ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 4, Issue 12, July 2015

Analysis of RC Flat Slab System for Thermal Loads

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Abstract— ***In normal practice, restrained stresses in reinforced concrete (RC) structures due to temperature variation may be overcome by enforcing expansion joints every certain length limit, according to codes of practice. Nevertheless, expansion joints have their architecture and durability problems. In this paper, reinforced concrete flat slab systems of lengths much greater than the codes limits, if temperature effect is disregarded, are studied under dead and live loads, and thermal loads in order to examine the effect of temperature variation. The systems are modeled properly by accounting for material nonlinearity, particularly cracking. Different temperature gradients, uniform and nonlinear, are considered. The finite element method is employed for conducting the analysis by utilizing the finite element code ABAQUS, where different features of material nonlinearities are considered. The obtained results for the studied cases reveal that material modeling of reinforced concrete flat slab systems makes plays a major role in how these structures react to temperature variation. Cracking contributes to the release of significant portion of temperature restrain and in some cases this restrain is almost eliminated. The response of a system significantly deviates based on the temperature profile and the presence of gravity loads.***

Index— **ABAQUS, finite element, flat slab, material nonlinearity, reinforced concrete, thermal loads.**

I. INTRODUCTION

Due to the continuity of reinforced concrete flat slab and the interaction between the slab and the supporting columns with the assumption of rigid connections between slab and columns, the slab is not completely free to move under temperature variation. Hence additional stresses due to thermal loads, due to either uniform temperature variation or temperature gradients, will be produced in the slab and columns. In such condition, exterior and corner columns will be the most critical columns. The stiffness of different elements of the structural system plays a major role in the resulting stresses; for instance, cracks due to existing loadings relieves significant portion of such stresses.

In order to release restrained stresses from temperature variation many designers use "rules of thumb" that set limits on the maximum length between building expansion joints. Although widely used, rules of thumb have the drawback that they do not account for the many variables which control volume changes in reinforced concrete buildings. Examples of the variables which affect the amount of thermally induced movement include the percentage of reinforcement, which limits the amount of movement and cracking in the concrete; the restraint provided at the foundation, which limits the movement of the lower stories; the geometry of the structure, which can cause stress concentrations to develop, especially at abrupt changes in plan or elevation; and provisions for insulation, cooling, and heating, which affect the ability of a building to dampen the severity of outside temperature changes [1].

Due to the complexity of the problem and the previous limitations for using expansion joints in addition to its bad appearance and difficulty of construction and maintenance, designers become interested in the design of buildings without expansion joints and take the effect of temperature variations and additional stresses into account during the design stage.

The analysis of reinforced concrete flat slabs under temperature variation is a three dimensional problem but it may be assumed as a two dimensional problem since the temperature varies only within the slab thickness and can be assumed constant all over the slab length. In this study, the effect of thermal loads, in the presence of gravity loads, on the behavior of flat plate system utilizing the finite element method, is examined. The employed analysis accounts for material nonlinearity which has a significant effect, particularly cracking, on the structure response. Three models of flat plates are included in this paper under the names ST1, ST2 and ST3. The computer code ABAQUS is utilized to perform the finite element analysis.

II. FLATE PLATE MODELS

A. *Model ST1*

Geometry and Dimensions

Fig. 1 shows the geometry of the slab ST1 which consists of one story flat plate of thickness 250mm resting on square columns of dimensions 500×500mm with clear height equal to 4.0m. In the x-direction there are seven spans, each span is equal to 8.0m from the center lines of columns, so the total slab length in the x-direction is equal to 56.5m. In the z-direction there are five spans, each span is equal to 8.0m from the center line of columns, so the total slab length in the z-direction is equal to 40.5m.

Reinforcing Steel

The slab is reinforced with a bottom and top steel mesh of bar diameter Φ10 mm every 150mm in the x- and z-directions. The slab is provided with additional top reinforcement at the intersection zones of column strips such that the total top reinforcement is equivalent to a bar of diameter Φ18 mm every 150mm in the x- and z-directions at these zones. The top and bottom concrete covers are equal to 25mm measured from the slab exterior fibers to the center of the rebar. The vertical and horizontal reinforcements of columns are shown in Fig. 2.

ISSN: 2277-3754
ISO 9001:2008 Certified
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Loads and Boundary Conditions

The slab is carrying a total working load equal to 12.75kN/m^2 applied at the top surface of the slab as a uniform pressure. This load covers the slab own weight and a live load equal to 3.0kN/m^2 in addition to 2.0kN/m^2 for partitions and 1.5kN/m^2 flooring materials. The columns own weights are neglected in the analysis.

In addition to the gravity loads, the slab is assumed to carry thermal loads in the form of temperature gradients which are uniform and nonlinear gradients as shown in Fig. 3, whereas the temperature gradients on the columns are neglected. Thus, there are three loading cases, for nonlinear analysis, as given in the following:

- CASE A - gravity loads only.
- CASE B - gravity loads + uniform temperature gradient (T1).
- CASE C - gravity loads + nonlinear temperature gradient (T2).

All columns are assumed to be fixed at their bases (Ux, Uy and Uz =0.0 for the column section plane). There are two axis of symmetry in the x- and z-directions (the boundary conditions along the x- axis of symmetry is Ux, URy and URz =0.0 and the boundary conditions along the z- axis of symmetry is Uz, URx and URy =0.0) so that one quarter model only is analyzed.

B. Model ST2

Model ST2 is similar to model ST1 except in the number of spans in the x-direction, which is 13, making a total slab length in this direction equal to 104.5m. The reinforcement, element types, meshing rules, loads and boundary conditions are the same as those used for ST1.

C. Model ST3

Model ST3 which consists of three stories flat plates of thickness 250mm resting on square columns of dimensions 500 x 500mm with clear height is equal to 4.0m, all columns have the same dimensions. In the x-direction there are nine spans, each span is equal to 8.0m from the center line of columns, so the total slab length in the x-direction is equal to 72.5m. In the z-direction there are seven spans, each span is equal to 8.0m from the center line of columns, so the total slab length in the z-direction is equal to 56.5m.

The reinforcement, element types, meshing rules, loads and boundary conditions are the same as those used for ST1 and ST2.

III. MODELING

A. Finite Element Modeling

In this study, concrete is modeled as 3-D solid continuum elements which are the standard volume elements of ABAQUS. The continuum solid element C3D8RT which is an 8-node thermally coupled brick, tri-linear displacement and temperature control with reduced integration is used to model concrete in slabs and columns under gravity loads plus thermal loads. The steel reinforcement is modeled as surface element containing rebar using a 4-node quadrilateral surface element with reduced integration named SFM3D4R.

The mesh size is a very important issue in this analysis because increasing mesh size helps the model to converge to solution faster than if the mesh size is small but the obtained results may be poor. In addition, the steel bars must be meshed so that each concrete element contains a rebar in order to help the model to converge to a unique solution. Many trials have been made in order to obtain the best mesh size for good results. Fig. 4 shows the meshes used in these problems and table *I* indicates the number of elements and nodes employed in the problems.

In this paper Abaqus/Explicit is used, applying a quasi-static analysis by controlling the time step and the loading rate, for the analysis and modeling of the studied slabs instead of Abaqus/Standard which takes a long time for solving the problem and large disc space. Abaqus/Explicit is the most efficient in this kind of high number of nonlinearity problems and it contains many modeling capabilities that do not exist in Abaqus/Standard. For example, material failure with element deletion for elastic-plastic materials is an option; it can simulate larger models more readily with a given amount of computer hardware [2].

B. Material modeling

Stress –Strain Curve of Concrete in Compression

The model developed by Hognestad [3] is used by ABAQUS and hence it is adopted here to represent the behavior of concrete in compression in this model, Fig. 5a.

$$\varepsilon = \varepsilon_e + \varepsilon_p \quad (1)$$

$$\varepsilon_e = \sigma / E_c \quad (2)$$

$$\frac{\sigma}{\sigma_u} = 2\frac{\varepsilon}{\varepsilon_0}\left(1-\frac{\varepsilon}{2\varepsilon_0}\right) \quad \text{for} \quad 0 < \varepsilon < \varepsilon_0 \quad (3)$$

$$\frac{\sigma}{\sigma_u} = 1-.15\left(\frac{\varepsilon-\varepsilon_0}{\varepsilon_{cu}-\varepsilon_0}\right) \quad \text{for} \quad \varepsilon_0 < \varepsilon < \varepsilon_{cu} \quad (4)$$

where ε is the strain, εe is the elastic strain, εp is the plastic strain, Ec is the modulus of elasticity of the concrete, ε0 is the strain corresponding to the peak stress and is equal to 0.002 and εcu is the strain at failure and is equal to 0.0035.

Tension Stiffening

In this study, concrete smeared cracking is adopted in the analysis. This is implemented in the analysis by representing the stress-strain curve of concrete in tension as shown in Fig. 5b, where tension stiffening is accounted for by a post-failure stress-strain relation, where a plastic strain at which the cracking stresses causing tensile failure of the concrete reduces to zero is specified. This reduction of tensile cracking stresses with plastic strain can be expressed by linear or multi-linear curve. There is a direct relationship between the stiffness degradation and stress drop after cracking [4-6].

The selection of tension stiffening parameters is important in nonlinear analysis since greater tension stiffening makes it easier to obtain numerical solutions; otherwise, failure due to

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 4, Issue 12, July 2015

local cracking in the concrete will take place, thus introducing temporarily unstable behavior in the overall response of the model. In this study, tension stiffening is taken as a single line in which the tensile stresses across the cracks are vanished when the total tensile strain becomes equal to 0.001.

Failure ratios

To define the failure surface four failure ratios can be specified as shown in Fig. 5c.

1. Ratio of the ultimate biaxial compressive stress to the uniaxial compressive ultimate stress. A value of 1.16 is specified;
2. Absolute value of the ratio of uniaxial tensile stress at failure to the uniaxial compressive stress at failure. A value of 0.07 is used;
3. Ratio of the magnitude of a principal component of plastic strain at ultimate stress in biaxial compression to the plastic strain at ultimate stress in uniaxial compression. A value of 1.28 is used; and
4. Ratio of the tensile principal stress value at cracking in-plane stress, when the other nonzero principal stress component is at the ultimate compressive stress value, to the tensile cracking stress under uniaxial tension. A value of 0.333 is assumed.

Steel Material Modeling

The reinforcing steel is assumed to be elastic-perfectly plastic material in both tension and compression with elasticity modulus, E_s, equal to 2×10^5MPa and Poisson's ratio equal to 0.2.

The steel reinforcing bars are assumed to be embedded into the concrete by using constrain called (embedded region) so that full bond is assumed between concrete and steel. The mechanical and thermal properties of concrete and steel adopted in this study are given in table *II*.

C. Analysis Verification

The output of the finite element results from the computer program ABAQUS with the adopted models, have been verified and the results were reliably accurate [7-9].

IV. RESULTS

The results obtained from the analysis of the three models are beyond the size of any normal published paper; and therefore, few samples of the results are presented here in addition to the significant parameters. The results obtained include the following:

i. The normal stresses in the x-direction, S11, at the top and bottom surfaces of the slabs for loading cases, A, B and C.

ii. The normal stresses in the x-direction, in the top and bottom steel of the slabs for the different loading cases.

iii. The normal stress, in columns and columns reinforcement, C1, C2, C3 and C4 of all the slabs for the diferent loading cases.

iv. The vertical displacement, U2, of the slabs.

The reinforcement stresses in the columns of model ST2 for case B are illustrated in Fig. 6. Samples of the reinforcement stresses for the slabs of model ST3 are presented in Fig. 7.

From the obtained results the values tabulated in tables *III-VII* can be noted, knowing that those values represent the **peak** values obtained from the analysis.

$$change\ \% = \frac{value\ due\ to\ temperature\ and\ gravity\ loads - value\ due\ to\ gravity\ loads\ only}{value\ due\ to\ gravity\ loads\ only}$$

Another case of loading has been made for the slab moel ST3, in this loading case the nonlinear temperature gradient (positive and negative) acts only on the slab of the third story in addition to the gravity loads acting on the whole model. The results obtained from this loading case, **peak** values, are tabulated in tables *VIII-XII*.

The slab model ST2 has been analyzed again under the assumption that the concrete is linear elastic and homogeneous material, no reinforcing steel, neglecting the effect of material nonlinearity and post-failure due to cracks. In this analysis the effect of temperature gradients only has been studied, with the absence of the gravity loads. The results obtained from this analysis are given in table *XIII*; these values are given at the same regions which have been tabulated before for slab model ST2 in tables *III*, *IV* and *VII*. The obtained results reveal the following remarks:

1. The effect of uniform temperature gradient (T1) on the slab deflection is less than the effect of nonlinear gradient (T2) and in some cases it may be neglected. On the other hand, this case of loading has a drastic effect on the outer columns, particularly the corner column.

2. Nonlinear temperature gradient (T2) cause additional compressive stresses on the slabs top fibers greater than that due to uniform gradient (T1) and hence it is more critical.

3. In zones of high bending moments due to the gravity loads, near columns, the effect of temperature gradient is less than that for those zones of low bending moments, at mid-spans.

4. Nonlinear temperature gradient (T2) cause additional tensile stresses in bottom steel grater then uniform gradient (T1).

5. For multi-story flat slab model ST3, the response of the building is varying significantly based on the temperature gradient shape and the cases of loading for temperature acting on the slabs.

6. The results from nonlinear analysis, where different features of material nonlinearity and the coupling effect between thermal loads and gravity loads are accounted for, vary significantly from those from linear elastic analysis, where the material is assumed to be elastic homogenous and the thermal loads are studied with the absence of the gravity loads.

ISSN: 2277-3754
ISO 9001:2008 Certified
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V. SUMMARY AND CONCLUSIONS

In order to show the effect of temperature variation on reinforced concrete flat plates, different models have been analyzed under different temperature gradients which may be uniform, linear and nonlinear gradients depending on various factors, in the presence of the serviceability gravity loads. These examples are three flat plates with spans equal to 8.0m and total length of up to 104m; two examples are one story and one example is three stories. In the analysis, different features of material nonlinearity, particularly cracking in concrete, have been taken into account. Different temperature gradients have been considered in order to examine the different effects of these gradients in the thermal analysis and which gradient is more critical and realistic in the analysis. The finite element computer program ABAQUS has been used for the modeling and analysis of the examples. Based on the results obtained from the analysis, the following conclusions are drawn:

1. The mesh size is a very important issue in this analysis because increasing mesh size helps the model to converge to solution faster than if the mesh size is small but the obtained results may be poor.
2. Material modeling plays a major role in how reinforced concrete structures react to temperature variation. Cracking contributes to the release of significant portion of temperature restrain and in some cases this restrain is almost eliminated.
3. In the analysis for thermal loads, it is recommended to carry out such analysis in the presence of working gravity loads which cause tension stresses in concrete and cracks and hence the effect of temperature is reduced in comparison with the case of uncracked concrete sections.
4. The structure response deviates significantly based on the temperature profile; hence, it is important to implement a realistic profile in the analysis.

VI. FUTURE WORK

The authors aims to study the thermal behavior of long bridges without expansion joints. Also the thermal characteristics of one unit extended multistoried constructions has to be investigated.

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ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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APPENDIX

Table I Number of elements and nodes of the models

Model	ST1	ST2	ST3
Number of elements	22368	39936	105120
Number of nodes	27555	48930	127037

Table II Mechanical and thermal properties of concrete and steel

Material	Modulus of elasticity, E, MPa	Coefficient of thermal expansion, α	Thermal conductivity, W/MK	Specific heat, c, J/kg.K.	Density, ρ, kN/m^3
Steel	$2x10^5$	$1x10^{-5}/^0C$	45	480	78
Concrete	$4400\sqrt{f_{cu}}$	$1x10^{-5}/^0C$	1	1000	24

$f_{cu} = 30MPa and f_y = 360MPa$

Table III Variation of slabs deflection due to temperature gradients from nonlinear analysis

Slab model	Slab deflection	
	Uniform gradient (T1)	Nonlinear gradient (T2)
ST1	No significant effect	Increase 26%
ST2	No significant effect	Increase 31%
ST3-first story	7% reduction	Increase 9.6%
ST3-second story	6.5% reduction	Increase 28%
ST3-third story	2% reduction	Increase 20%

Table IV Variation of slabs compressive stresses due to temperature gradients from nonlinear analysis

Slab model	Top fibers		Bottom fibers	
	Uniform gradient (T1)	Nonlinear gradient (T2)	Uniform gradient (T1)	Nonlinear gradient (T2)
ST1	1% increase	31.8% increase	1% increase	16% reduction
ST2	13% increase	27.4% increase	7% increase	18% reduction
ST3-first story	14% reduction	29% increase	8% increase	17% reduction
ST3-second story	1.5% reduction	24% reduction	4% reduction	6.5% increase
ST3-third story	1% increase	38% increase	4.5% reduction	12% reduction

Table V Variation of stresses in slabs top steel due to temperature gradients from nonlinear analysis

Slab model	Tensile stresses in top steel		compression stresses in top steel	
	Uniform gradient (T1)	Nonlinear gradient (T2)	Uniform gradient (T1)	Nonlinear gradient (T2)
ST1	13.6% increase	7% increase	98% reduction	35.5% reduction
ST2	20% increase	5.2% increase	94% reduction	38% reduction
ST3-first story	38% increase	12% increase	110% reduction	22% reduction
ST3-second story	16.6% increase	1.4% increase	118% reduction	24% increase
ST3-third story	22% increase	7% increase	100% reduction	31% reduction

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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Table VI Variation of stresses in slabs bottom steel due to temperature gradients from nonlinear analysis

Slab model	Tensile stresses in bottom steel		compression stresses in bottom steel	
	Uniform gradient (T1)	Nonlinear gradient (T2)	Uniform gradient (T1)	Nonlinear gradient (T2)
ST1	48% increase	98% increase	62.5% reduction	12% reduction
ST2	48.3% increase	105% increase	51% reduction	13% reduction
ST3-first story	58% increase	76% increase	68% reduction	20% reduction
ST3-second story	59% increase	24% increase	72% reduction	20% reduction
ST3-third story	50% increase	97% increase	68% reduction	10% reduction

Table VII Variation of stresses in the slabs corner column due to temperature gradients from nonlinear analysis

Slab model	Compression stress in corner column		Tension stress at base in corner column	
	Uniform gradient (T1)	Nonlinear gradient (T2)	Uniform gradient (T1)	Nonlinear gradient (T2)
ST1	28% increase	13% increase	575% increase	178% increase
ST2	32.5% increase	19% increase	650% increase	327% increase
ST3-first story	38.7% increase	23% increase	2000% increase	580% increase

Table VIII Variation of deflection of the slab model ST3 due to temperature gradients from nonlinear analysis

Slab model	Slab deflection	
	Nonlinear gradient (-T2)	Nonlinear gradient (T2)
ST3-first story	5.5% reduction	5% reduction
ST3-second story	5% reduction	4% reduction
ST3-third story	26% increase	20% increase

Table IX Variation of compressive stresses of slab model ST3due to temperature gradients from nonlinear analysis

Slab model	Slab compression stresses in top fibers		Slab compression stresses in bottom fibers	
	Nonlinear gradient (-T2)	Nonlinear gradient (T2)	Nonlinear gradient (-T2)	Nonlinear gradient (T2)
ST3-first story	7.5% reduction	6% reduction	6% reduction	5% reduction
ST3-second story	7.8% reduction	11% reduction	6% reduction	9% reduction
ST3-third story	78% reduction	31.5% increase	1% reduction	16% reduction

Table X Variation of stresses in top steel of slab model ST3 due to temperature gradients from nonlinear analysis

Slab model	Tensile stresses in top steel		compression stresses in top steel	
	Nonlinear gradient (-T2)	Nonlinear gradient (T2)	Nonlinear gradient (-T2)	Nonlinear gradient (T2)
ST3-first story	1.3% reduction	2% reduction	7% reduction	6% reduction
ST3-second story	1% reduction	No significant effect	6% reduction	5% reduction
ST3-third story	25.5% increase	5% increase	71% increase	31% reduction

ISSN: 2277-3754
ISO 9001:2008 Certified
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Table XI Variation of stresses in bottom steel of slab model ST3 due to temperature gradients from nonlinear analysis

Slab model	Tensile stresses in bottom steel		compression stresses in bottom steel	
	Nonlinear gradient (-T2)	Nonlinear gradient (T2)	Nonlinear gradient (-T2)	Nonlinear gradient (T2)
ST3-first story	3.2% reduction	3% reduction	6% reduction	5% reduction
ST3-second story	3% reduction	2.5% reduction	6% reduction	10% reduction
ST3-third story	1% increase	96% increase	12% increase	13% reduction

Table XII Variation of stresses in corner column of slab model ST3 due to temperature gradients from nonlinear analysis

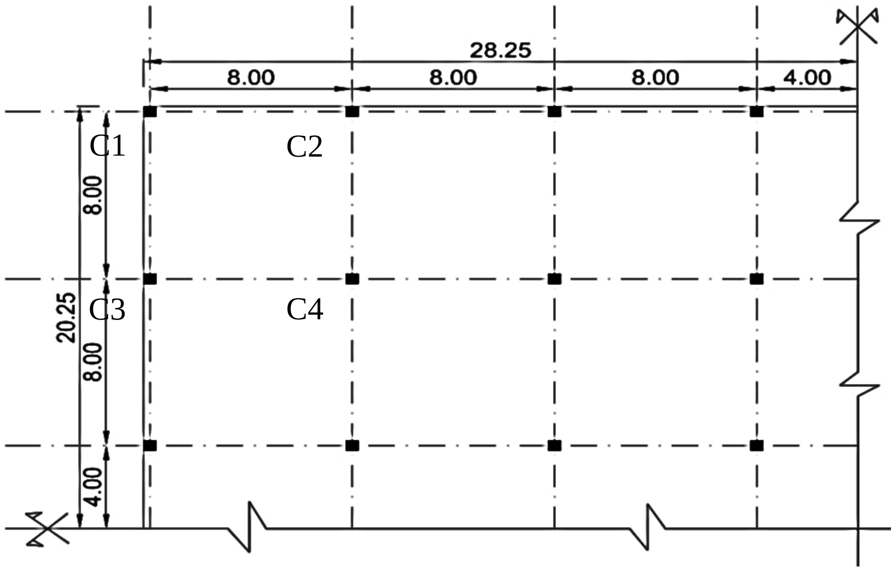
Slab model	Compressive stress in corner column		Tensile stress at base of corner column	
	Nonlinear gradient (-T2)	Nonlinear gradient (T2)	Nonlinear gradient (-T2)	Nonlinear gradient (T2)
ST3-first story	15% increase	10% increase	8% reduction	2% increase

Table XIII Effect of temperature gradients on the slab model ST2 from linear and nonlinear analyses

Response	Uniform temperature gradient, (T1)		Nonlinear temperature gradient, (T2)	
	Analysis 1	Analysis 2	Analysis 1	Analysis 2
Deflection, mm	+2.70	No significant effect	+3.03	-8.42
Compressive stress in top fibers, MPa	-1.00	-0.60	-3.00	-1.27
Compressive stress in bottom fibers, MPa	-6.00	-0.98	+3.20	+2.51
Compressive stress in corner column, MPa	-5.81	-3.53	-2.98	-2.07

Analysis 1 is linear elastic analysis, assuming that the concrete is linear homogenous material and the temperature loads acting on the model without the presence of the gravity loads.

Analysis 2 is nonlinear analysis, where different features of material nonlinearity are accounted for and the temperature loads acting on the model with the presence of the gravity loads.



(a) Plan.

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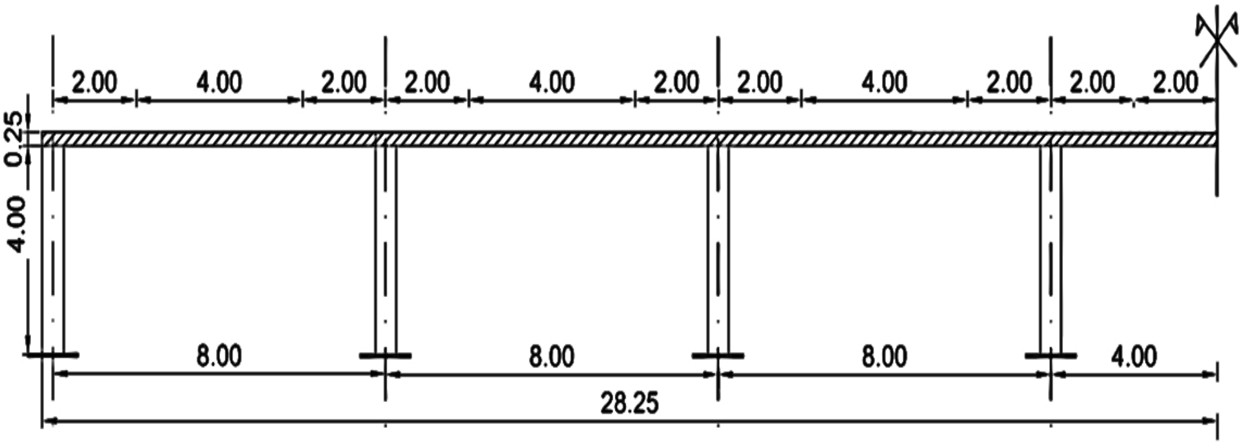


(b) Elevation in the x-direction.

Fig. 1 Geometry and dimensions of Model ST1.

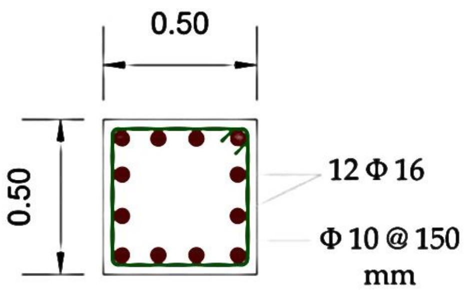
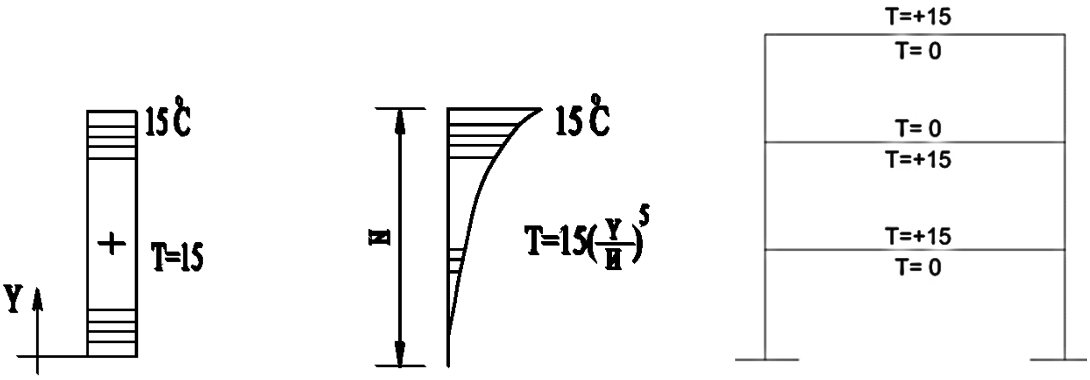


Fig. 2 Column Reinforcement in models ST1, ST2 and ST3.



(a) Uniform gradient (T1) (b) Nonlinear gradient (T2) (c) Nonlinear temperature for ST3

Fig. 3 Positive temperature gradients.

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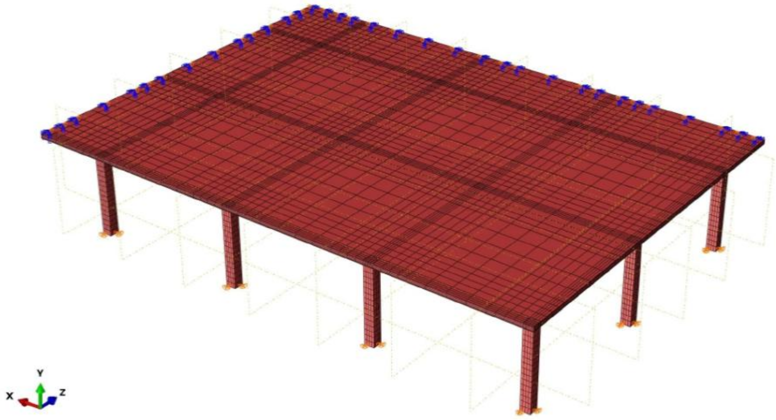
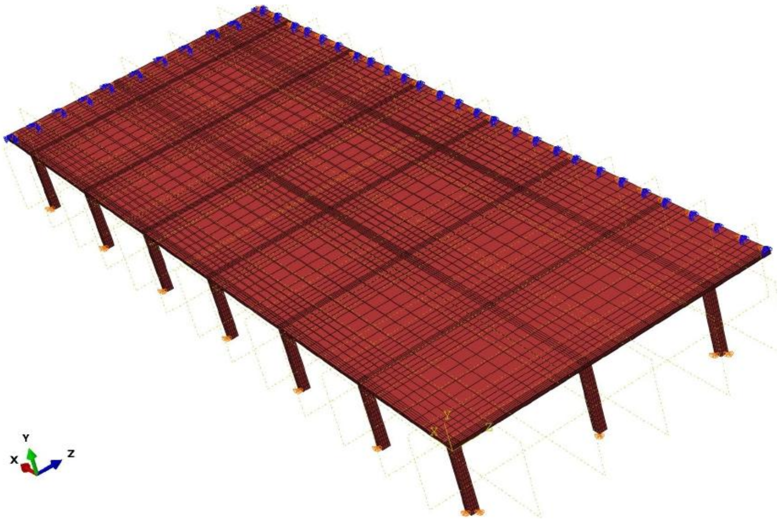
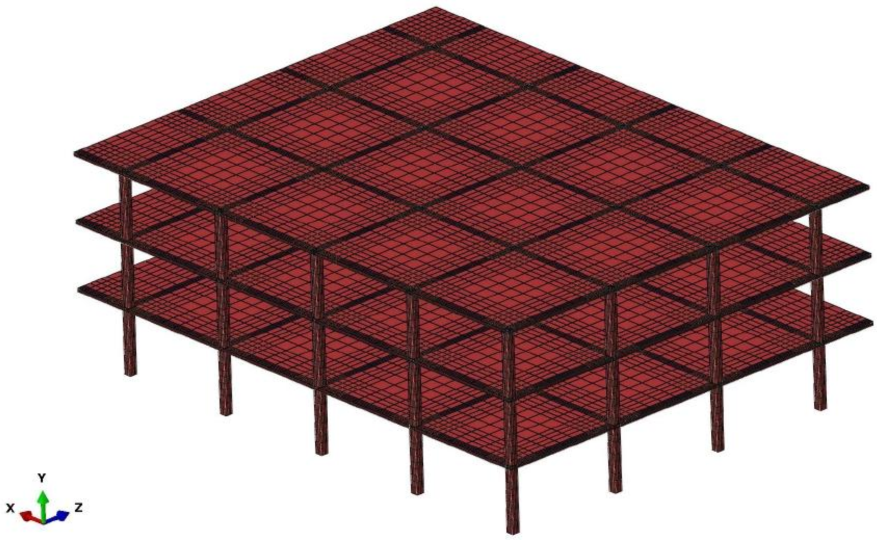


(a) Modeling of model ST1



(b) Modeling of model ST2

Fig. 4 Finite element modeling.



(c) Modeling of model ST3

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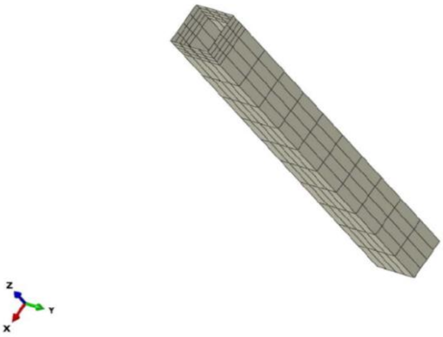
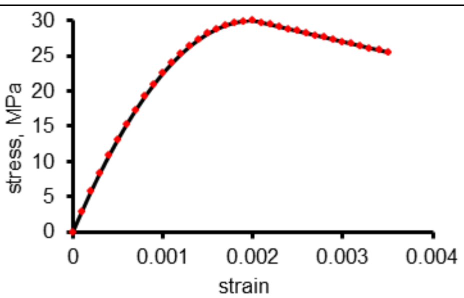
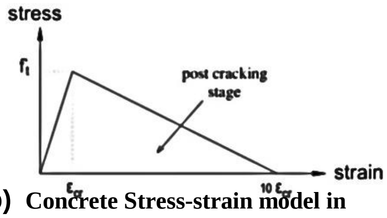


(d) Column steel modeling for all models

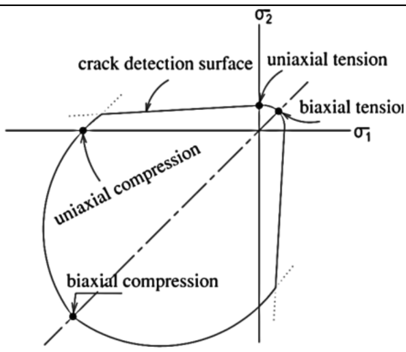
Fig. 4 Cont.



(a) Concrete model in compression



(b) Concrete Stress-strain model in tension including tension stiffening [2]



(c) Concrete failure surface in plane stress [2]

Fig. 5 Concrete modeling.

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 4, Issue 12, July 2015

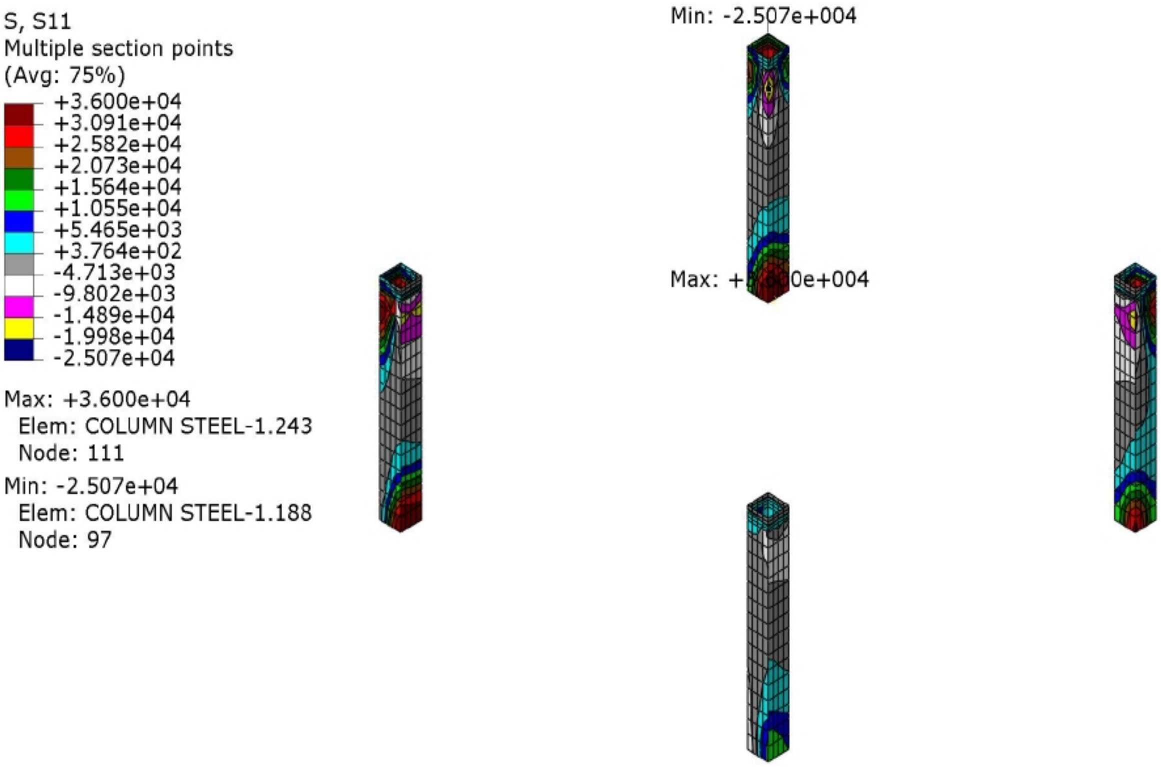
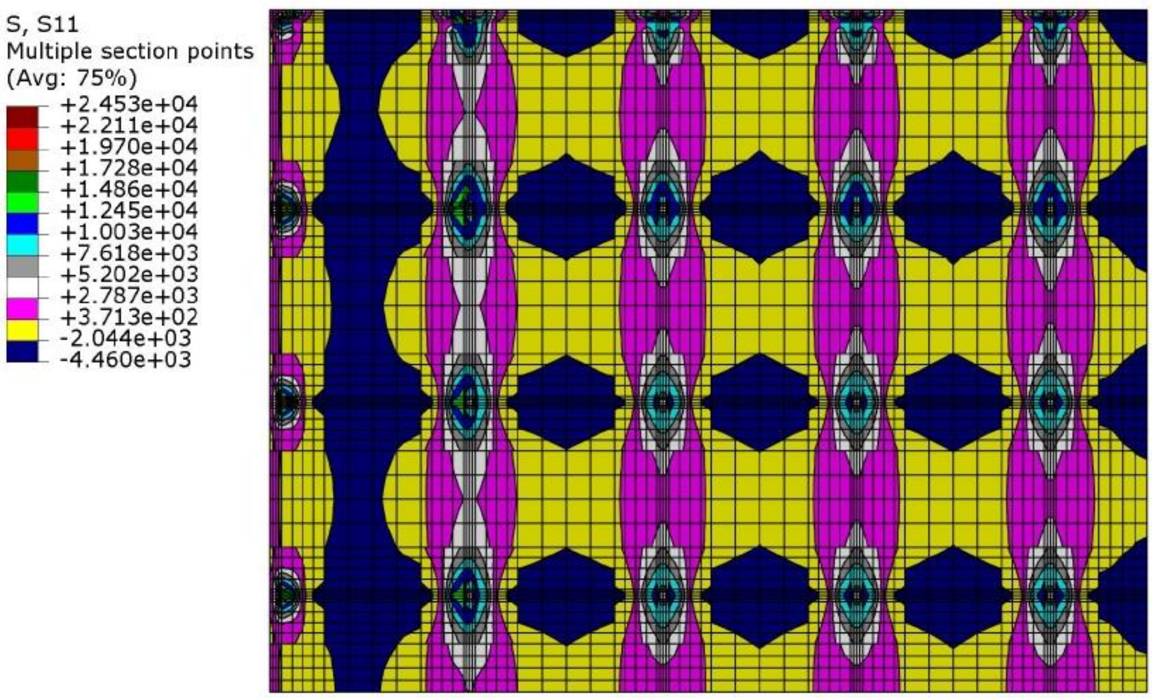
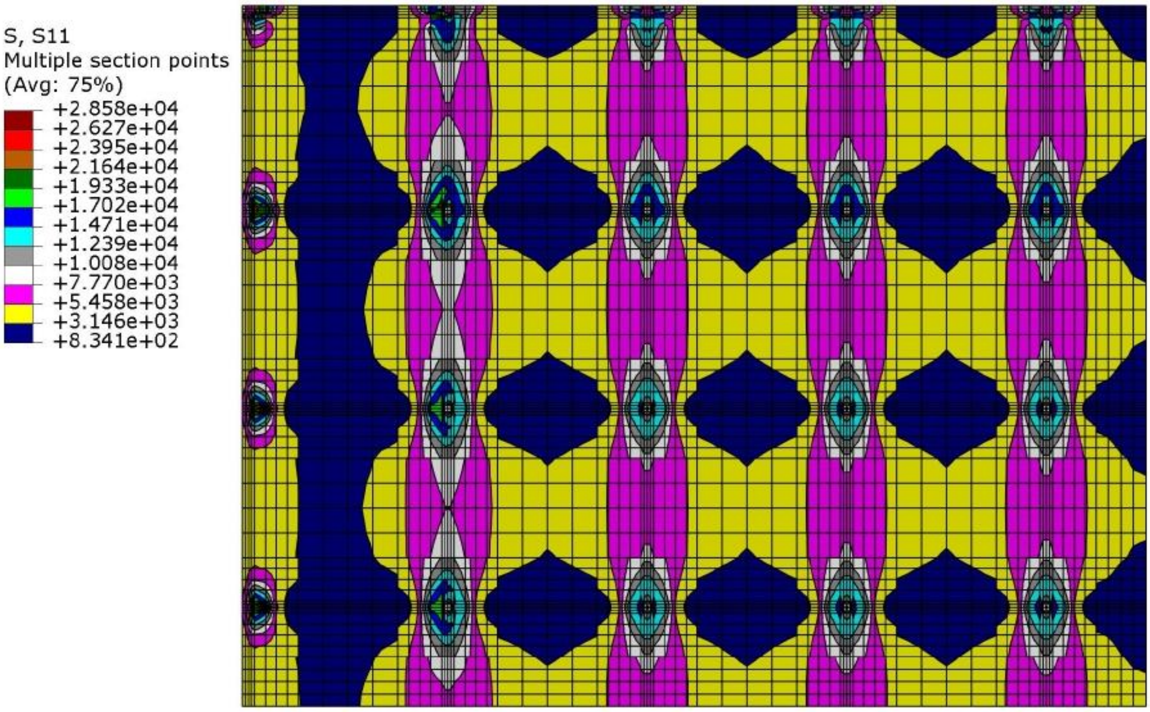


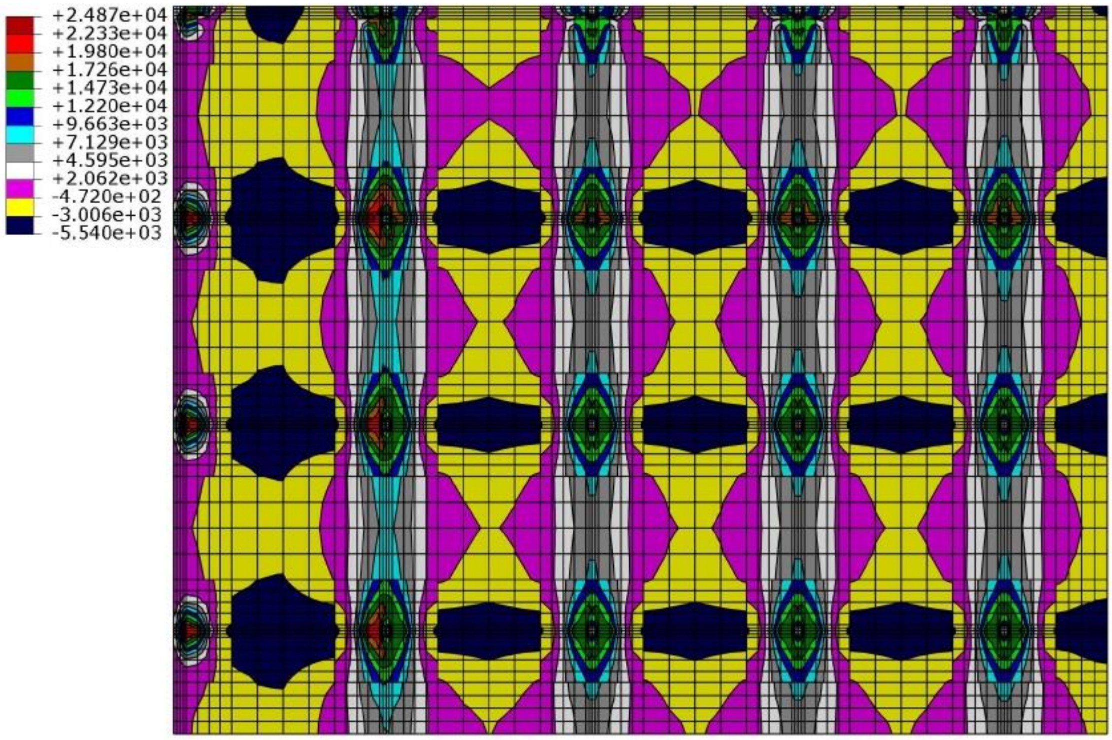
Fig. 6 Steel stresses in columns C1, C2, C3 and C4 of model ST2 for case B.



(a) Stress in top steel, x-direction, of second story of model ST3 for case A.



(b) Stress in top steel, x-direction, of second story of model ST3 for case B.



(c) Stress in top steel, x-direction, of second story of model ST3 for case C.

Fig. 7 Samples of the reinforcement stresses for the slabs of model ST3.