying effect.

Bounding force between section steel and concrete

Bounding force between section steel and concrete is mainly composed of chemical bounding force, frictional resistance and mechanical interaction. On account of the bounding force between section steel and reinforced concrete, section steel can work along with concrete to shoulder load [14].

Construction leveling of high-rise building

In construction, core tube and external framework will both deform under the effects of their own weights and construction loading; due to the compression of structure, the height of buildings will decrease [15]. To solve the problem, construction leveling is adopted in actual construction to make up the loss caused by vertical compressive deformation [16, 17]. The following two methods are usually adopted to perform construction leveling.
(1) Improve rigidness of vertical component. In this way, vertical component can achieve the same deformation under vertical loading effect.
(2) Constrain degree of freedom of vertical component. When construction is over, deformation of different floor can be obtained using the following formula.

$$\Delta_n = \sum_{k=1}^{n} \frac{L_k}{E_k A_k} \sum_{i=1}^{N} P_i \qquad (3)$$

where Δn stands for deformation of structural layer of any floor; L_k stands for the height of floor k; $E_k A_k$ stands for rigidness of floor k; P_i stands for the load loaded by floor i.

ACTUAL MEASUREMENT

Protocol of actual measurement

Steel reinforced concrete filled double-tube structure with shear wall and truss at the bottom was measured. In Fig. 3, Shenzhen Peace Finance Building (Fig. 4) adopts a novel structure system - steel reinforced concrete filled double-tube structure with shear wall and truss at the bottom, which is different from the conventional tube structure. Floors 1 ~ 6 are equipped with shear wall and the internal and external tubes of floors above the standard floor are all steel reinforced concrete columns.

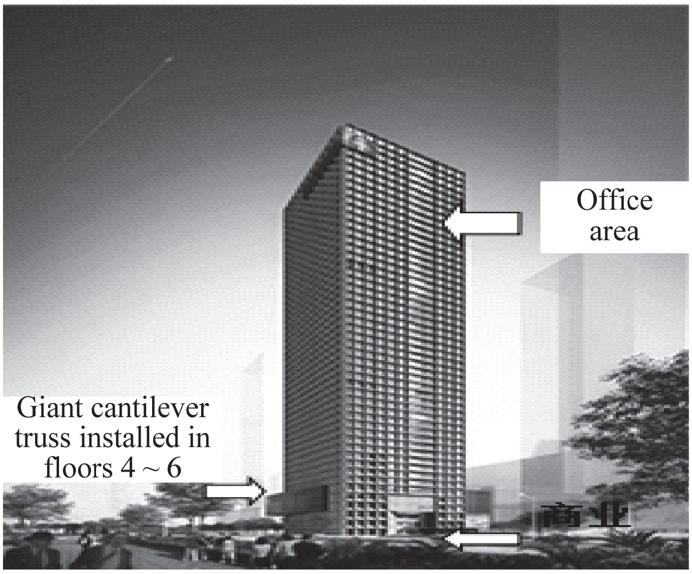

Figure 4: Entitative graph of Shenzhen Peace Finance Building.
Note: Floor 1 ~ 3 are commercial districts; floor 4 ~ 6 are installed with giant cantilever truss; and the 6th floor above are office areas.

Test instruments

XHX-115W embedded strainometer, XHX-215W surface strainometer and XHX-322W reinforcement meter were used as test instruments in this study. XHX-115W embedded strainometer is usually embedded in beam, column, pile foundation and retaining wall to monitor development rule of strain and stress [18]. The calculation formula is as follows.

$$\varepsilon = K \times f^2 \tag{4}$$

$$\Delta\varepsilon = \varepsilon_i - \varepsilon_0 \tag{5}$$

where ε stands for absolute strain capacity (10^{-6}), f stands for wire vibrating frequency, K stands for calibration coefficient (K =0.002), ε_i stands for strain in state *i* (i.e., at the moment of deformation) (unit: με), ε_0 stands for strain at time 0 (unit: με), and Δε stands for relative strain value (unit: με).

$$\Delta\varepsilon = (\varepsilon_i - \varepsilon_0) + 1.8(T - T_0) \tag{6}$$

where T stands for measured temperature in state I (i.e., at the moment of deformation) and T_0 stands for measured temperature at time 0.

Major test works

Test works mainly involve template erection of floor above the measured floor, beam-column and plate-column rebar binding of floor above the measured floor [19], concrete pouring above the measured floor, removal of template of floor above the measured floor, removal of template of floor above and below the measured floor, large live load such as loading or uploading of large equipments and materials [20] and adjustment of times of tests according to special conditions appearing during construction. It should be pointed out that, on-the-spot monitoring is needed during concrete pouring so as to prevent strainometer from the damage of vibration and protection of port of strainometer is also needed.

Experimental test

Setting and installation: First, observation spots needs to be selected according to structure requirements and designing scheme. Then a strainometer is installed paralleling to the direction of strain. Whether protection cover for the mounting base of strainometer needs to be installed or not depends on testing requirements. Testing wires are led along with steels and bound with winding sires. After pouring of concrete is over, initial readings on the strainometer are tested to confirm its normal operation.

Layout of on-the-spot observation spots: To meet the requirements on loading bearing and rigidness of the structure, four corner posts are designed into L-shaped multilateral columns. Load of columns, evenly distributed load of floors and live load of floors are transmitted to every column through column. Strain sensors are installed on the corner posts on the bottom floor, 10th, 19th, 29th, 35th, 36th, 39th, 42th and 45th floor and every corn post is set with two observation spots. Besides, the horizontal coupling beams of the corner posts on the 5th, 18th and 38th floor are installed with strain sensors. To be specific, the upper and lower flanges of corner posts are installed with sensors, one on each side. Strain rosettes are installed on web plate. In this way, the bending moment and shearing force loaded by the steel beam can be monitored.

ANALYSIS WITH SAP2000 SOFTWARE [21]

Procedures of analysis of SAP2000 software

SAP2000 is a finite element analysis software aiming at structure and it provides various forms of unit composition. Herein we adopt SAP2000 to make a force analysis on the simulated structure during construction. The analysis procedures are shown in Fig. 5.

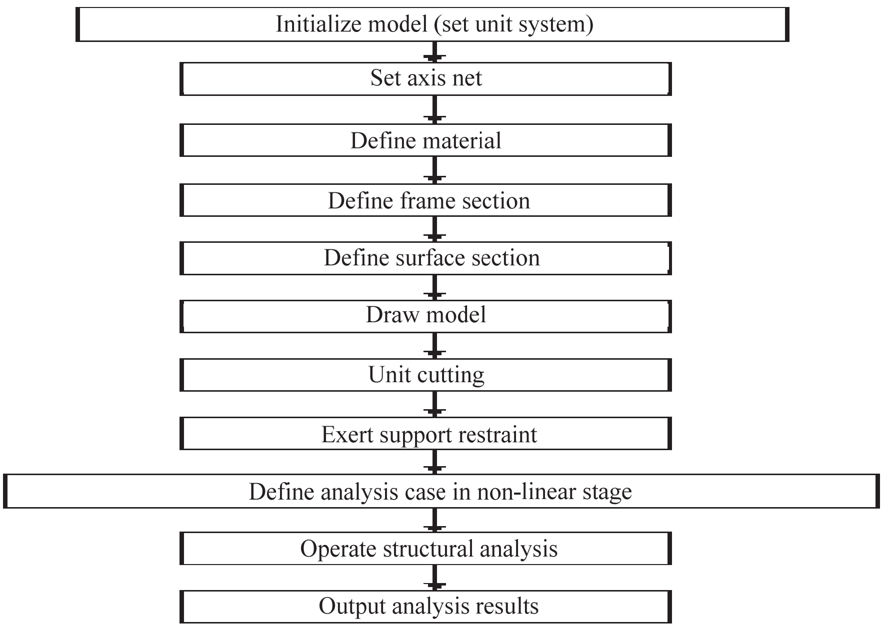

Figure 5: Procedures of analysis with SAP2000.

Note: axis net: right click, edit data of axis net and add new systems; define material: define steel and concrete, but when there is no materials which need to be defined in quick addition of materials, user-defined is needed; define section: frame unit is used to stimulate beam, column, inclined strut, truss, net rack and so on; draw model: section is usually drawn after definition is over; exert support restrain: switch to the top layer - select joint of support which needs to be defined – restrain the specified joint; define analysis case in non-linear stage: define – load pattern including dead load, live load, wind load, etc.

Model simplification

The achievable level of SAP2000 was improved to ensure the practicability and accuracy of the analysis. A building model which was 48-floor high was simplified. In the process of non-linear simulation analysis, only the weight of structure was considered, and the ffect of live load and earthquake on the deformation of structure was not taken into account. To simply modeling and calculation, the fresh concrete was given an initial age of five days. When the model was being established, compressive strength, elastic modulus and time-varying properties of contraction and creep of concrete were considered. Finite element method was used to divide the plate. Considering effect of the rigidness of floors, the time-varying property of concrete material was not taken into account in the process of simplification of floor design [21]. Using the simplification method mentioned above, we set up a model using definite element analysis software (Figs. 6 and 7).

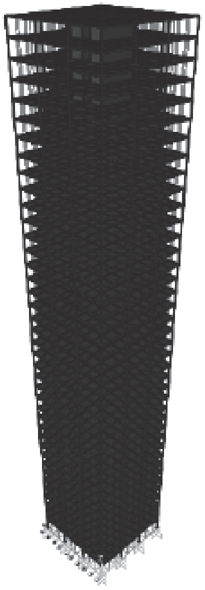

Figure 6: Simulation model of construction

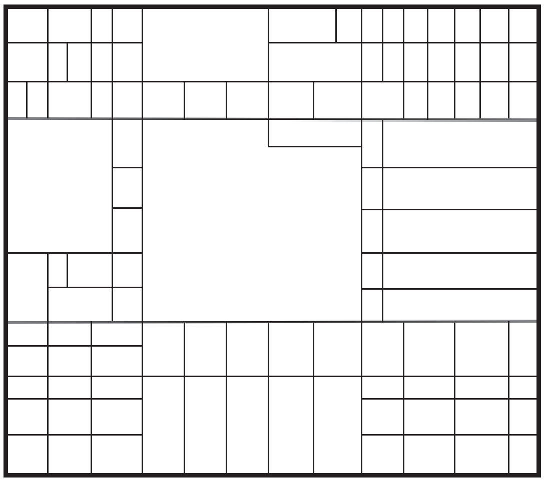

Figure 7: Model of the standard floor

RESULTS AND DISCUSSION

Analysis of computing results

Analysis and comparison of the simulated results and the measured value of vertical deformation of C60 concrete component is shown in Figs. 8 ~ 10.

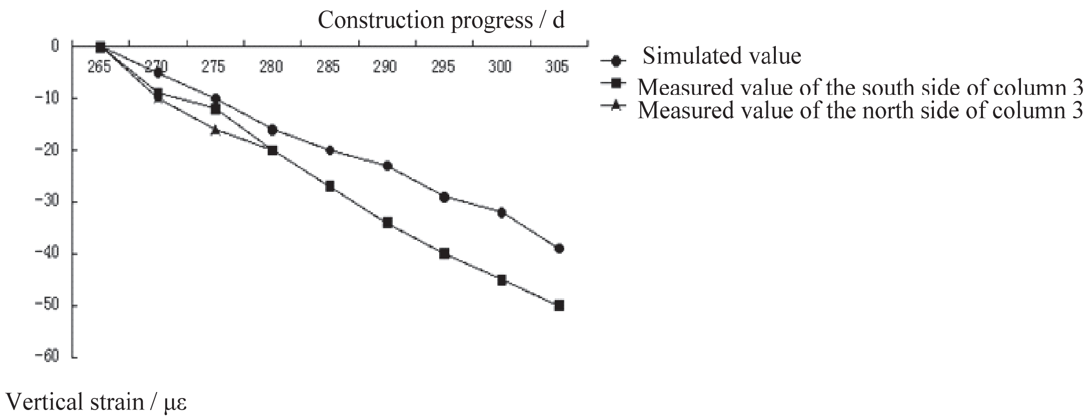

Figure 8: Comparison of the measured value and the simulated value of the vertical deformation of bottom column 3

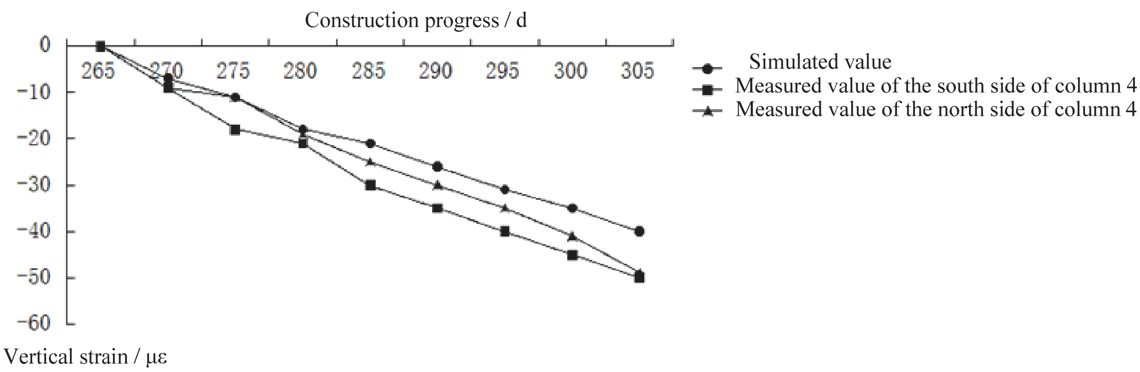

Figure 9: Comparison of the measured value and the simulated value of the vertical deformation of bottom column 4.

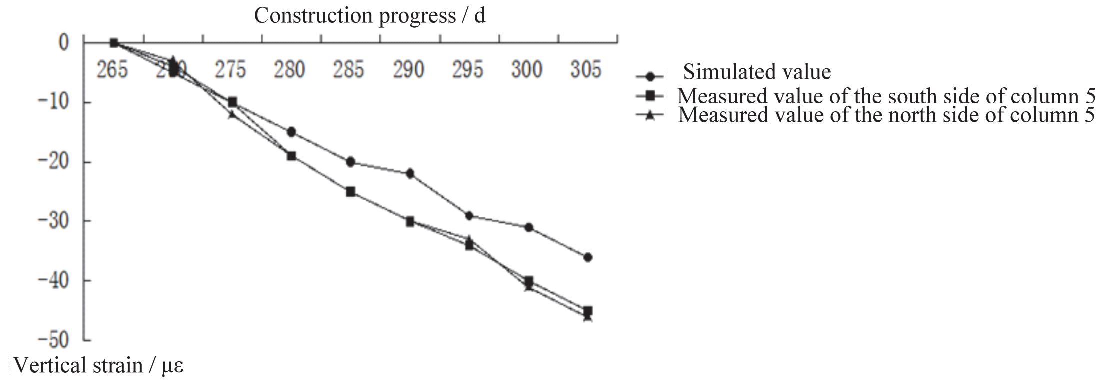

Figure 10: Comparison of the measured value and the simulated value of the vertical deformation of bottom column 5.

It can be seen from Figs. 8 ~ 10 that, development rate of the measured value of the vertical deformation of steel reinforced concrete (C 60) in the late stage was larger than that of the simulated value in the same period, and the difference of deformation became more and more obvious as time went on.

Analysis and comparison of the simulated results and the measured results of vertical deformation of C50 concrete component is shown in Fig. 11.

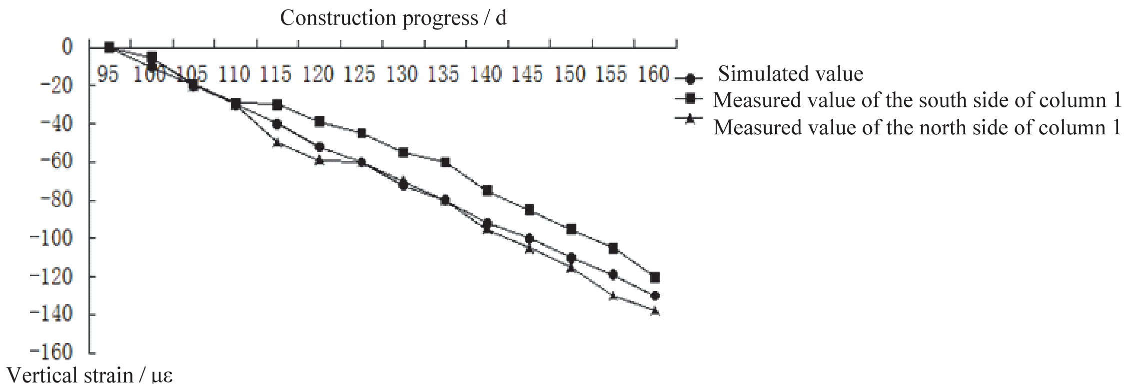

Figure 11: Comparison of the measured value and the simulated value of the vertical deformation of bottom column 1 of the 20th floor.

It can be seen from Fig. 11 that, development rate of the measured value of the vertical deformation of steel reinforced column (C50) was highly fitted with that of simulated value; and the eccentricity of the frame column was relatively low.

Analysis and comparison of the simulated results and the measured results of the vertical deformation of C40 concrete component is shown in Fig. 11.

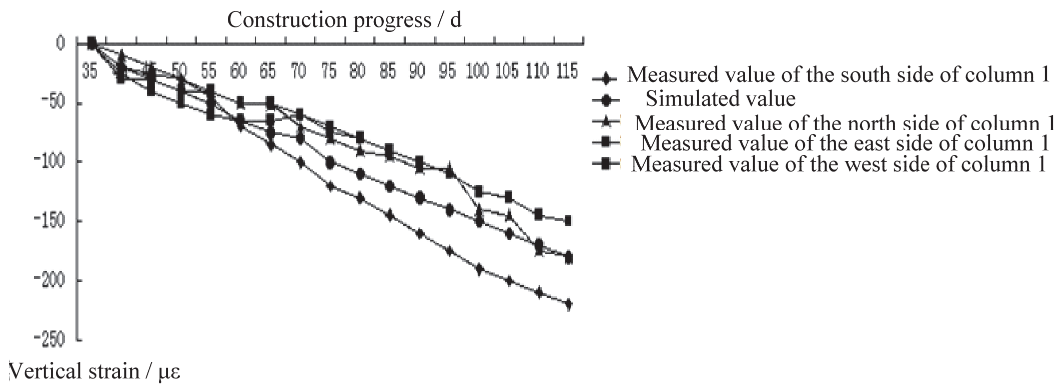

Figure 12: Comparison of the measured value and the simulated value of the vertical deformation of bottom column 1 of the 29th floor.

It can be seen from Fig. 12 that, development rate of the measured value of the deformation of steel reinforced concrete (C40) column was large in early age, much larger than that of the simulated value; but development rate of the measured value of the deformation was smaller than that of the simulated value in the late stage.

CONCLUSION

With the rapid development of economy and constant progress of society, high-rise building has been favored by more and more people [22]. Steel reinforced concrete structure featured by high bearing capacity, good anti-seismic performance and good ductility has been applied more and more in high-rise building. Hence it is of great importance to understand the crack formation of steel reinforced concrete structure under stress in construction period.

In this study, we discussed over the reasonability of definite element analysis of steel reinforced concrete structure [23]. It can be known from the actual measurement of deformation that, deformation rate of steel reinforced concrete (C60, C50) column in low floor became higher than the simulated value in the late period; and the vertical deformation of steel reinforced concrete (C50, C60) column was smaller than that of steel reinforced concrete (C40) column [24]. During construction, deformation of structural component and accumulation of stress are different as construction order and procedures of exerting construction load are different. Timely adjusting strength and section size of steel reinforced column of internal and external tubes can not only save building materials and narrow the gap of vertical deformation, but also benefit structural safety and construction [25]. The number of floors has large impact on accumulative vertical deformation difference. With the increase of the number of floors, accumulative vertical deformation of vertical component sharply increases. But the impact of construction speed on accumulative vertical deformation difference is small. In such a special structural system, accumulative deformation of steel reinforced concrete column of internal and external tubes is different. With the increase of constructed floors and load, accumulative deformation difference becomes larger. During construction, relevant measures need to be adopted to avoid the generation of additional stress.

SUGGESTIONS FOR CONSTRUCTION

Several points are suggested for construction. First, the adjustment of fabrication length is needed in the construction [26]. Preadjustment measures can be considered to deal with the deformation of steel structure. When construction period is short, form removal should be performed in advance [27]. Besides, rigid connection needs to be performed after hinged connection. Strain of column needs to be improved if construction slows down due to the influence of development of strength of column and support system [28]. Concrete placement sequence needs to be ensured consistent in every area of every floor [29]. Field needs to be utilized effectively to accelerate the progress of construction.

REFERENCE

[1] Zheng, S., Su, Y., Zhang, W., Li, Q., Experimental study on seismic performance of joints in the castellated portal frame of light-weight steel, Building Structure, 44(12) (2014) 80-84.

[2] Yang, X., Xueyi, FU., Dynamic elasto-plastic analysis of the Shenzhen Ping'an Financial Center Tower, Journal of Building Structures, 32(7) (2011) 40-49.

[3] Baev, A. R., Asadchaya, M. V., Features of the reflection of an acoustic beam from a surface with nonuniform boundary conditions, I. Theoretical analysis, Russian Journal of Nondestructive Testing, 46(8) (2010) 547-558.

[4] Huttunen, H., Tohka, J., Model selection for linear classifiers using Bayesian error estimation, Pattern Recognition, 48(11) (2015) 3739-3748.

[5] Gerilla, G. P., Teknomo, K., Hokao, K., An environmental assessment of wood and steel reinforced concrete housing construction, Building & Environment, 42(7) (2007) 2778-2784.

[6] Vayas, I., Adamakos, T., Iliopoulos, A., Three dimensional modeling for steel-concrete composite bridges using systems of bar elements — Modeling of skewed bridges, International Journal of Steel Structures, 11(2) (2011) 157-169.

[7] Deierlein, G. G., Noguchi, H., Overview of U.S.–Japan Research on the Seismic Design of Composite Reinforced Concrete and Steel Moment Frame Structures, Journal of Structural Engineering, 130(2) (2004) 361-367.

[8] Hierro, J., Aznar, A., Hernando, J. I., De, I. T. J. F., Ortiz, J., Criteria for steel structures reinforcement: Restoration of the "Círculo de Bellas Artes" building and the Cultural Center "Casa Encendida", Informes De La Construcción, 29(2) (2014) 5-21.

[9] Zhao, K., Zhu, Z., Experimental study on behavior of the channel - masonry - concrete composite structures, Applied Mechanics & Materials, 578-579 (2014) 1251-1256.

[10] Tong, J. X., Jia, N., Luo, P. F., Experimental Study on Base Reaction and Deformation Characteristic of Variable Modulus Foundation for Frame-Tube Structure, Applied Mechanics & Materials, 638-640 (2014) 445-451.

[11] Goel, M. D., Deformation, energy absorption and crushing behavior of single-, double- and multi-wall foam filled square and circular tubes, Thin-Walled Structures, 90 (2015) 1-11.

[12] Movahed, S. O., Ansarifar, A., Karbalaee, S., Far, S. A., Devulcanization and recycling of waste automotive EPDM rubber powder by using shearing action and chemical additive, Progress in Rubber Plastics Recycling Technology, 31(2) (2015) 87-117.

[13] Matthieu, V., Franz-Josef, U., Nanogranular origin of concrete creep, Proceedings of the National Academy of Sciences of the United States of America, 106(26) (2010) 10552-10557.

[14] Yan, C. W., Jia J. Q., Zhang J. Crack Pattern and Ductility of Steel Reinforced Ultra High Strength Concrete Composite Joint Subjected to Reversal Cycle Load, Key Engineering Materials, 417-418 (2010) 845-848.

[15] Cheng, P., Chen, X. F., Wu, L., Construction Technology of High-Rise Building Structure, Applied Mechanics & Materials, 580-583 (2014) 2316-2319.

[16] Zhu, C. M., Hao, J. M., Li, C., Shuang, W. Y., Liu, P. H., Well-facilitied capital farmland construction based on cultivated land comprehensive quality, Transactions of the Chinese Society of Agricultural Engineering, 31(8) (2015) 233-242.

[17] Oh, H. K., Park, S. M., Hong, S. I., Hot Deformation and Cracking during Compression of 21-4N Steel, Advanced Materials Research, 1102 (2015) 12-21.

[18] Dierenfeldt, R., Lindsteadt, G., Laan, J., Sobba, K. N., Big Brother as a Contract Monitor: An Assessment of the Use of Contract Staff to Monitor Offender Communications, American Journal of Criminal Justice, (2015) 1-17.

[19] Guo, J. S., Xie, X. Y., Experimental Study on the Influence of Slab's Reinforcement on Seismic Bearing Capacity of Beam's Cross-Section in Cast- In Situ Frame Structure, Applied Mechanics & Materials, 353-356 (2013) 1986-1989.

[20] Kocsis, P., Discussion of "Simplified Method of Lateral Distribution of Live Load Moment", Journal of Bridge Engineering, 10(5) (2015) 630-631.

[21] Hocker, J., Bein, B., Bohm, R., Steinfath, M., Scholz, J., Horn, E. P., Correlation, accuracy, precision and practicability of perioperative measurement of sublingual temperature in comparison with tympanic membrane temperature in awake and anaesthetised patients, European Journal of Anaesthesiology, 29(29) (2012) 70-4.

[22] Bentick, B. L, Lewis, M. K., Real Estate Speculation as a Source of Banking and Currency Instability: Some Different Lessons from the Asian Crisis, Economic & Labour Relations Review, 14(2) (2004) 256-275.

[23] Hellwig, F. L, Tong, J., Hussell, J. G., Hip joint degeneration due to cam impingement: a finite element analysis, Computer Methods in Biomechanics & Biomedical Engineering, 19(1) (2016) 1-8.

[24] Gzyl, M., Pesci, R., Rosochowski, A., Boczkal, S., Olejnik, L., In situ analysis of the influence of twinning on the strain hardening rate and fracture mechanism in AZ31B magnesium alloy, Journal of Materials Science, 50(6) (2015) 2532-2543.

[25] Wang, J., Xu, J., Gao, D., Numerical relationship between creep deformation coefficients of prestressed concrete beams, Materials & Structures, (2015) 1-11.

[26] Xiong, H., Zeng, G., Ding, C., Wu, C., Wang, W., Extending Parallel Computing with Constraint of Fixed Structure by Adjusting Graph, Iete Journal of Research, (2015) 1-16.

[27] Smalley, P. J., Laser safety: Risks, hazards, and control measures, Laser Ther, 20(2) (2011) 95-106.

[28] Wu, X., Li, W., Wang, Y., Preliminary safety analysis of the PWR with accident-tolerant fuels during severe accident conditions, Annals of Nuclear Energy, 80 (2015) 1-13.

[29] Sanz, B., Planas, J., Sancho, J. M., A closer look to the mechanical behavior of the oxide layer in concrete reinforcement corrosion, International Journal of Solids & Structures, 62 (2015) 256–268.