Analysis on Super-Long Frame Structure of Main Building of Conventional Island

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Abstract Longitudinal length of main building of conventional island of nuclear power plant is far beyond the stipulation of relevant specifications about the maximum interval of the expansion joint. In this article, the influence of structure internal force and material utilization amount is analyzed from considering anti-seismic and thermal action. And the conclusion is given in the end.

Keywords Main building of conventional island of nuclear power plant · Super-Long frame structure · Thermal action

1 Introduction

The longitudinal length of main building of conventional island of nuclear power plant is general between 110 and 120 m. When using of reinforced concrete structure, the longitudinal length is far beyond the requirement of 75 m which is the maximum distance of the temperature expansion joint in the norms. If the expansion joint is not considered, the temperature function is calculated and the effective measures are taken to meet the design requirements. How much impact on the internal forces and the amount of material the temperature effect has? There are two options about the main building with joint or not to compare the effect. In this article, the influence of structure internal force and material utilization amount is analyzed from considering anti-seismic and thermal action.

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2 A Brief Introduction of Main Building of Conventional Island

2.1 Main Building of Conventional Island Layout Scheme

A main building of conventional island of nuclear power plant uses aboveground layout scheme and reinforced concrete frame structure.

The longitudinal axis length of turbine generator building and deaerator bay is 115.5 m, and column spacing has three kinds as 12.5, 12, and 9.5 m. The span of turbine generator building is 42.5 m, and deaerator bay is 13 m. The bottom elevation of roof truss of turbine house is about 40.0 m. Chemical workshop is along the lateral of deaerator bay, and single-layer reinforced concrete frame structure, with the height of 10.0 m. Two bridge cranes with lifting capacity 300/60 t and 90/20 t are placed in turbine generator building, and the elevation of rail-top is 35.7 m.

The main structure floors of turbine generator building are turbine generator building zero meter floor (±0.0 m), middle floor (8.0 m), operation floor (18.0 m), and roof; the main structure floors of deaerator bay are zero meter floor (0.0 m), middle floor (8.0 m), electrical mezzanine (13.0 m), operation floor (18.0 m), deaerator floor (27.0 m), and roof.

The plan and section of operation floor without expansion joint are shown in Figs. 1 and 2.

Project with expansion joint has an expansion joint on the right of axis T.6, and the distance of double column axis is 1.5 m. The distance of T.6'–T.7 is 11 m. The length of the plant remains unchanged and is still 115.5 m. Plane layout is shown in Fig. 3. The rest is not changed.

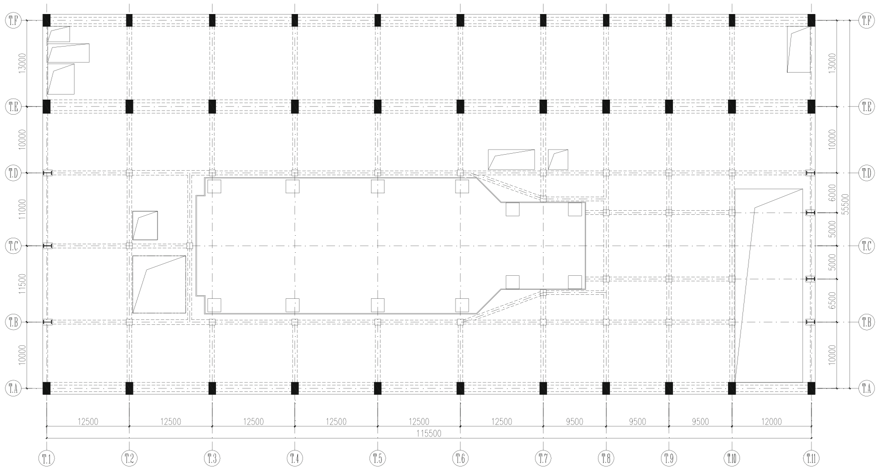

Fig. 1 Plan of operation floor

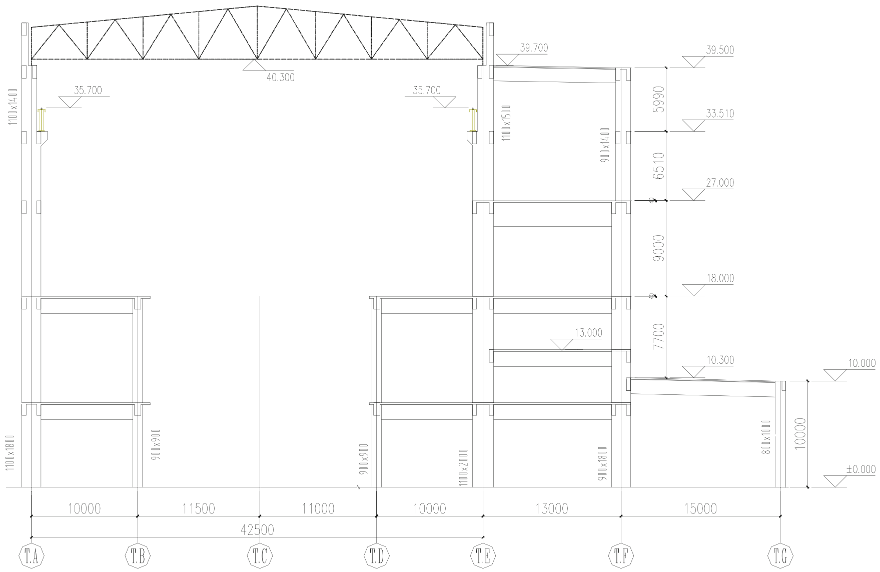

Fig. 2 Section

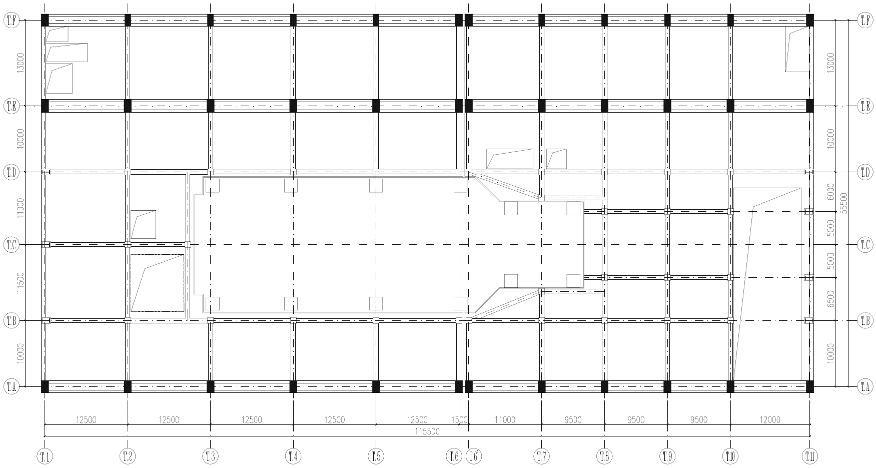

Fig. 3 Plan of operation floor

2.2 *Material and Main Section*

Concrete strength grade of frame beams, columns, and slabs is all C40.

Column section of grid A is 1100 × 1800, column section of grid B is 1100 × 2000, column section of grid C is 900 × 1800, and column section of platform is 900 × 900.

The section of transverse main frame beam is 700 × 1400, 700 × 1600, 700 × 2400, and the section of longitudinal main frame beam is 2–400 × 1200.

Slab thickness of middle floor, operation floor, and deaerator floor is 150 mm; slab thickness of electrical mezzanine is 100 mm or 120 mm, and slab thickness of roof is 100 mm.

2.3 Seismic Design Requirements and Natural Conditions

Seismic precautionary intensity used for seismic measures of main building of conventional island is considered as intensity 7. Grade of seismic design details of main building of conventional island is considered as intensity 8.

Reference wind pressure: $W_0 = 0.45$ kN/m^2. Surface roughness category: A. Reference snow pressure 0.35 kN/m^2.

2.4 Thermal Action

Maximum temperature rise: 26 °C, maximum temperature drop: −43 °C, concrete shrinkage effect are translated into 12.5 °C temperature drop.

2.5 Live Load

The live load value of floor and roof follows "Technical code for design load of main building in fossil-fired power plant and the conventional island of nuclear power plant" (DL/T5095-2013) and "Load code for the design of building structures" (GB 50009-2012).

3 Contrast Analysis of Structure Internal Force and Deformation of Frame Structure with Joint or not Under Earthquake

Seismic performance analysis and comparison of the amount of material will be done from structural vibration period, floor displacement (or displacement ratio), scrambling.

3.1 Structural Vibration Period

Column spacing of main building is large between axis T.1 and T.6, and there is turbine generator foundation which is completely disengaged from main building between axis T.3 and T.6. Middle floor and operation floor are partial discontinuous. Structural rigidity is small, and period is long. Structural misalignment is large. The component of torsional vibration is large in the first two translational modes. Periodic ratio of the structure: T3/T1 = 0.76 < 0.9. The overall torsional rigidity meets the requirements.

Column spacing of main building is not very large between axis T.6’ and T.11, and there is turbine generator foundation which is completely disengaged from main building between axis T.6’ and T.8. There is also the lifting hole between axis T.10 and T.11. Middle floor and operation floor are partial discontinuous, but the overall layout is better than the T.1–T.6. Structural rigidity is relatively larger, and period is short. Structural misalignment is small. The component of torsional vibration is small in the first two translational modes. Periodic ratio of the structure: T3/T1 = 0.85 < 0.9. The overall torsional rigidity meets the requirements.

For the overall structure with no temperature joint, structure between T.1 and T.6 which is flexible and structure between T.6’ and T.11 which is rigid become to a unitary structure. The circs that middle floor and operation floor are partial discontinuous is improved, and structural misalignment is also reduced. Natural period of the overall structure is between the periods of the first two structures. The component of torsional vibration in the first two translational modes is also between the first two structures. Periodic ratio of the structure: T3/T1 = 0.80 < 0.9. The overall torsional rigidity is also between the first two structures.

To sum up, the overall structure is more reasonable than the structure with joint. Structural misalignment is small. The structure can be better coordinated to work together.

3.2 Floor Displacement

With temperature expansion joint, floor horizontal displacement and story drift of the two-part structure are shown in Tables 1 and 2.

Floor horizontal displacement and story drift of the overall structure with no joint is shown in Table 3.

LX is (0.0°) specified horizontal force
PX is (0.0°) positive misalignment specified horizontal force
MX is (0.0°) negative misalignment specified horizontal force
LY is (90.0°) specified horizontal force
PY is (90.0°) positive misalignment specified horizontal force

Table 1 Floor horizontal displacement and story drift of the structure between T.1 and T.6

	Floor maximum horizontal displacement (mm)	Range of maximum horizontal displacement of each floor and floor average displacement ratio	Maximum story drift angle
LX	27.09	1.09–1.12	1/1156
PX	28.69	1.16–1.19	1/1072
MX	25.48	1.02–1.06	1/1253
LY	25.93	1.03–1.12	1/1195
PY	28.63	1.14–1.25	1/1123
MY	26.71	1.05–1.12	1/1199
EX	28.25	1.20–1.22	1/1020
EY	25.16	1.09–1.16	1/1224

Table 2 Floor horizontal displacement and story drift of the structure between T.6’ and T.11

	Floor maximum horizontal displacement (mm)	Range of maximum horizontal displacement of each floor and floor average displacement ratio	Maximum story drift angle
LX	21.54	1.01–1.11	1/1365
PX	23.20	1.11–1.21	1/1236
MX	23.27	1.03–1.08	1/1387
LY	25.74	1.01–1.06	1/1077
PY	26.87	1.06–1.12	1/1034
MY	27.56	1.08–1.17	1/1048
EX	21.18	1.07–.17	1/1315
EY	22.42	1.05–1.08	1/1123

Table 3 Floor horizontal displacement and story drift of the structure between T.1 and T.11

	Floor maximum horizontal displacement (mm)	Range of maximum horizontal displacement of each floor and floor average displacement ratio	Maximum story drift angle
LX	24.22	1.03–1.05	1/1269
PX	25.00	1.06–1.09	1/1223
MX	24.01	1.00–1.04	1/1268
LY	26.34	1.05–1.17	1/1217
PY	27.65	1.05–1.12	1/1062
MY	30.61	1.22–1.36	1/1064
EX	23.85	1.06–1.09	1/1214
EY	27.56	1.20–1.29	1/1052

MY is (90.0°) negative misalignment specified horizontal force
EX is (0.0°) earthquake action
EY is (90.0°) earthquake action

Horizontal displacement ratio of the structure between T.1 and T.6 under earthquake action in the X direction is more than 1.2 but less than 1.4 and belongs to torsional irregular. Maximum story drift angle all can meet requirement.

Under earthquake action in the X direction, the displacement of the structure between T.6’ and T.11 is both smaller than the displacement of the structure between T.1 and T.6 in two directions. Horizontal displacement ratio is also more than 1.2 but less than 1.4 and belongs to torsional irregular. Maximum story drift angle all can meet requirement.

For the overall structure with no temperature joint, the displacement in the X direction is between the first two structures, and the displacement in the Y direction is larger than both. Horizontal displacement ratio is also more than 1.2 but less than 1.4, belongs to torsional irregular. Maximum story drift angle all can meet requirement.

By comparison analysis, the overall structure can meet the requirement of relevant floor displacement (displacement ratio) and flat, vertical irregular for seismic design. The circs that middle floor and operation floor are partial discontinuous is improved, and structural misalignment is also reduced. The structure can be better coordinated to work together.

3.3 *The Amount of Material Analysis*

Without considering thermal action, contrast analysis of the amount of material between the overall structure without considering thermal action and the structure with joint. The result is shown in Table 4.

From the table, we can see that without considering thermal action, the amount of material of the overall structure is less than the structure with joint. This is mainly because the structure with joint has one more frame structure of reinforced concrete and steel roof truss.

Table 4 Contrast of the amount of material

The amount of structural material	With joint (A)	Without joint (B)	Difference (B-A)
	Total (two part)	T.1–T.11	
Reinforcement in beam (t)	255.1	251.8	−3.3
Reinforcement in column (t)	378.5	349.3	−29.2
Steel of steel seam (t)	3063	2961	−102
Concrete of beam (m^3)	4335.2	4236.4	−98.8
Concrete of column (m^3)	3820	3515.6	−304.4

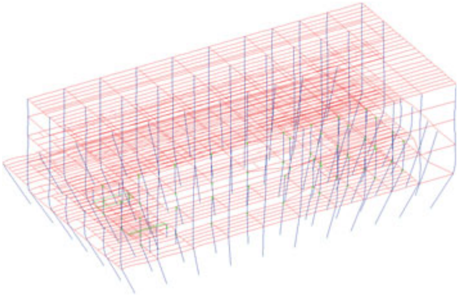

Fig. 4 Structural deformation under the thermal action

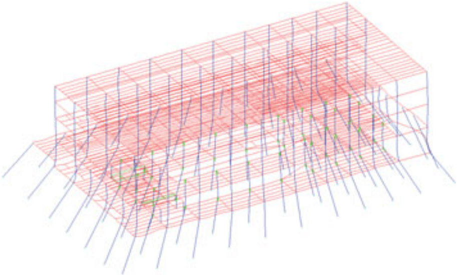

Fig. 5 Structure deformation with elevated temperatures and cooling

4 Calculation and Analysis of the Super-Long Frame Structure Under the Thermal Action

4.1 Structural Deformation Under the Thermal Action

Structure deformation with elevated temperatures and cooling is shown in Figs. 4 and 5.

According to the deformation diagram, the relative deformation of the structure is almost all concentrated in the bottom layer. The internal force of the bottom column and the beam of one floor under the temperature load is the maximum. Under working condition of elevated temperatures, the deformation of the structure is expanding; cooling condition, the deformation of the structure is shrinkage.

4.2 Analysis of the Internal Force Under the Thermal Action

By calculation, the internal force analysis is as follows:

(1) The ratio relationship of internal force of beam and column with cooling 43° and heating 26° is 1.654 times, that is, internal force of beam and column with

cooling 43° = internal force of beam and column with heating 26°*(43/26), but the direction is opposite.

(2) The internal force of 12.5° of concrete shrinkage and cooling 43° is proportional (error within 5%).

(3) The maximum tensile force in the frame beam is 1671.3 kN, and when using HRB400 reinforcement, the reinforcement area is $1671.3 * 1000/360 = 4642.5\,\mathrm{mm}^2$.

The cross section of longitudinal beam is $2{-}400 * 1200$. If the diameter of lumbar reinforcement is 18 mm, and the number of each side is 5, the pulling force of lumbar reinforcement is $20 * 254.5 \times 360 = 20 * 91.62 = 1832.4\,\mathrm{kN}$, fully able to meet the requirements of the maximum tension.

Reference to the relevant nuclear power conventional island project, the diameter of lumbar reinforcement in longitudinal frame beam takes 16 mm, and the number of each side is 5.

The tension of the single bar received $201.1 \times 360 = 72.4\,\mathrm{kN}$.

The tension of normal reinforcement is able to provide $4 * 5 * 72.4\,\mathrm{kN} = 1448\,\mathrm{kN}$ and can completely meet the tension of the vast majority beam.

(4) Under the thermal action, the maximum axial pressure of the frame column is −353.8 kN, and the maximum axial tension is 585.1 kN, both in grid A. In grid A, the maximum axial force is −8645 kN under the action of dead load, and the minimum is −3981 kN. So, the effect of the axial force of the column under the thermal action is very small.

(5) Under the thermal action, the maximum shear force of the frame column in the X direction is 924 kN and in the Y direction is 1114 kN. Under the action of earthquake, the maximum shear force of the frame column in the X direction is 350 kN and in the Y direction is 605 kN. So, the effect of the shear force of the column under the thermal action is big. But the shear capacity of the concrete section of the bottom column is

$$\mathrm{Vc} = 1/\gamma \mathrm{R_E} * 0.15\beta\mathrm{c} * \mathrm{fc} * \mathrm{b} * \mathrm{h_0} = 6674\,\mathrm{kN}$$

Shear force under the thermal action has no effect on the calculation of stirrups.

(6) Under the thermal action, the maximum bending moment of the frame column in the X direction is 6279.4 kNm and in the Y direction is 7699.6 kNm. Under the action of earthquake (without considering seismic adjustment), the maximum bending moment of the frame column in the X direction is 2317 kNm and in the Y direction is 4626 kNm. So, the effect of the bending moment of the column under the thermal action is big. Longitudinal reinforcement in the column increases slightly.

4.3 Analysis of the Material Consumption Under the Earthquake Action and Thermal Action

After a variety of working conditions, the amount and increment of the reinforcement in the frame beam and column are shown in Table 5.

From the table,

(1) When do not consider the earthquake action and only consider the effect of the thermal action, the increase of reinforcement in beam is relatively large, and the change of the reinforcement in column is very small. The maximum increment of the reinforcement in beam is 21 tons. The increment is 21/191 = 11% of beam reinforcement and 5.16% of the overall framework.

(2) When considering the earthquake action, the amount of the reinforcement in beam and column under various thermal actions is increased. The maximum increment of the reinforcement in beam is 13.4 tons. The increment is 13.4/252 = 5.3% of beam reinforcement. The maximum increment of the reinforcement in column is 7 tons. The increment is 7/349 = 2% of column reinforcement. But they are not in the same condition. The whole reinforced maximum increment is 16.5 tons, and the increment is 2.74% of the overall framework.

(3) When do not considering thermal action, and the anti-seismic grade of the structures is 2, the amount of the reinforcement in beam is 60 tons more than without considering the earthquake action, and the increment is 32% of beam reinforcement. The amount of the reinforcement in column is 138 tons more, and the increment is 66% of column reinforcement. The increment is 50% of the overall framework.

(4) When considering of the thermal action, the anti-seismic grade of the structures is 2, and the increment of reinforcement is less than 3% of the framework.

Further analysis of the distribution of longitudinal reinforcement in the up and bottom of the beam, stirrups, and torsional longitudinal reinforcement, by do not considering temperature as a benchmark, the amount of the reinforcement in beam is all increased when considering temperature. The maximum increment is 13 tons. However, the amount of the longitudinal reinforcement in the bottom of the beam with considering temperature is all less than the amount without considering temperature. The amount of the longitudinal reinforcement in the up of the beam is increased at part load conditions, especially the beam of the first floor which force is bigger. The upper floors and part load conditions are decreased. Under different temperature conditions, stirrups is increased, and the maximum increment is $63 - 53 = 10$ tons; torsional longitudinal reinforcement is also increased, and the maximum increment is $3.821 - 2.48 = 1.34$ tons.

Further analysis of changes of the longitudinal reinforcement and stirrup in the frame column is not considering the earthquake action, and the amount of the reinforcement in column is basically unchanged under various conditions of

Table 5 Amount and increment of the reinforcement in the frame beam and column

Calculation combination		Reinforcement in beam (t)	Reinforcement in column (t)	Total	With thermal action as the benchmark, the reinforcement increment	Increment percentage (%)
Seismic action is not considered	No thermal action	190.896	210.785	401.68	0	0.00
	Heating up 26 °C	207.271	210.937	418.20	16.527	4.11
	Cooling 43 °C	208.642	210.735	419.37	17.696	4.41
	Cooling 43 °C 12.5 °C of shrinkage	211.682	210.735	422.41	20.736	5.16
	Cooling 55.5 °C	210.12	210.752	420.87	19.191	4.78
Anti-seismic grade of the structures is 2.	No thermal action	251.792	349.3	601.09	0	0.00
	Heating up 26 °C	254.753	351.575	606.32	5.236	0.87
	Cooling 43 °C	257.787	352.434	610.22	9.129	1.52
	Cooling 43 °C 12.5 °C of shrinkage	265.159	352.424	617.58	16.491	2.74
	Heating up 26 °C Cooling 43 °C	259.805	353.894	613.69	12.607	2.10
	Heating up 26 °C Cooling 55.5 °C	261.261	356.252	617.51	16.421	2.73
	No thermal action Elastic plate	252.741	348.485	601.22	0.134	0.02

thermal action. In the normal design of considering seismic action, the column reinforcement has a slight increase, and the maximum increment is 7 tons. The incremental percentage is 7/349.3 = 2%. The reinforcement is almost all concentrated in the change of the first layer of column longitudinal reinforcement. On the whole structure, considering the temperature effect, in addition to one layer, the column reinforcement basically has no change.

4.4 The Comparison of the Frame Materials with the Super-Long Frame Structure and the Joint Structure

The comparison of the materials with the overall structure with the most unfavorable temperature effect and the joint structure is shown in Table 6.

For the overall structure with considering temperature, the reinforcement in beam and column saves 8 tons. Steel saves 102 tons. The volume of concrete frame beam and column saves 400 m^3.

4.5 Analysis and Comparison of the Material Quantity of Floor Slab Considering Temperature Effect

Temperature rises under working conditions, and the maximum tensile strength in the floor is 81 kN/m. The tensile strength in each floor is less than the tension that the floor can withstand. Reinforcement of floor slab is unchanged.

Table 6 Material quantity comparison

Structural style	The structure with joint	The overall structure without considering temperature	B-A	The overall structure with considering temperature	C-A
Component name	Total: A	T.1–T.11: B		T.1–T.11: C	
Reinforcement in beam (t)	255.1	251.8	−3.3	268.547	13.447
Reinforcement in column (t)	378.5	349.3	−29.2	356.25	−22.25
Steel (t)	3063	2961	−102	2961	−102
Concrete of beam (m^3)	4335.2	4236.4	−98.8	4236.4	−98.8
Concrete of column (m^3)	3820	3515.6	−304.4	3515.6	−304.4

Under cooling conditions, because large tensile force is produced in the floor with contractile structure, the maximum tension in the floor is 792 kN/m. The tensile strength in each floor is larger than the tension that the floor can withstand, so each layer of the slab reinforcement has a growth. Considering the double two-way reinforcement type, the amount of the reinforcement in floor will increase 220 tons than without considering temperature.

5 Conclusions

(1) The overall structure is more reasonable than the structure with joint. Structural misalignment is small. The structure can be better coordinated to work together.
(2) The internal force of beam and column is proportional completely, but the direction is opposite. The internal force under the condition of concrete shrinkage and cooling is proportional (error within 5%).
(3) Considering the thermal action, the amount of the reinforcement in beam is increased. But the amount of the longitudinal reinforcement in the bottom of the beam with considering temperature is all less than the amount without considering temperature. The amount of the longitudinal reinforcement in the up of the beam is increased at part load conditions, especially the beam of the first floor which force is bigger. The upper floors and part load conditions are decreased. Stirrups and torsional longitudinal reinforcement is also increased.
(4) Considering the thermal action, the column reinforcement has a slight increase. The reinforcement is almost all concentrated in the change of the first layer of column longitudinal reinforcement.
(5) Considering the thermal action, and considering the double two-way reinforcement type, the amount of the reinforcement in floor will increase 220 tons than without considering temperature.
(6) When the anti-seismic grade of the structures is 2 and considered thermal action, comparing the two structures with joints with not considering thermal action, the reinforcement in beam and column saves 8 tons. The reinforcement in the floor increases 220 tons. Steel saves 102 tons. The volume of concrete frame beam and column saves 400 m^3.

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