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ASSESSMENT OF FLAT SLAB AXIAL STIFFNESS IN THERMAL ANALYSIS

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الملخص العربى:

يعد التحليل الإنشائي للمباني تحت تأثير التمدد / الانكماش الحراري جزءًا لا يتجزأ من عملية التحليل الشاملة للمصممين. في التحليل الحراري ، يمكن أن تنتج الصلابة المحورية العالية لبلاطات المبنى قوى جانبية كبيرة نسبيًا على الأعمدة الداعمة. يكون تأثيرها أكثر وضوحًا في حالة المباني ذات الأطوال الكبيرة وتواجد عناصر عالية الصلابة مثل حوائط القص عند حواف المبنى. بالنسبة لبلاطات الخرسانة المسلحة، فإن وجود شروخ الانحناء بها يمكن أن يقلل من صلابتها المحورية العالية. وبالتالي فأن الهدف من هذه الدراسة هو التحقق من تأثير هذه التشرخات على الصلابة المحورية للبلاطات المسطحة ، بهدف إجراء تقييم لعوامل التخفيض المناسبة لتطبيقها على صلابة البلاطات المحورية والتي يجب أخذها في الاعتبار عند التحليل في حالتيالضغط والشد تحت تأثير التحميل الحراري.
تم تطوير خوارزمية تحليلية لحساب قيمة واقعية للصلابة المتشرخة لقطاعات بلاطات مسطحة عند قيم محددة لعزم الانحناء والقوة المحورية المؤثره عليها. يتم تطبيق هذه الخوارزمية في تطوير حزمة برامج ، تُستخدم لتحليل البلاطات المسطحة تحت الأحمال الحرارية ، ولتحديد قيم عوامل تقليل الصلابة المحورية التي سيتم تطبيقها في التحليل من خلال عملية تكرارية. تم توسيع تطبيق الخوارزمية المطورة على العديد من حالات التحليل الفعلي للمباني لتشمل تأثير العوامل المختلفة ، مثل طول المبنى وسمك البلاطة والتسليح ، ووجود حوائط القص متفاوتة الصلابة بالقرب من حواف المبنى. تستخدم نتائج هذه الدراسة لتزويد المصممين بقيم واقعية لعوامل تقليل الصلابة المحورية ليتم تطبيقها في التحليل ثم مقارنة النتائج بمواصفات الكود الحالي وبناء عليه يتم تقديم التوصيات في هذا الصدد.

الكلمات الدالة : التحليل الحرارى، نمذجة العناصر المحدودة، الصلابة المحورية للبلاطات، تشرخ الخرسانة المسلحة، اجهادات الشد.

ABSTRACT:

Structural analysis of buildings under effect of thermal expansion/contraction is an integral part of the overall analysis process for designers. In thermal analysis, the high axial stiffness of the building floors can produce relatively large lateral forces on the supporting columns. This effect is more pronounced in case of buildings of large lengths, and when high-stiffness elements such as shear walls, or cores exist at the building edges. For RC floors, the existence of flexural cracks can reduce this high axial stiffness. The aim of this study is to investigate

the effect of these cracks on the axial stiffness of flat slabs, with the objective of making an assessment of suitable reduction factors to be applied to the slabs axial stiffness to be considered in analysis, in both cases of floor compression and tension under effect of thermal loading.
An analytical algorithm is developed for computation of a realistic value for the cracked stiffness of flat slab sections at specific values of bending moment and axial force acting on them. This algorithm is applied into the development of a software package, utilized for analysis of flat slabs under thermal loads, and to determine the values of axial stiffness reduction factors to be applied in analysis through an iterative process. Application of the developed algorithm to several cases of actual buildings analysis is extended to include the effect of various parameters, such as building length, slab section and reinforcement, and the existence of shear walls of varying stiffnesses near the building edges. Results of the study are used to provide designers with realistic values for axial stiffness reduction factors to be applied in analysis.The results are compared to current code specification, and recommendations are presented in this regard.
KEYWORDS: Thermal Analysis, Finite Element Modeling, Axial Stiffness of slabs, Reinforced Concrete Cracking, Tensile Stresses.

1- INTRODUCTION

In thermal analysis of reinforced concrete flat slab structures, the increase in temperature produces a compressive force on the slab, which in turn produces horizontal deformations, causing shear forces and moments on the columns [1]. These forces and moments are caused by the restraining action of the vertical elements of the structure [2], and increase with the increase of their lateral stiffness. Since the value of the axial stiffness of the slab is much greater than the columns' bending stiffness, it is expected that most of the horizontal deformation will occur in the columns.

For a designer, an increase in the columns' sections to increase their strength and resistance will certainly increase their stiffness, and thus increase the value of the restraint forces too. The designer is therefore sometimes in confusion between increasing the column sections to increase their strength, or reducing them in order to reduce the resulting shear forces and bending moments caused by thermal expansion/contraction.

A very important factor to be considered in analysis is the effect of flexural cracking of concrete on the axial stiffness of the flat slab. It is not suitable to use the full uncracked axial stiffness in analysis, as this would lead to exaggerated values of shear forces and bending moments in the structures' columns [3] [4].

While the Egyptian Codespecifies a reduction factor of 45% to be applied to the axial stiffness of members in analysis, this specification is based on long-term creep considerations, neglecting the effect of working level flexural cracks on the axial stiffness of members [5].

The objective of this research study is to investigate the effect of flexural cracking in the working level on the actual axial stiffness of the flat slab floors, with an emphasis on computation of the reduction factors to be applied to the axial stiffness of flat slabs, while conducting thermal analysis of concrete structures under uniform temperature change.

2- LITERATURE REVIEW

Guruprasad and Nisarga [6] analyzed a seven storey RC structures considering temperature load due to fire exposure using ETABS. The study showed that increasing the temperature increased the axial forces values in the structure's members comparing to the same structure in the ambient temperatures. Additional compressive stresses are developed in beams and columns that restrained to expand. These additional stresses cause additional internal forces added to gravity loads.The shear forces and bending moments in columns also increased by temperature change.

ACI 349.1R [7]mentioned that the effect of thermal loads on reinforced concrete structures produceadditional axial forces and moments due to their restraint for thermal expansion and contraction. It's known that concrete is weak in tension, so it cracks under thermal tensile stresses then these tensile stresses are relieved but cracks are not good for serviceability of structure and its strength. So, it is very important in design to consider the thermal effect. Using a simplified procedure might be suitable to calculate the thermal effects. ACI allows for reduction of concrete modulus of elasticity in elastic finite element analysis equal to (0.5) to account in a very simple method for the effects of cracking, and creep.

Sydnaoui et al,[8] analyzed 272 ETABS model of one storey. The models are categorized according to column support conditions and development of concrete properties over time. The results showed that the thermal displacement increased with the increase in the column height and the length of the slab. Increasing slab thickness has higher stiffness with lower thermal deformations and higher reactions.The analysis showed that Increasing column height reduces significantly the forces and stresses due to reducing the column stiffness. And in case of considering time dependent properties of concrete the thermal response of super long reinforced concrete structures is more than those for non-time dependent properties for all analyzed cases, and this variance increased with time throughout life time of the building. Due to this variance, more additional strains, forces, and stresses are imposed.

El-Arabaty et al,[9] developed an analytical approach to take the effect of existing bending cracks along the beam length on the beam's axial stiffness. The analysis showed that the stiffness reduction factors increased with increasing the compressive axial forces and decreased with increasing the tensile axial forces. The parametric study showed that the amount of tension steel in the beam sections is the most important factor that affect the axial stiffness reduction factors. Also, beam section dimensions were found to affect the reduction factors values. Theyrecommended that it is not suitable to use a fixed value of reduction factor for all cases of temperature analysis in order to simulate the effect of thermal effects more accurate which can reduce the straining actions of supporting columns.

Pooja and Karthiyaini[10] analyzed six models with length of 90-m, 138-m, and 180-m with and without expansion joints using ETABS. The results showed that the displacement increased as the length of slab increases. The stresses for different slab lengths increased in case of not using expansion joints due to temperature loads which increased the reinforcement steel area. From results by considering temperature loads during design of flat slab structures the provision of expansion joints can be eliminated.

Sabouni and Sydnaoui [11] analyzed 68 ETABS models of one-story reinforced concrete frame buildings under thermal loads. The results of research confirmed the considerable additional lateral deformations at slab level and horizontal forces at supports due to temperature loads.

El-Tayeb et al,[12] studied the behavior of reinforced concrete elements under temperature change with the presence of vertical loads and found that material modeling of reinforced concrete is important for realistic behavior. Also, cracking of reinforced concrete helps to release the restraint forces developed depending on the reduction in the structural stiffness.

Badrah and Jadid [13]parametric investigation study carried out to analyze 3-D frame structures subjected to member-temperature change loading cases, and they found that the most affected members from temperature change are columns and beams of the lowest two stories and these elements need to be designed for additional shear force and moment due to temperature change. Also, they found that no matter how high the structure is, the greater the length or width, the greater are the force values on the affected members.

Ahmed [14] performed a two and three-dimension analysis to investigate the temperature effect on multi-story concrete buildings, A uniform temperature change results in forces and moments at the constraints. Due to fixation of supporting columns with foundation, the internal forces and stresses produced by temperature change are high at the ground floor. The forces almost disappear after the third floor, the number of floors has no effect on the resulted forces while higher values of forces are encountered by increasing the concrete strength, length and or the number of bays. The analysis showed that the most affected elements by temperature change are the most internal panel and the most external columns. Daily and seasonal temperature changes have a significant influence in concrete structures. Thermal forces resulted must be taken into consideration when designing the structures.

El-Metwally et al,[15] used non-linear finite element to analyze one model of long span reinforced concrete flat plate and raft foundation supported directly on soil or piles under effect of temperature gradients and shrinkage effect, where shrinkage is introduced as a drop in temperature of 30 C using ABAQUS software. From the analysis results, it is important to account temperature change and shrinkage in the design of slabs for an accurate assessment of deflection. And the effect of temperature change and shrinkage can be accommodated by additional reinforcement.

3- PROBLEM DESCRIPTION

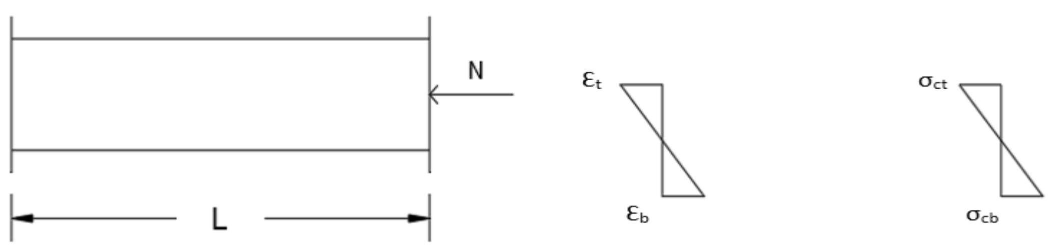
Flat slabs are used widely in buildings, they provide large surface area, have static effectiveness allow reaching large span-depth ratios, support directly on the columns providing more space, easy to carry out and more economical [16].

The change of the temperature in the reinforced concrete structures cause thermal stress which is defined as the effect of thermal load. If member expansion is restrained then thermal stresses are developed. High temperature causes loss of strength and stiffness which weaken the structure [17].

The different sections in a flat slab are subject to varying levels of stress and strain, based on their location within the plan, and the magnitude of the acting bending moment produced by the existing vertical loads.

When considering the level of cracking to be considered in analysis, it is important to note that expansion/contraction of the slabs is likely to occur, while the slab is under working load conditions. The effect of slab movement (expansion/contraction) is more significant to the design of columns, as it produces high lateral forces on them. Its effect on the slab is only to increase the axial forces in the slab. However, these additional axial forces are relatively small compared to the section's capacity. The level of stresses considered here on the flat slab, are therefore the working level stresses.

For a slab section not subjected to any bending moments, a compressive force acting on the section will produce the shown stress and strain diagrams in Fig.1.



a. Slab element **b. Strain diagram** **c. Stress diagram**

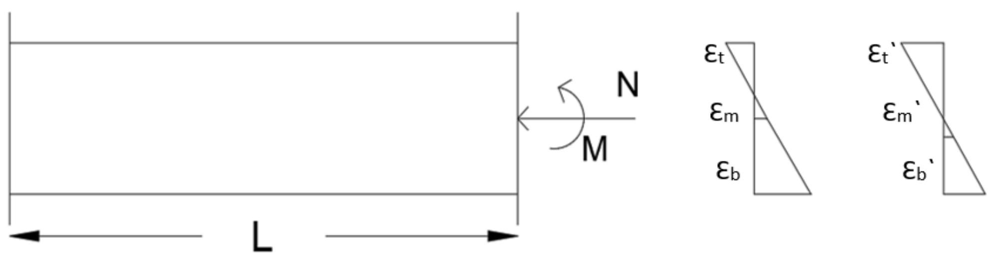
Figure 1. Effect of compressive axial force on uncracked slab section

The axial stiffness of the slab element of Length (L), and width (B), can be expressed as follows:

$$K_{Axial\text{-}Uncracked} = E.A/L \quad (1)$$

This expression is typically used by commercial structural analysis programs in computing the axial stiffness of slab elements, and is thus used in all computations related to the thermal analysis of buildings. While most programs allow for the introduction of reduction factors to this stiffness value, these factors need to be input by the user.

The stresses and strains produced by an acting moment on the cracked slab section are shown in figure 2a. The effect of an acting axial force on this section is to produce a change in the existing strain diagram, by increasing the compressive axial strain, and reducing the tensile axial strain, as shown in figure 2b.



a. Slab Element **b. Strain diagram due to BM only.** **c. Strain diagram due to BM and compressive axial force**

Figure 2. Effect of compressive axial force on uncracked slab section

The above changes produce a change in the neutral axis location, and produces "partial closing" of the existing cracks. In order to determine the actual stiffness of the cracked slab element, the change in deformation at the center of the section (Δ_m), caused by the axial force can be estimated and used to compute the axial stiffness, as follows:

$$\Delta_m = L\,(\varepsilon_{m2} - \varepsilon_{m1}) \qquad (2)$$

$$K_{Axial\text{-}Cracked} = N / \Delta_m \qquad (3)$$

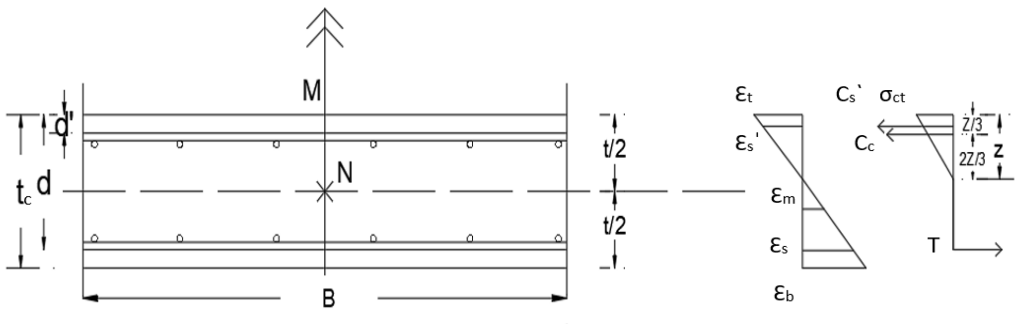
Computation of the above-mentioned axial stiffness of a cracked slab element is therefore a function of both the acting moment, and existing strain pattern, together with the magnitude of the acting axial force. The complexity of the computation process necessitates the development of an algorithm, and a software for its calculation. This task is undertaken in the next section.

The case of a tensile force acting on the section can be treated in a similar manner to the compressive force case. In case of pure tension on the section, the stiffness can be computed using equation (1), after substituting the steel reinforcement area, and young's modulus of steel to that of the concrete section. However, this case is very unlikely to occur in a flat slab section.

The more likely case to be considered is the tensile force being applied to a section under effect of a bending moment produced by the vertical loads. In this case, equations (2) & (3) can be used, after applying (N) as a tensile force. All the above cases will be considered in the algorithm and software package developed in the next section, for estimation of the "Cracked Axial Stiffness" of flat slab elements.

4- ANALYTICAL ALGORITHM

The typical strain diagram produced by a combination of bending moment and axial force acting on the slab section is shown in Figure 3.



a. Slab section under M&N **b. Strain diagram** **c. Stress diagram**

Figure 3. Strain & Stress diagrams in slab section due to M & N (working stage)

Assuming the strains at the top and bottom of the section to be [ε_B& ε_T] respectively, all other strain values in the diagram can be derived from them, as follows:

$\varepsilon_s = (\varepsilon_t\ (t_c - d) + \varepsilon_b\ (d)) / t_c$ (4)

$\varepsilon_s' = (\varepsilon_t\ (t_c - d') + \varepsilon_b\ (d')) / t_c$ (5)

$\varepsilon_m = (\varepsilon_t + \varepsilon_b) / 2$ (6)

For a specific slab section thickness, and reinforcement, if the shown strain diagram is multiplied by any factor, all strains, the values of M & N will all be increased by the same factor. However, the ratio (M/N) will not change. This ratio is therefore independent of the actual value of ε_t&ε_b, but dependent only on their ratio.

For any assumed values of [ε_B& ε_T], the corresponding straining actions (M & N) acting on the section can be determined using the corresponding stress diagram (linear in the working stage). The corresponding stresses in concrete at the top and bottom are [σ_T& σ_B], and can be computed as follows:

$\sigma_T = E_C * \varepsilon_T$ (7)

$\sigma_B = E_C * \varepsilon_B$ (8)

Where E_C is Young's modulus of concrete.

The location of the neutral axis relative to the section top is indicated as [Z], and can be computed as:

$Z = t_C * (\varepsilon_T / (\varepsilon_B + \varepsilon_T))$ (9)

The stresses in the steel reinforcement, and the corresponding forces can also be computed as:

$T = A_s * E_s * \varepsilon_s'$ (10)
$C_s' = A_s' * E_s * \varepsilon_s'$ (11)
$C_c = ((\sigma_{ct} * Z) / 2) * B$ (12)
$N = C_c + C_s' - T$ (13)
$M = (C_c * (t/2 - Z/3)) + (C_s' * (t/2 - d')) + (T_s * (d - t/2))$ (14)

By varying the ratio of [$\varepsilon_B / \varepsilon_T$], a corresponding ratio of (M/N) can be obtained. The proposed algorithm is based on computation of the ratio of (M/N) for a large number of values of [$\varepsilon_B / \varepsilon_T$]. These values are stored to be used as a base for computation of the slab stiffness values. Figure 4 illustrates the results obtained for a typical flat slab section.

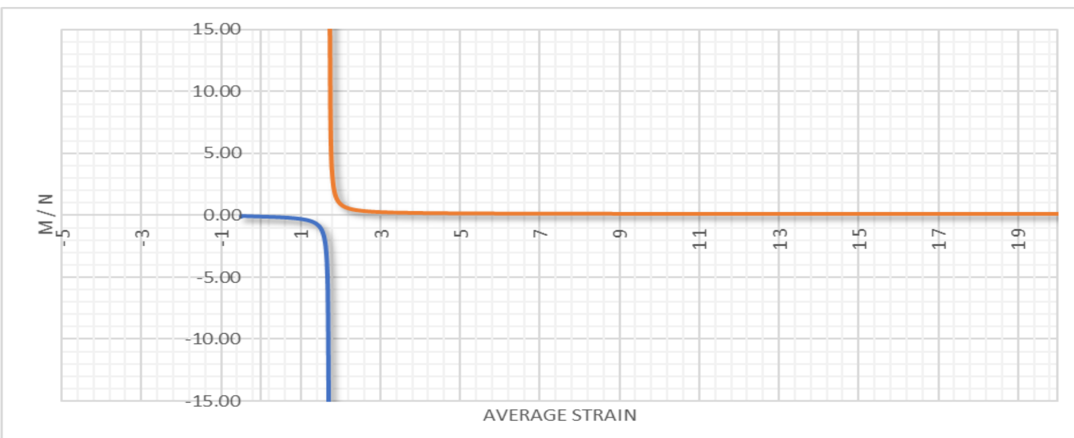


Figure 4. Variation of (M/N) ratio with ($\varepsilon_b / \varepsilon_t$) ratio, for a typical flat slab section.

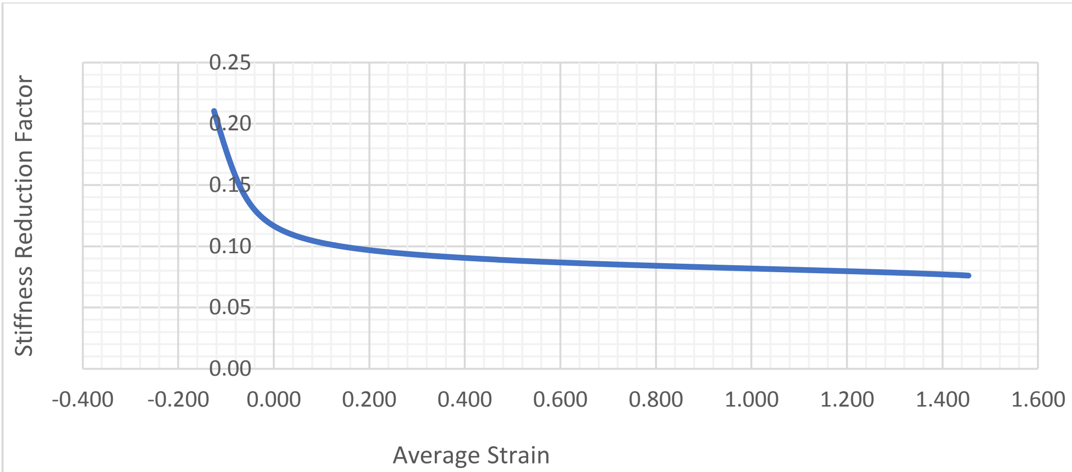


Figure 5. Variation of Stiffness Modification Factor with Average Strain, for a typical flat slab section.

The above equations can be used to determine the values of M & N for any specific combination of top and bottom strains acting on the section. The proposed analytical algorithm (explained in detail in section 3), is based on dividing the expected range of strain ratio into a large number of steps, and determination of the corresponding M & N for each strain configuration. The results are stored in a matrix to be used in the next steps, for this specific section. This matrix describes the variation of the ratio M/N with the strain at the middle of the section ($\mathcal{E}_m$).

In order to determine the strain values acting on the section for specific values of M & N. The value of M is used to scale the above-mentioned matrix. A search routine is subsequently utilized to determine the value of the strain ($\mathcal{E}_m$) corresponding to the axial force (N). The cracked stiffness value of the section can be obtained using the secant stiffness, as shown in figure 6.

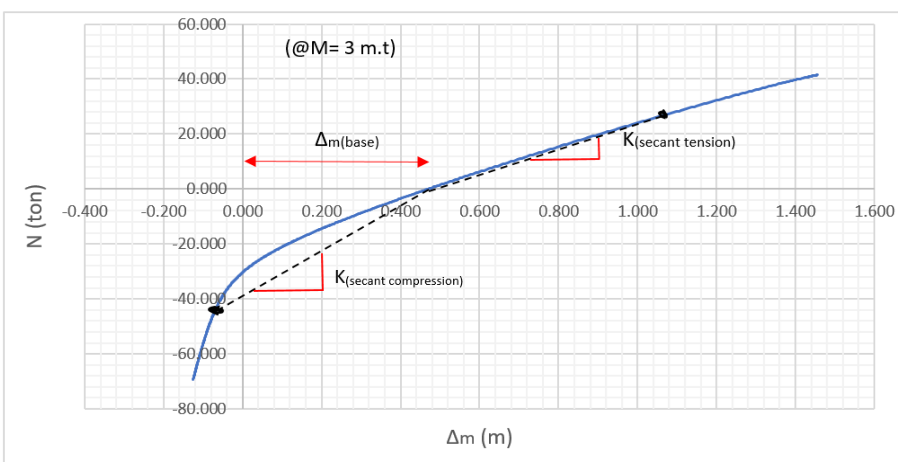


Figure 6. Variation of Axial Stiffness with Displacement in cracked section for 1m length element

4.1 Step by Step Procedure for Computation of Slab Axial Stiffness

In this section, a step-by-step technique is charted for the application of the above-described analytical algorithm. The flowchart illustrated in Fig. 7 shows the outline of the adopted technique, and can be briefed in the following steps:

Stage 1:

1. Input of section properties into the developed software package.
2. Input of range of expected strain levels on section.
3. Computation of variation of strain values with normal force values on section at a specific level of bending moment acting on the section, using the above described equations (4 to 14).
4. The above variation values are saved into a matrix for use in stage 2 of the procedure.

Stage 2:

5. Analysis of model using ETABS software package.
6. Output of bending moment results [M_v] due to vertical loads (working) for the individual shell element results to the designated Excel sheet location.
7. Similarly, producing output of axial forces [Nth] obtained due to the case of temperature change (+20&-20) to the designated Excel sheet location.
8. Scaling the N-Δ variation obtained in step 4, to the actual moment level [M_v], acting on each shell element.
9. Computation of strain diagram produced by the effect of both [Mv & Nth] acting together, for each shell element.
10. Determination of the cracked stiffness of each shell element, using “secant stiffness” as described in figure 6.
11. Computation of stiffness modification factors (the ratio of the cracked stiffness to the standard uncracked axial stiffness of each element).
12. Applying the above modification factors to the finite element model (ETABS), and re-performing the thermal analysis, based on the updated axial stiffness.
13. Repetition of steps 5 to 12, until convergence is reached.

The above-described procedure is summarized in the flowchart presented in figure 7.

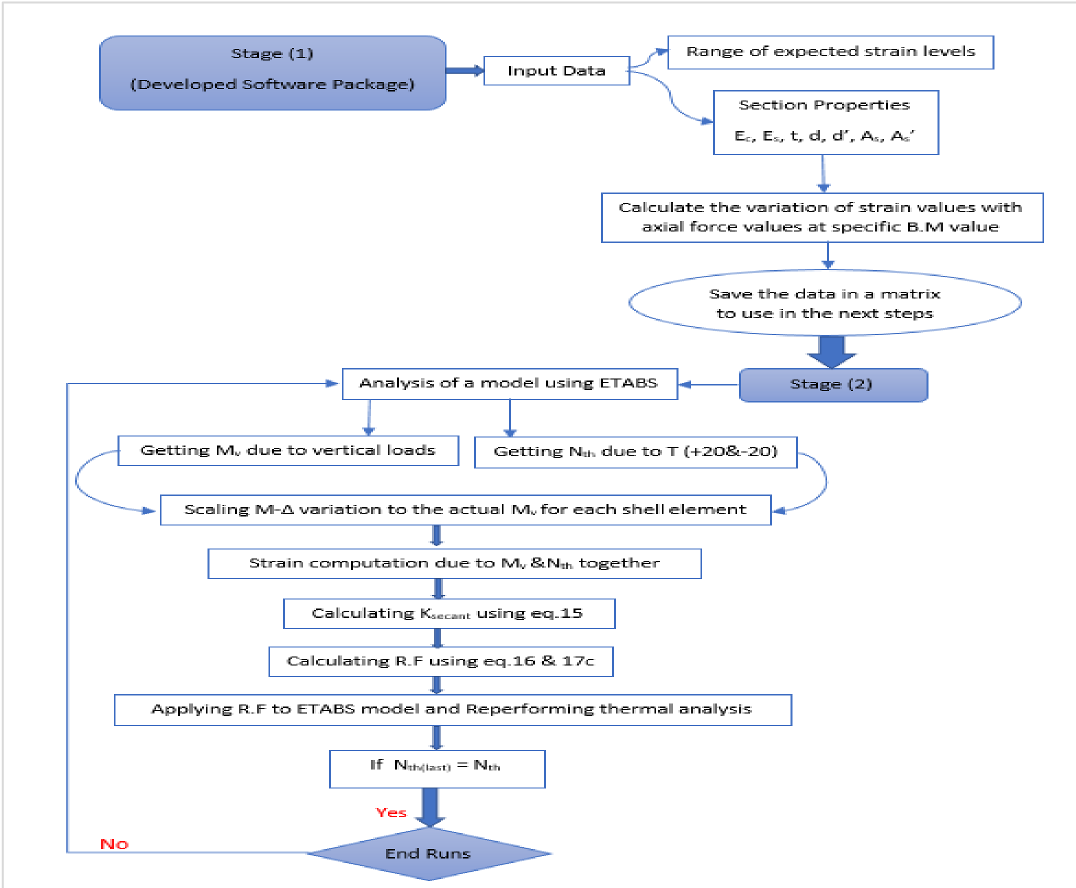
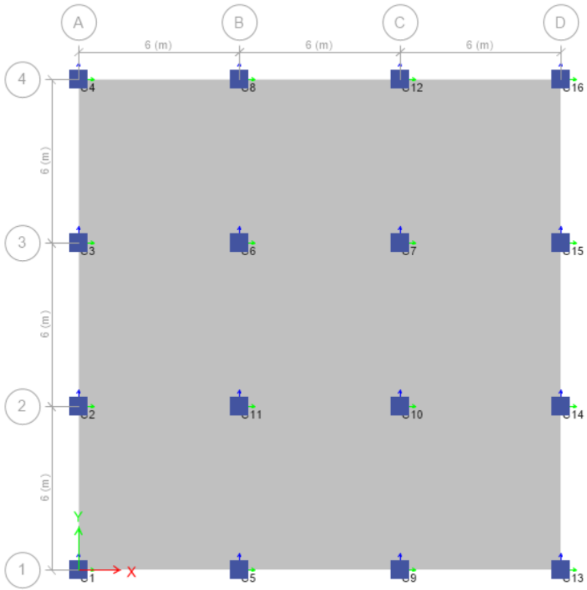


Figure 7. Analysis procedure flowchart to calculate the axial modifiers for Slab's stiffness

4.2 Effect of section cracking on thermal analysis of flat slabs

The above-described software package is used here to determine the variation of axial stiffness of a sample slab subjected to temperature change, for both expansion and contraction cases. A symmetrical flat slab plan is chosen here similar to that shown in Fig. 8 & 9. The typical slab span is selected as 6-m. Design of the slab is performed according to the Egyptian Code of Practice, while column sections are assumed based on designconsiderations.



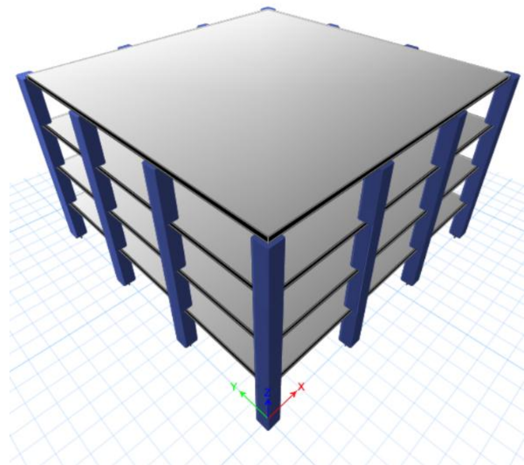
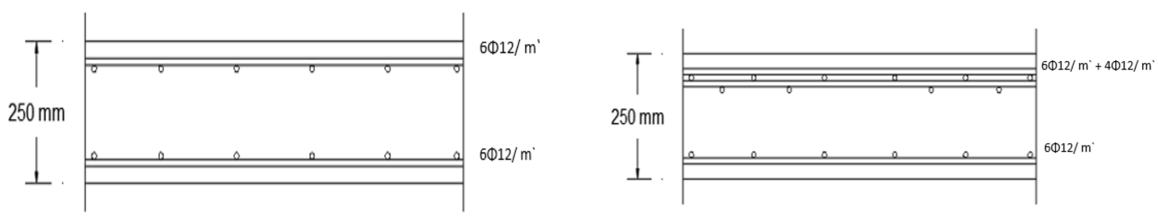


Figure 8. plan of flat slab floor **Figure 9. 3D-view**

The dimensions and reinforcement of the flat slab sections in this analysis are shown in figure 10.



a. Slab section [I] in midspan areas **b. Slab section [II] around columns**

Figure 10. Top and bottom reinforcement of flat slab section

For both sections [I & II], the developed software package is used to determine the variation of the axial force acting on the section with the expected displacement in the section. The results in case of section [I] for the above-mentioned case, for a specific value of acting bending moment, are illustrated in Fig. 11.

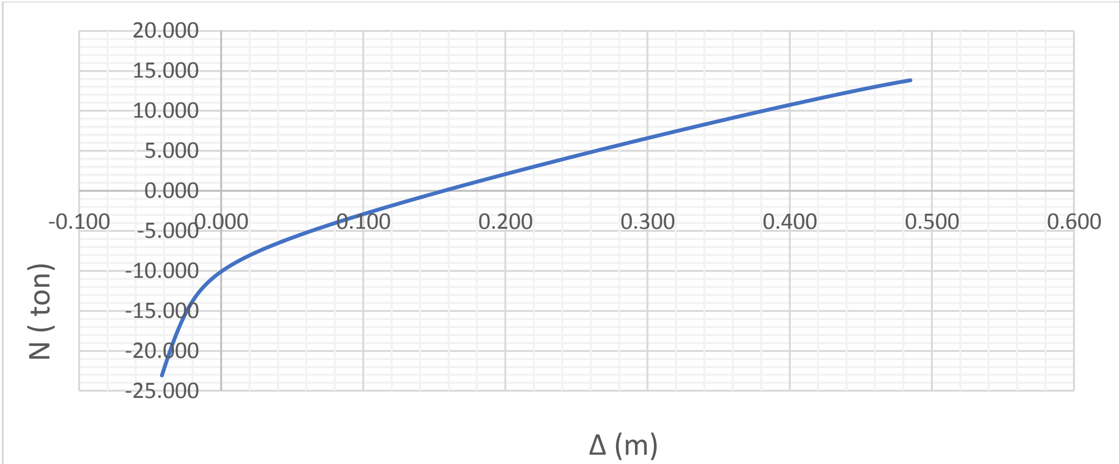


Figure 11. Scaled Force-Average Displacement curve for Slab in axial direction at specific moment value

(Section I, M = 1 mt)

Fig. 11 illustrates the relationship between the axial load acting on the cracked section of the slab, and the resulting axial displacement. The positive direction of the y-axis represents tensile axial forces, while the negative direction represents compressive axial forces. The value of the slab axial stiffness at any specific axial load value can be computed using a secant approach (15).

$$K_{secant} = P_{axial} / (\Delta_m - \Delta_m(N=0)) \qquad (15)$$

The axial stiffness of the slab computed for both the compression and tension cases corresponds to the cases of slab expansion and contraction respectively, and can be computed using the secant approach, as shown in figure 6.

Reduction factors for the compression and tension cases can be computed as follows:

$$RF_{comp.} = K_{comp.} / (E.A/L) \qquad (16)$$

$$RF_{tens.} = K_{tens.} / (E.A/L) \qquad (17)$$

The variation of RF_{comp}& RF_{tens} with the acting axial force on the section in this case, are illustrated in Fig. 12.

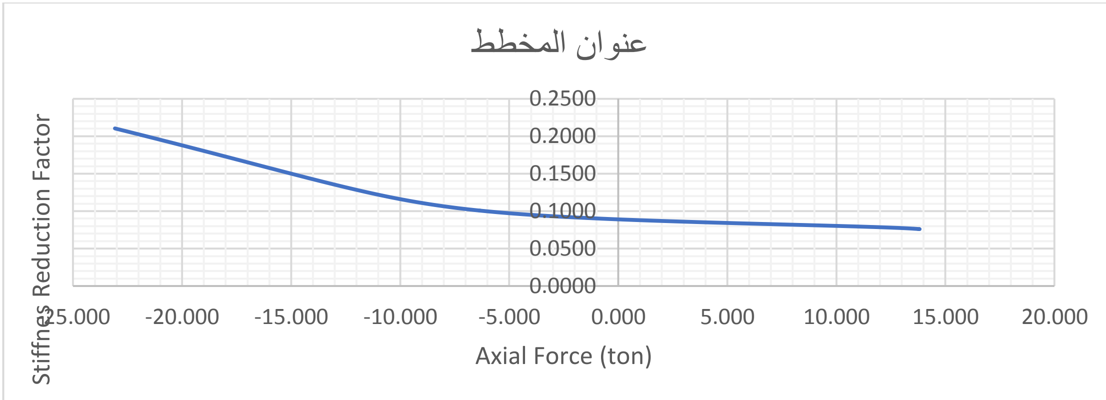


Figure 12. Force-Reduction factor curve for slab in axial direction at specific moment value (Section I, M = 1 mt)

Fig.12 shows the structural behavior of flat slab under effect of temperature change. For the compression case (thermal expansion), the slab stiffness increases considerably. This can be explained by the closing of cracks initially caused by the bending behavior of the loaded slab. As the cracks close more and more, the slab stiffness starts to approach the uncracked axial stiffness value. Whereas the axial force-displacement curve in the tension zone shows an almost linear variation, and its change is slight, and the values are always less than the axial compression case, and far away from the uncracked stiffness value.

The "Axial Stiffness Reduction Factors" (RFcomp & RFtens) showed in Fig.12 illustrate that in this sample case, the effect of slab flexural cracking on the axial stiffness of the flat slab is very significant. For compressive forces, the value of the reduction factor is in the range of 0.20 to 0.09. And the tension case shows values in the range of 0.09 to 0.07. These low values of the stiffness reduction factors show the important effect of combined bending and axial cracking on the expected slab stiffness. Including such low stiffness reduction factors in the structural analysis can be very effective in reducing the final resulting lateral loads induced into the columns, which are produced by the slab confinement during expansion/contraction.

5- PARAMETRIC STUDY

A number of analysis runs were performed, using the developed analytical algorithm, in order to determine the effect of different factors on the expected reduction factors to the axial stiffness of the flat slab, which would account for the effect of cracking on this stiffness.

Table 1. lists the different parameters used in the analysis runs.

Case No.	Slab Thickness (mm)	Span Length (mm)	No. of Spans	Steel Reinforcement Area	Shear Wall Length(mm)
1	250	6000	3	As (based on ECP design)	No Shear Wall
2	250	6000	5	As	No Shear Wall
3	250	6000	7	As	No Shear Wall
4	250	6000	9	As	No Shear Wall
5	250	6000	11	As	No Shear Wall
6	250	6000	11	1.5 As	No Shear Wall
7	300	6000	11	As	No Shear Wall
8	250	6000	11	As	2000
9	250	6000	11	As	3000
10	250	6000	11	As	4000
11	250	6000	7	As	2000
12	250	6000	7	As	3000
13	250	6000	7	As	4000

Table 1. Summary of the Data Used in the Analysis

5.1Effect of Building Length

Different configurations of the 6-m flat slab spans (3, 5, 7, 9 & 11 spans respectively) were used, as basis for different models, varying from 18 m to 66 m in length. For each case, design of the slab was performed according to the Egyptian Code of Practice. The data used is illustrated in Table 2.

E_c	220 t/cm^2
E_s	2000 t/cm^2
t_s	25 cm
d	22 cm
d`	3 cm
A_s **	6 Φ 12 / m`
A_s` **	6 Φ 12 / m`

** A_s& A_s`: Main mesh for top and bottom of flat slab, respectively.

Table 2. data used in analysis and design of flat slab

The analysis was performed using ETABS, and the developed algorithm and software package were used interactively with ETABS to determine the expected axial stiffness modification factors, and the corresponding shear forces and bending moments produced by the expansion in the supporting end-columns.

The analysis results for the case of “no stiffness modification” (M.F =1) are shown in table 3.

NO. of spans	Span length	Building length along X-axis	Column	Load Case	M.F	V2	M3	Load Case	M.F	V2	M3
3	6	18	C2	T+	1	-11.6491	13.0042	T-	1	11.6491	-13.0042
5	6	30	C2	T+	1	-18.2133	19.7223	T-	1	18.2133	-19.7223
7	6	42	C2	T+	1	-23.8222	25.2191	T-	1	23.8222	-25.2191
9	6	54	C2	T+	1	-28.3616	29.2214	T-	1	28.3616	-29.2214
11	6	66	C2	T+	1	-31.9565	31.8999	T-	1	31.9565	-31.8999

Based on the results obtained, a value of 0.25 was selected as a base modification factor for the initial analysis, in order to reach convergence more speedily.

The analysis results for the case of “stiffness modifiers” (MF =0.25) are shown in table 4.

NO. of spans	Span length	Building length along X-axis	Column	Load Case	M.F	V2	M3	Load Case	M.F	V2	M3
3	6	18	C2	T+	0.25	-9.2693	8.709	T-	0.25	9.2693	-9.4968
5	6	30	C2	T+	0.25	-13.469	13.0254	T-	0.25	13.469	-13.0254
7	6	42	C2	T+	0.25	-16.1189	14.3745	T-	0.25	16.1189	-14.3745
9	6	54	C2	T+	0.25	-17.8588	14.5355	T-	0.25	17.8588	-14.5355
11	6	66	C2	T+	0.25	-19.0826	14.0577	T-	0.25	19.0826	-14.0577

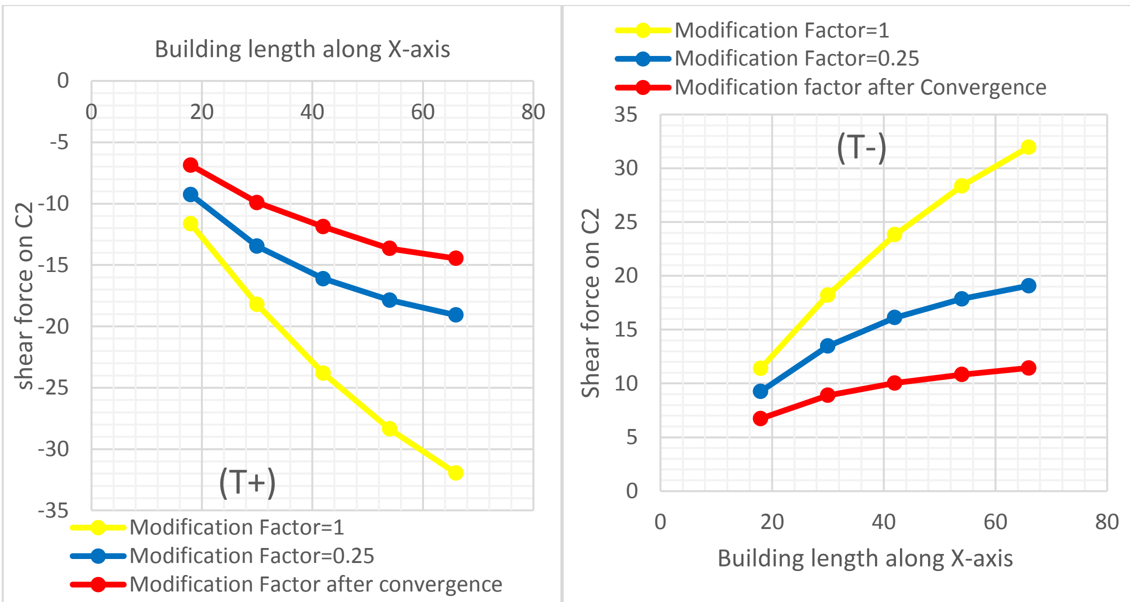
The final modification factors after convergence are shown in Table 5.

NO. of spans	Span length	Building length along X-axis	Column	Load Case	M.F	V2	M3	Load Case2	M.F	V2	M3
3	6	18	C2	T+	0.096	-6.8764	6.1207	T-	0.091	6.7384	-5.932
5	6	30	C2	T+	0.115	-9.9129	8.0688	T-	0.0915	8.8944	-6.6709
7	6	42	C2	T+	0.1256	-11.887	8.5527	T-	0.0897	10.0344	-6.0818
9	6	54	C2	T+	0.14	-13.653	8.86	T-	0.089	10.826	-5.2331
11	6	66	C2	T+	0.14	-14.4654	8.0129	T-	0.0884	11.4301	-4.3395

The above-mentioned results are summarized in figure 13.

The figure illustrates the effect of the modification factor applied in analysis to the axial stiffness of the slab, on the resulting lateral column forces. Column C2 is the outermost column on both sides of the symmetrical building (on an intermediate column strip), and is therefore taken as a measure of the resulting forces.

Figure 13a shows the variation of the lateral reaction of C2 with building length in case ofslab compression (caused by temperature increase/ slab expansion), while figure 13b illustrates the same variation in case of tension (caused by temperature decrease/ slab contraction).



a. Temperature increase effect axial force in compression

b. Temperature decrease effect axial force in Tension

Figure 13. Effect of Number of spans on the Shear force produced on the top of column (C2)

It can be seen that as the number of spans (building length) increases, the axial forces in the slab increase, and consequently the shear forces resulting in the building columns increase also. This is caused by the increased deformations at the building edges produced by expansion. The axial stiffness modification factor corresponding to the axial force level in the slab increases with the increase in building length, as shown. However, it is noted that the modification factors obtained are in a low range (less than 20% in case of compression, and less than 10% in case of tension).

When the proposed reduction factors for slab axial stiffness are applied, the resultant shear forces in the columns show a considerable reduction, where the lateral force was reduced to 45 % of its value, when the stiffness reduction factor was applied in analysis of the longest case (66m), andto 60 % of its value, when the stiffness reduction factor was applied in analysis of the shortest case considered (18m).

5.2 Effect of Shear wall Stiffness

Two cases are considered here, in order to determine the effect of existence of shear walls (or stiff members in general) near the building edges. The first case is for a building composed of

7 spans, each 6 m long. The overall length (42 m) is close to the limit specified by code where temperature effect is not to be considered. The second case is for a building composed of 11 spans, each 6 m long, with an overall length of (66 m), which requires temperature analysis according to code specs.

- **Case [1]: 42 m long building:**

Tables 6, 7 & 8 illustrate the analysis results for different modification factors applied to the flat slab stiffness. While table 6 includes results obtained using the typical axial stiffness (no stiffness reduction), table 7 illustrates the results obtained after applying a factor of 25% to the slab's axial stiffness, and table 8 shows the results obtained after applying the actual factors reached at convergence. The results are also shown in figure 14.

shear wall length	Span length	Building length along X-axis	wall	Load Case	M.F	V2	Load Case	M.F	V2
2	6	42	P1	T+	1	-68.842	T-	1	68.842
3	6	42	P1	T+	1	-123.176	T-	1	123.1758
4	6	42	P1	T+	1	-175.568	T-	1	175.5676

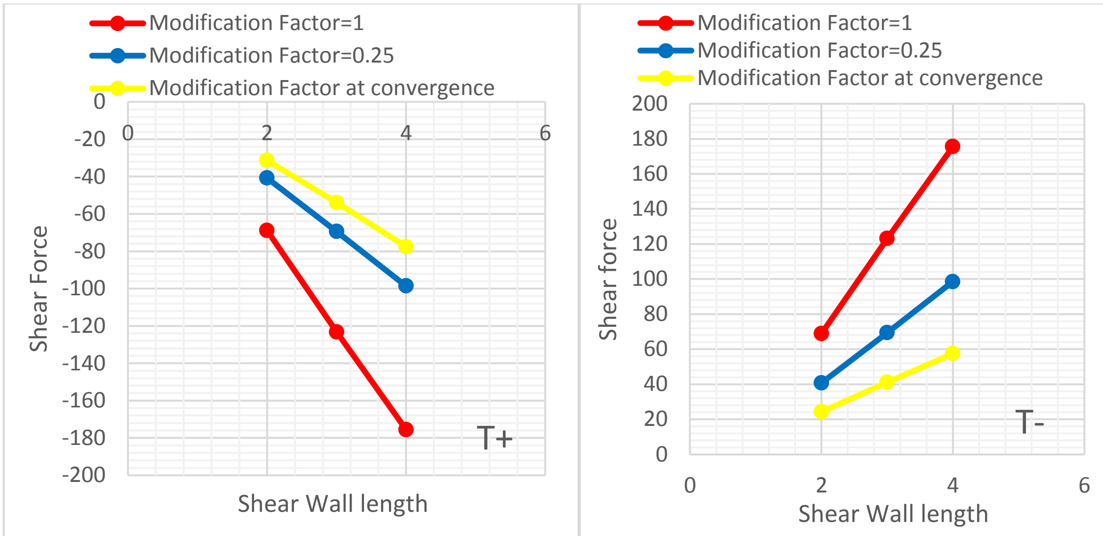
Table 6. Internal forces in edge shear wall (P1) due to slab expansion/contraction [applying no modification factor to the axial stiffness of slabs]

shear wall length	Span length	Building length along X-axis	wall	Load Case	M.F	V2	Load Case	M.F	V2
2	6	42	P1	T+	0.25	-40.713	T-	0.25	40.713
3	6	42	P1	T+	0.25	-69.3915	T-	0.25	69.3915
4	6	42	P1	T+	0.25	-98.6027	T-	0.25	98.6027

Table 7. Internal forces in edge shear wall (P1) due to slab expansion/contraction [applying a selected modification factor of 25% to the axial stiffness of slabs]

shear wall length	Span length	Building length along X-axis	wall	Load Case	M.F	V2	Load Case	M.F	V2
2	6	42	P1	T+	0.1447	-31.3209	T-	0.0866	24.2267
3	6	42	P1	T+	0.148	-53.8272	T-	0.0867	41.0917
4	6	42	P1	T+	0.152	-77.5448	T-	0.0866	57.5082

Table 8. Internal forces in edge shear wall (P1) due to slab expansion/contraction [applying actual modification factors on convergence to the axial stiffness of slabs]



a. Temperature increase effect axial force in compression

b. Temperature decrease effect axial force in Tension

Figure 14. Effect of Shear Wall length on building response (Case [1]: 42 m long building)

The studied case of existence of stiff shear walls at the building edges is a major case of concern, as the presence of these stiff elements (shear walls, or otherwise) causes restraint of the slab, and thus the forces produced by expansion/contraction of the slab produce maximum effect.

The results obtained show that the applicable modification factors corresponding to this case have increased compared to the case where no shear walls were added. However, this increase from around 12% to 15% in case of compression (slab expansion) is still within the low range of modification factors. No significant change in range is noted in case of tension (slab contraction), and the modification factor range is below the 10% limit.

The effect of variation in shear wall length can be seen in Fig. 14. While increasing the length of the shear wall increases the shear force and bending moment on the wall, this is due to the increased stiffness of the wall. A better indicator of the effect of shear wall length is the reduction obtained in the lateral force by applying the axial stiffness modification factor. The lateral force in the compression case after applying the modification factor (table 8) is around 44 to 45% of the corresponding values obtained when not applying the modification factor (table 6). The change in wall length (and stiffness) does not have a major effect. The same ratio is found to be within 33 to 35% in case of tension.

- **Case [2]: 66 m long building:**

Tables 9, 10 & 11 illustrate the analysis results for different modification factors applied to the flat slab stiffness. Similar to the previous case, table 9 includes results obtained using no stiffness reduction, table 10 illustrates the results obtained based on a reduction factor of 25% to the slab's axial stiffness. Table 11 shows the results obtained after applying the actual factors reached at convergence. Figure 15 illustrates these results.

shear wall length	Span length	Building length along X-axis	wall	Load Case	M.F	V2	Load Case	M.F	V2
2	6	66	P1	T+	1	-91.6398	T-	1	91.6398
3	6	66	P1	T+	1	-164.308	T-	1	164.3081
4	6	66	P1	T+	1	-236.827	T-	1	236.8267

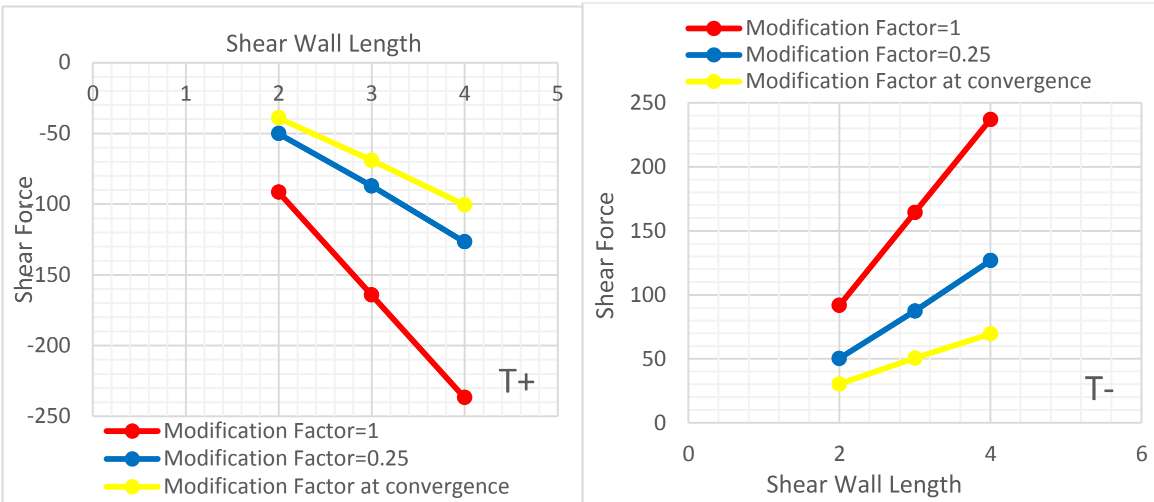
Table 9. Shows the internal forces of shear wall (P1) due to temperature change applied on flat slab without applying modification factor on axial stiffness of slab.

shear wall length	Span length	Building length along X-axis	wall	Load Case	M.F	V2	Load Case	M.F	V2
2	6	66	P1	T+	0.25	-50.2508	T-	0.25	50.2508
3	6	66	P1	T+	0.25	-87.3203	T-	0.25	87.3203
4	6	66	P1	T+	0.25	-126.764	T-	0.25	126.7641

Table 10. Shows the internal forces of shear wall (P1) due to temperature change applied on flat slab with applying modification factor on axial stiffness of slab = (0.25).

shear wall length	Span length	Building length along X-axis	wall	Load Case	M.F	V2	Load Case	M.F	V2
2	6	66	P1	T+	0.151	-39.1456	T-	0.0915	30.3562
3	6	66	P1	T+	0.1565	-69.2183	T-	0.0865	50.5713
4	6	66	P1	T+	0.16	-100.636	T-	0.0863	69.4476

Table 11. Shows the internal forces of shear wall (P1) due to temperature change applied on flat slab with applying modification factor on axial stiffness of slab corresponding to each case.



a. Temperature increase effect axial force in compression

b. Temperature decrease effect axial force in Tension

Figure 15. Effect of Shear Wall length on building response (Case [2]: 66 m long building)

As explained in the previous section, the existence of stiff shear walls at the building edges poses a critical case for consideration, as the presence of such stiff elements produces restraint of the slab, and thus the forces produced by expansion/contraction of the slab are quite high. This effect is further increased by the longer building floor dimension considered in this case [2], (66 m as compared to 42 m in case [1]).

The results obtained show that the applicable modification factors corresponding to this case have increased compared to the case where no shear walls were added. The range of increase is around 8% to 14% in case of compression (slab expansion) is still within the low range of modification factors. The tension case still shows very little change, and the modification factor range is still below the 10% limit.

Figure 15 shows the effect of variation in shear wall length on the thermal analysis results. While increasing the length of the shear wall increases the shear force and bending moment on the wall, this is due to the increased stiffness of the wall. The reduction noted in the lateral force by applying the axial stiffness modification factor, is around 42% of the corresponding values obtained when not applying the modification factor, for all 3 cases of different wall sections. As noted in the previous section, the results point to fact that changes in the wall length (and stiffness) does not affect the force reduction significantly. In fact, both values obtained for Case [1] (42 m length building with shear walls on the edges), and those obtained for Case [2] (66 m length building with shear walls on the edges) are very close to those obtained for the case of a 66 m building supported by ordinary columns at the edges.

These results point to the fact that the implementation of the axial stiffness reduction factors has a significant effect on the final analysis results, and resulting shear forces in the supporting elements. However, the lateral force reduction ratios are not affected much by the presence or absence of shear walls, especially in long building spans. This points to the possibility of specifying a fixed range of stiffness reduction as a recommendation in analysis and design work in general.

5.3 Effect of Steel Reinforcement Area

The effect of variation in steel reinforcement of the same flat slab thickness can be seen in table 12 & 13, and Fig.16. It can be noted that the reduction factor of the slab with 150% of A_s is higher than that in the slab with 100% of A_s. This can be directly credited to the increase in tension steel that significantly increases the cracked stiffness of the slab, thus producing higher reduction factors.

				As			1.5 As		
Story	Column	Load Case	Station	M.F	V2	M3	M.F	V2	M3
			m		ton	ton-m		ton	ton-m
Story1	C2	T+	3	1	-35.7122	35.2328	1	-35.7122	35.2328
Story1	C2	T+	3	0.25	-20.9652	14.853	0.25	-20.9652	14.853
Story1	C2	T+	3	0.133	-15.4142	7.6778	0.1887	-18.3433	11.3951

Table 12. Shows the internal forces of column (C2) due to temperature increase applied on flat slab with applying modification factor on axial stiffness of slab corresponding to each case.

				As			1.5 As		
Story	Column	Load Case	Station	M.F	V2	M3	M.F	V2	M3
			m		ton	ton-m		ton	ton-m
Story1	C2	T-	3	1	35.7122	-35.2328	1	35.7122	-35.2328
Story1	C2	T-	3	0.25	20.9652	-14.853	0.25	20.9652	-14.853
Story1	C2	T-	3	0.082	11.9744	-3.6505	0.1178	14.4857	-6.5458

Table 13. Shows the internal forces of column (C2) due to temperature decrease applied on flat slab with applying modification factor on axial stiffness of slab corresponding to each case.

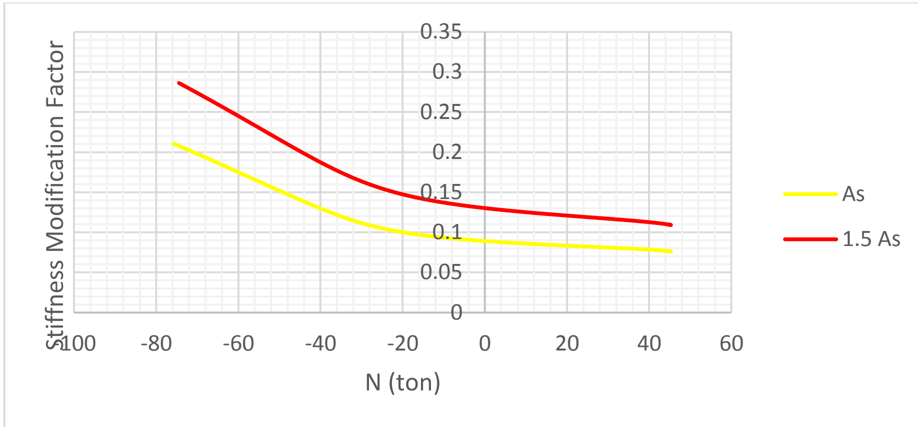


Figure 16. Effect of variation in steel reinforcement Area on axial stiffness reduction factors

The above results indicate that the low values of axial stiffness reduction factors observed in the previous sections would need modification in cases where the steel reinforcement area is higher than the actual design values. However, in general the modification factors are still within the 25% range proposed by the authors and tested all along the analysis runs.

5.4 Effect of Section Dimensions

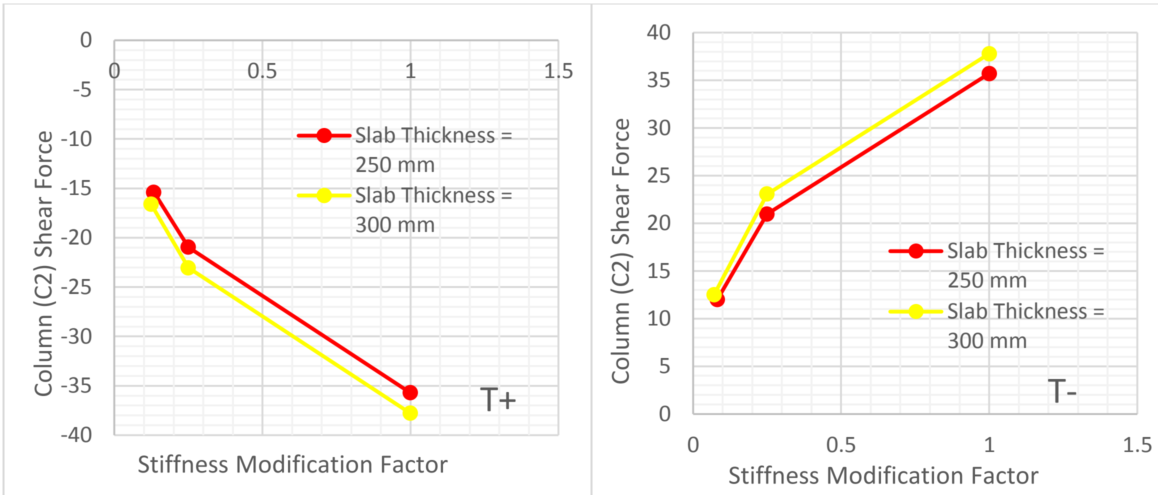
The effect of variation in section dimensions can be seen the results summarized below in table 14 & 15, and illustrated in Fig.17 & 18.

				t_s = 250 mm			t_s = 300 mm		
Story	Column	Load Case	Station	M.F	V2	M3	M.F	V2	M3
			m		ton	ton-m		ton	ton-m
Story1	C2	T+	3	1	-35.7122	35.2328	1	-37.7871	38.3259
Story1	C2	T+	3	0.25	-20.9652	14.853	0.25	-23.0565	17.8658
Story1	C2	T+	3	0.133	-15.4142	7.6778	0.124	-16.6025	9.4341

Table 14. Shows the internal forces of column (C2) due to temperature increase applied on flat slab with applying modification factor on axial stiffness of slab corresponding to each case.

				ts = 250 mm			ts = 300 mm		
Story	Column	Load Case	Station	M.F	V2	M3	M.F	V2	M3
			m		ton	ton-m		ton	ton-m
Story1	C2	T-	3	1	35.7122	-35.2328	1	37.7871	-38.3259
Story1	C2	T-	3	0.25	20.9652	-14.853	0.25	23.0565	-17.8658
Story1	C2	T-	3	0.082	11.9744	-3.6505	0.071	12.4905	-4.5903

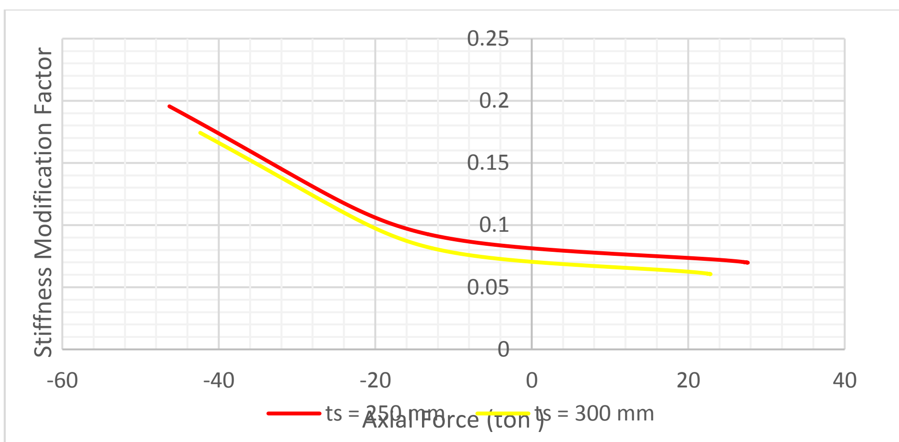
Table 15. Shows the internal forces of column (C2) due to temperature decrease applied on flat slab with applying modification factor on axial stiffness of slab corresponding to each case.



a. Temperature increase effect axial force in compression

b. Temperature decrease effect axial force in Tension

Figure 17. Effect of Slab Thickness on the internal forces of column (C2)



(M = 2 m.t for t_s = 250 mm, M = 2.2 m.t for t_s = 300 mm)

Figure 18. Effect of Slab Thickness variation (at the same point in slab) on axial stiffness reduction factors

The larger thickness of the slab produces values for the stiffness reduction factor, which are slightly smaller than the case of the smaller section. However, the difference is not significant, and this factor does not seem to affect the reduction factors considerably.

6- SUMMARY AND CONCLUSIONS

This paper investigated the flexural cracking effect on the actual axial stiffness of flat slab floors. An emphasis is placed on computation of the reduction factors to be applied to the axial stiffness of the flat slabs, in the finite element analysis under thermal loading.

A new analytical algorithm is developed, and a software package is prepared to apply this algorithm in the determination of the axial stiffness of the cracked slab sections, consequently the reduction factors. The new algorithm is used to chart the relationship of the "cracked stiffness" with the acting axial force and bending moments on the section. In combination with performing analysis of flat slab floors using ETABS software, applying the developed software package through several iterations leads to convergence, and is utilized to make a realistic assessment of the actual slab axial stiffness for a specific floor.

A parametric study performed included investigation of the effects of several parameters on the "cracked stiffness" values, and consequently the axial stiffness reduction factors to be applied in analysis. An increase in floor length was shown to increase the thermal expansion effect, and to produce an increase in the value of the reduction factors, and increases the lateral forces produced in the supporting columns, especially outer edge columns. Existence of high-stiffness elements near the building edges also produced a similar effect.

In general, the analysis results showed that the stiffness reduction factors increased with increase of the compressive axial forces, and decreased with the increase of tensile axial forces. However, the values of the "axial stiffness reduction factors" were found to be in a low range (less than 20% for in compression case, and less than 10% in tension case). A proposed reduction factor of 25% was applied to all analysis runs throughout the study, and was found to always produce conservative results (lateral forces higher than the actual).

The Egyptian code allows reduction of the axial stiffness of slabs and beams in case of thermal analysis by a factor of 45%, citing effect of creep. Based on the results obtained from this study, the authors recommend performing a more extensive wide-range study, encompassing varying cases of buildings, and parameters, in order to incorporate a value of 25%, citing the effect of flexural cracking. It is also recommended to extend the study to take into consideration the effect of creep, in order to modify this factor further.

REFERENCES

[1] SungjinBae, Alternative Design Approach for Thermal Effects, 22nd Conference on Structural Mechanics in Reactor Technology, 2013

[2] Pham Thai Hoana, Nguyen Minh Tuan, Effect of Uniform Temperature Load OnDesign of Long Reinforced Concrete Structures Without Expansion Joints, Journal of Science and Technology in Civil Engineering, NUCE 2021. 15 (3): 68–80

[3] Sang-Whan Han, Young-Mi Park, and Seong-HoonKee, Stiffness Reduction Factor for Flat Slab Structures underLateral Loads, Journal of Structural Engineering, 10.1061/(ASCE)ST.1943-541X.0000001, 2009

[4] Md. Safiuddin, A. B. M. AmrulKaish, Chin-OngWoon, and Sudharshan N. Raman, Early-Age Cracking in Concrete: Causes, Consequences, Remedial Measures, and Recommendations, 2018
[5] ECP 203 (2020), Design & Construction of concrete structures, pp. 6-22.
[6] Guruprasad Y.K., Ravi N. (2022) Evaluation of Failure Criteria in RC Structural Elements Due to Additional Internal Stresses Developed in Structural Elements Due to Temperature Exposure. In: Kolathayar S., Ghosh C., Adhikari B.R., Pal I., Mondal A. (eds) Resilient Infrastructure. Lecture Notes in Civil Engineering, vol 202. Springer, Singapore.
[7] ACI Committee 349.1R-4, Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Structures.
[8] IkhlassSydnaoui, Roslli Bin Noor Mohamed, Mariyana Aida BintiAb.Kadir, The Thermal Response of Concrete Frame Buildings in Arabic Area Considering Time-Dependent Properties of Concrete, International Journal of Recent Technology and Engineering (IJRTE), 2019
[9] Hisham A. El-Arabaty, Gamal H. Mahmoud, Nasr E. Nasr, Mohamed A. Abdul Rahim, Finite Element Modelling of Structures Subjected to Thermal Loading, IOSR Journal of Mechanical and Civil Engineering, 2018
[10] Pooja M and Dr. Karthiyaini S, Investigation of Flat Slab Structures with and Without Expansion Joints for Thermal Stresses. International Journal of Civil Engineering and Technology, 8(4), 2017, pp. 1287–1295.
[11] SabouniReem, and SydnaouiIkhlass, Thermal Loads Effect on Response of One- Story Reinforced Concrete Frame Buildings in UAE, ISCEE 2016
[12] Essam H. El-Tayeb, Salah E. El-Metwally, Hamed S. Askar, Ahmed M. Yousef, Thermal analysis of reinforced concrete beams and Frames, HBRC Journal, 2015
[13] Mustafa K. Badrah and Mansour N. Jadid., Investigation of Developed Thermal Forces in Long Concrete Frame Structures, The Open Civil Engineering Journal, 2013
[14] K. Ahmed, Temperature Effects in Multi-Story Buildings, Journal of Engineering Sciences, March 2011
[15] Salah E. El-Metwally, Mohamed E. El-Zoughiby, Reda M. Elgarayhi, shrinkage and thermal effects in R/C flat plate and raft foundation, Engineering Research Journal, 2019
[16] Athraa H. Gharbi, Akram S. Mahmoud, Punching Shear Behavior of Reinforced Concrete Slabs under Fire usingFinite Elements, Journal of Engineering, 2020
[17] Dr. AmitBijonDutta, Er. Tapas Sarkar, Study of Temperature Load on Structure's,Imperial Journal of Interdisciplinary Research, Vol-3, Issue-3, 2017