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EFFECT OF UNIFORM TEMPERATURE LOAD ON DESIGN OF LONG REINFORCED CONCRETE STRUCTURES WITHOUT EXPANSION JOINTS

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Abstract

This study presents an investigation on the design of long reinforced concrete (RC) structures subjected to uniform temperature load by considering three RC frame building models with different lengths of 45 m, 135 m, and 270 m using Etabs. The uniform temperature load is considered being the change from the annual average highest to lowest air temperature at the construction site in the case of unavailable temperature data of concrete. The analysis results indicate that the uniform temperature load mainly influences on the internal forces of RC members at storey 1 and slightly effects on the internal forces of RC members at storey 2. For short-length RC structures, the effect of temperature load can be ignored in the design of RC elements, whereas it must be taken into account in design of slab, beams and some column positions at storey 1 of medium-length and long RC structures without expansion joints. For the present RC frame building models, the required slab reinforcement in long direction increases about 33.4% for medium-length RC structures (135 m) and about 48.2% for long RC structures (270 m) without expansion joints. The required reinforcement for positive moment at mid-span increases from 33.7 to 39.4%, whereas the total required reinforcement for negative moment at the supports of beams increases from 19.4 to 34.9% in long direction of 270 m long RC structures without expansion joints due to uniform temperature load. Column design of long RC structures without expansion joints under uniform temperature load must be concerned, especially for columns in the corners.

Keywords: beam; column; expansion joints; Etabs; long RC structures; slab; temperature load.

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1. Introduction

Temperature change is considered as an important load that has significant influence on the design of long reinforced concrete (RC) structures besides other well-known loads such as dead, super dead, live, wind, and seismic loads. According to TCVN 9345:2012 [1], expansion joints must be provided at every 35 m length of RC structure that is directly affected by solar radiation and every 50 m length of RC structure that is shielded by solar radiation (such as floors, roofs, indoor wall, or basement wall, ...). In other words, RC structures with lengths larger than the aforementioned values must have expansion joints otherwise temperature load needs to be taken into account for the design work.

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The requirement for the expansion joint spacing from other standards or studies as reported by ACI 224.3R-95 [2] is shown in Table 1. It can be seen from the table that the expansion joints must be provided in approximately 30-60 m depending on the standards.

Table 1. Requirement for expansion joint spacing [2]

Author	Spacing
Billig (1960)	100 ft (30 m) maximum building length without joints.
Indian Standards Institution (1964)	45 m (≈ 148 ft) maximum building length between joints.
PCA (1982)	200 ft (60 m) maximum building length without joints
ACI 350R-83	120 ft (36 m) in sanitary structures partially filled with liquid (closer spacings required when no liquid present)

The presence of expansion joint may help RC structures to avoid the excessive internal force due to the thermal deformation, but it may also seriously affect the aesthetics as well as the function of the building. In addition, expansion joints would lead to a complicate construction process, in which the waterproofing and filler materials are required, especially for the structures with larger basements. The service life of the insert materials is also a major obstacle affecting the quality of the expansion joint. The problem is further complicated with high-rise RC buildings with large premises, where the expansion joints will separate the building into different blocks. In order for the blocks not to collide with each other when subjected to lateral loads such as wind and earthquakes, the expansion joint width needs to be very wide, leading to an impossible task for architectural solution.

Therefore, structural design for long reinforced concrete structures without expansion joints subjected to temperature load is essential. However, the current design standards of reinforced concrete structures TCVN 5574:2018 [3] and TCVN 9345:2012 [1] are silent in the instructions for calculating RC structures subjected to temperature load, leading to difficulties for engineers in practical design. The main problems are how the temperature load is determined and how the temperature load affects the design of reinforced concrete structures, especially for long RC structures. Concerning these issues, there have been number of studies showing how to determine the temperature load [4] as well as the influence of the temperature load on the RC slabs [5], beams [6], or RC frames and buildings [7–10]. For example, the studies of Shirke at el. [5, 6] considered the temperature load as the change of air temperature suggested by Martin and Acosta [4] and then investigated the effects of this load on the lateral deformation of long RC slab as well as on the beam internal force in long RC structures. Other studies [7–10] considered the same aforementioned temperature load and then investigated the effects of this load on the behavior of RC frames and buildings. These above studies have mentioned the influence of temperature load on RC structures, however the determined temperature load in these studies was being carried out in the Middle East countries, which is not suitable for the conditions of Vietnam. Moreover, the nature of the temperature load that should be taken into account in the concrete structures was not clarified. In addition, there is no specific guide on how to incorporate temperature loads into the design of long RC structures.

The aim of this paper is to broaden the understanding of the temperature load that need to be considered in the design of long RC structures and how to incorporate temperature loads into the practical design of long RC structures. According to EN 1991-1-5 [11], there are two types of temperature load including uniform temperature component and temperature difference component. The uniform temperature component is the temperature, constant over the cross section, which governs the expansion or contraction of an element or structure, whereas the temperature difference component is the part of a temperature profile in a structural element representing the temperature difference between the outer face of the element and any in-depth point. Both temperature components should be considered in RC structural design. In this study, effect of uniform temperature is investigated since the expansion joints are more related to this component. The effect of the temperature difference component on the structural design shall be considered in a further work.

2. Temperature load and its effect on RC structures

Temperature load is the effect of temperature change on structures. The variation of ambient temperature acting on uncovered structures (roof floor, open floor...) causes the difference of temperature along the slab thickness. This effect is repetitive and the difference of temperature along the RC slab thickness depends on exposure level to the environment and the thickness of RC slab. Free objects tend to expand when the temperature increases and shrink when the temperature decreases. The elongation caused by temperature variation can be expressed as:

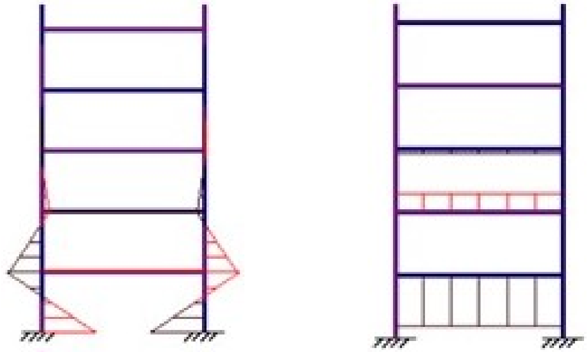
$$\Delta L = \alpha \times L \times \Delta T$$

where ΔL is the elongation due to temperature variation; α is thermal coefficient of materials; L is the length of the object; ΔT is the temperature change.

According to TCVN 5574:2018 [3], the thermal coefficient of heavy concrete is $\alpha_{bt} = 1.0 \times 10^{-5}{}^{\circ}\mathrm{C}^{-1}$ and can be considered the coefficient for normal reinforced concrete structures. As an assemblage of individual members, RC structure is always restrained from free expanding or shrinking when subjected to temperature change, resulting in additional deformation, stresses and internal forces. These deformation and internal forces due to uniform temperature change must be added to the action of other loads such as static load, live load, pre-stressed. When the temperature increases during the day time, the internal compressive force in the structure is generated due to the restraint to the expansion trend. Conversely, when the temperature drops at night, internal tensile force occurs. For reinforced concrete structures, the reduced temperature variation is the more disadvantageous case due to the poor tensile strength of the concrete. It is necessary to ensure that the structure can withstand the internal tensile forces arising from this change in temperature, for example by arranging reinforcement or increasing the size of concrete.

Fig. 1 presents an illustration of arising moment and axial forces in the members of a multi-storey frame when temperature changes, where the bases are blocked by the foundation. These internal forces decrease very quickly when going upstairs and may reach almost zero at 1-2 right upper floors. For long RC structures, the incurring internal forces due to temperature changes are significant and must be included in the design when the expansion joints are not provided.

The effect of temperature change on RC structures is obvious as aforementioned, however, what value of uniform temperature load that are used in design needs to be clarified. A concrete structure has generated heat from the hydration process during the curing of the concrete from the time it is poured, so there is an initial temperature in concrete. Then it should be aware of that ΔT is not the change of the air temperature, but the variation of temperature during the loading process compared to the initial temperature at the time when the structure begins to bear the loads. To determine the temperature at the time when the reinforced concrete structure begins to bear the load, it is necessary to understand the principle of temperature variation in concrete during the curing process. When cement is mixed with water, heat is generated from the exothermic chemical reaction between water



(a) Moments (b) Axial forces

Figure 1. Internal forces in a multi-storey frame due to temperature changes [12]

and cement and is called the heat of hydration. The temperature development and the heat distribution in concrete depend on the concrete mix, the shape and size of the pouring mass, the type of formwork, and the environmental conditions. An example of the temperature variation in concrete is illustrated in Fig. 2, which is referred from the literature [12].

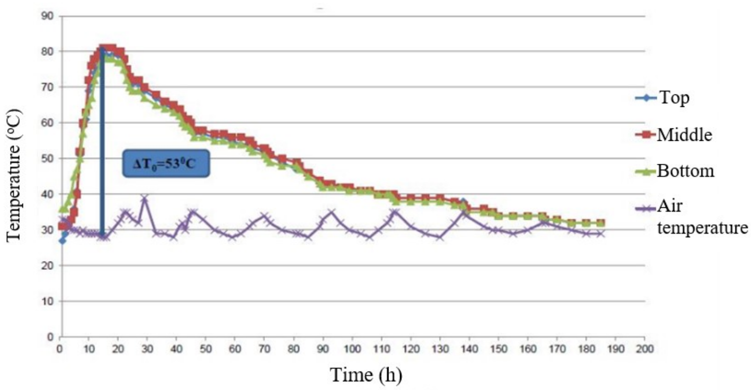
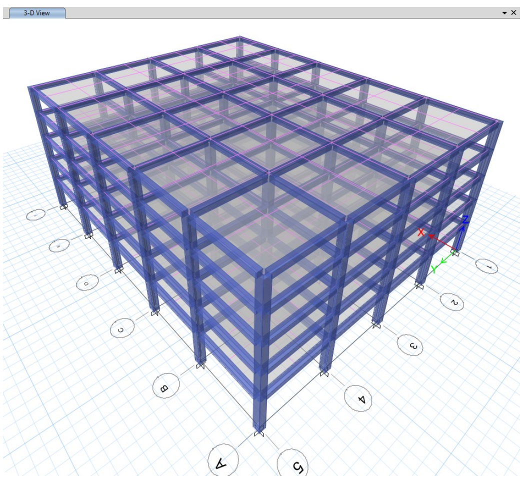


Figure 2. Illustration of temperature variation process in concrete [12]

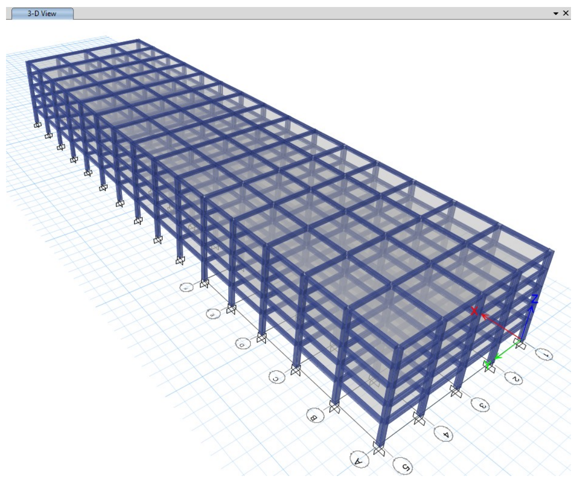
The temperature variation process in concrete can be expressed as follows: immediately after pouring, the concrete temperature is Tp, which is the temperature of the concrete mixture. The temperature in concrete increases and reaches to the maximum temperature of $T_m = T_p + T_r$, where T_r is the increment of temperature due to hydration of the cement, and then gradually decreases to a stable temperature value T_f. After the concrete has completely cooled to ambient temperature, the thermal stress mainly depends on the change in ambient temperature. From Fig. 2, it can be seen that the temperature in concrete usually reaches the ambient temperature value before the time when the structure starts to bear the loads, usually 14-21 days after pouring, i.e. the time of removing the floor formwork. Therefore, in the practical design when the temperature data of concrete is often unavailable, it is possible to consider the most critical case with the temperature variation being the difference between the annual average highest and lowest air temperature at the construction site. The annual average highest and lowest air temperature in Vietnam can be referred to QCVN 02: 2009 - Natural Physical and Climatic Data for Construction [13].

3. Design of RC structures with temperature load

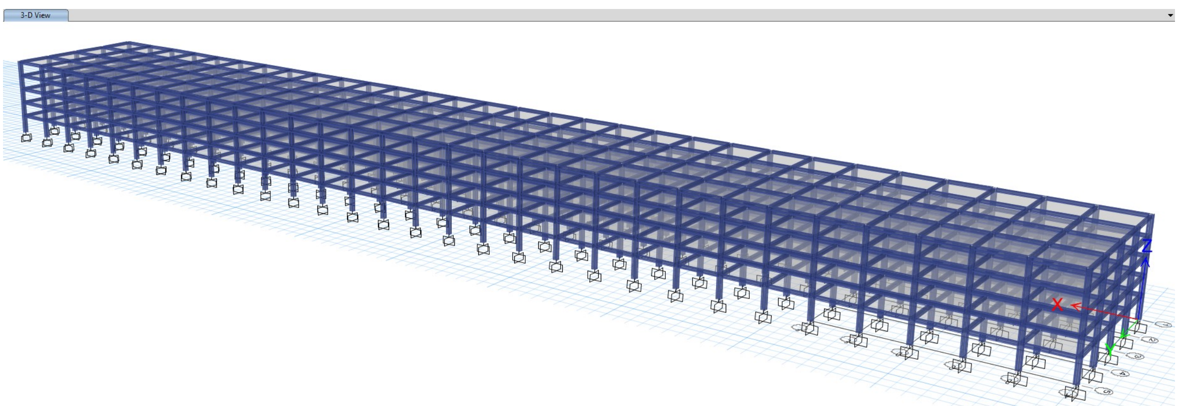
With the aid of computers and current structural analysis software, considering temperature load on design of reinforced concrete structures becomes a possible task. Common structural analysis software widely used by engineers, such as SAP and Etabs [14], allow declaring temperature load easily. After the temperature load is determined as described above, it is considered in the structural design as a type of long-term live load as indicated in TCVN 2737:1995 [15]. In order to clarify the influence of temperature load on structural design of RC structures, especially for structures with large plan, 3 RC frame building models namely S1, S2, and S3 with the same structure but different lengths are analyzed and evaluated using Etabs software. Note that Etabs software is used for building structural analysis in many studies [16, 17]. Five-storey RC frame buildings with 9 m regular grid of columns in both directions X and Y on rectangular plan are used. Three models S1, S2, and S3 have the same width of 36 m (4 spans of 9 m in Y direction), while the length is chosen to be of 45 m for S1 (5 spans of 9 m in X direction), 135 m for S2 (15 spans of 9 m in X direction), and 270 m for S3 (30 spans of 9 m in X direction). It is noted that the length of three models are chosen to be representative



(a) S1



(b) S2



(c) S3

Figure 3. Models of three RC frame from ETABS

for buildings with short-, medium-, and long- lengths. The materials used for the RC buildings are B30 for concrete and CB400-V for reinforcement [3]. The sizes of RC structural elements of three models were designed according to TCVN 2737:1995 [15] and TCVN 5574:2018 [3] to ensure the load carrying capacity with unfactored super dead load (DL) of 1.7 kN/m^2, partition load (PL) of 4 kN/m^2, and live load (LL) of 5 kN/m^2, leading to columns cross section of 600x600 mm, beams cross section of 600×600 mm, and slab thickness of 220 mm. Fig. 3 shows the models of three RC frame buildings from Etabs, in which the temperature load is taken into account.

The temperature load is defined in three models as the variation of air temperature from the annual average highest to the lowest air temperature at the construction site, where is assumed to be Hanoi, Vietnam. The annual average highest to the lowest air temperature at the construction site are used for the uniform temperature component as recommended in EN 1991-1-5 [11]. According to QCVN 02:2009 [13], the annual average highest and the lowest air temperature in Hanoi is 27.2°C and 21.2°C, respectively, leading to $\Delta T = \pm 6$°C. As noted, the reduced temperature variation is the more disadvantageous case for reinforced concrete structures due to the poor tensile strength of the concrete. Moreover, a trial analysis for S3 model is conducted showing that the decrease in temperature increases the internal force of RC members much more as the temperature increases. Thus, the temperature variation value of $\Delta T = -6$°C is defined in ETABS as the temperature load (Thermal) for all elements, including joints, columns, beams, and slabs, as illustrated in Fig. 4. Note that the thermal coefficient of materials is taken as $\alpha_{bt} = 1.0 \times 10^{-5}$°$C^{-1}$. To consider the effects of temperature load on the structural design, two different load combinations are defined according to TCVN 2737:1995 [15], as follows:

Comb 1 = 1.1DL + 1.15PL+ 1.2LL

Comb 1-T = 1.1DL + 1.15PL+ 1.2LL+1.2Thermal

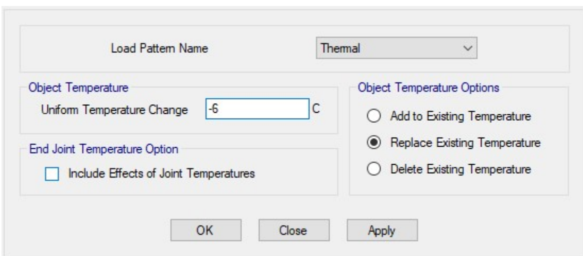


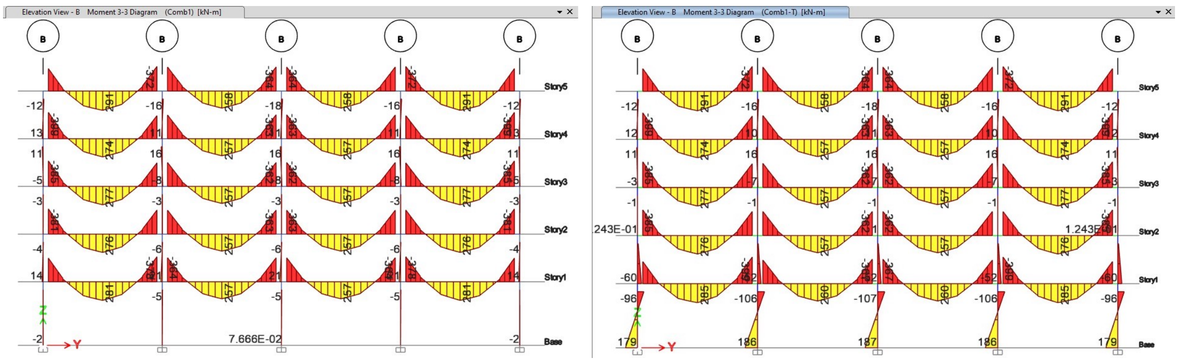
Figure 4. Definition of temperature load in Etabs

4. Results and discussion

4.1. Effect of temperature load on internal forces of RC members

Three models of RC frame buildings are analysed and the major internal forces of each element type including slab, beam, and column are observed. Based on the importance of internal force components in the design of RC elements, the bending moment of slabs and beams as well as the bending moment and axial force of columns are chosen to be evaluated, where the bending moment of slabs is considered through the strip moment. In this study, the main strips are defined as column strip and middle strip with the same width of 4.5 m in both direction X and Y. After a quick review for all models, it is recognized that the internal forces of structural elements are mainly increased from model without temperature (WoT) to corresponding model with temperature (WT) at storey 1, slightly increased at storey 2, and almost unchanged at upper stories. Thus, it can be concluded that the temperature load mainly influences on the internal forces of RC members at storey 1, of which the axial force of columns is trivially effected, whereas the axial force of beams are not important components in design. Therefore, only bending moment of slab, beams, and columns at storey 1 are considered for evaluation.

For model S1, which is representative for short-length building, the effect of temperature load on the bending moment of 1st RC slab and beams is insignificant, about less than 5%. The increment of less than 5% bending moment may not influence on the design solution of slab and beams. The bending moments of columns in both X and Y direction at storey 1 are much changed due to the temperature load as can be seen in Fig. 5, however, the design result of columns depends on both axial force and bending moment. So does the temperature load influence on the column design? That will be discussed in the next parts.

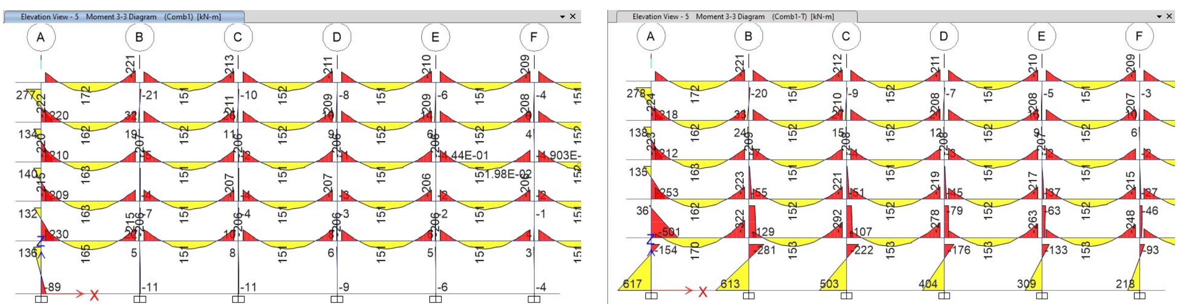


(a) WoT – B axis

(b) WT – B axis

Figure 5. Major bending moment of frame in Y direction of model S1

The bending moments of beams in Y direction and the positive bending moments of beams in X direction at storey 1 are kept almost unchanged, while a part of negative moment portion at the left support is shifted to the right support at each span in X direction due to temperature load (Fig. 6). Thus, the beam design in X direction (i.e. the long direction of building), especially for negative bending moment at the supports, should consider the effect of temperature load. The bending moments of columns in both X and Y direction at storey 1 are significantly increased due to the temperature load, as can be seen in Fig. 6.



(a) WoT – 5 axis

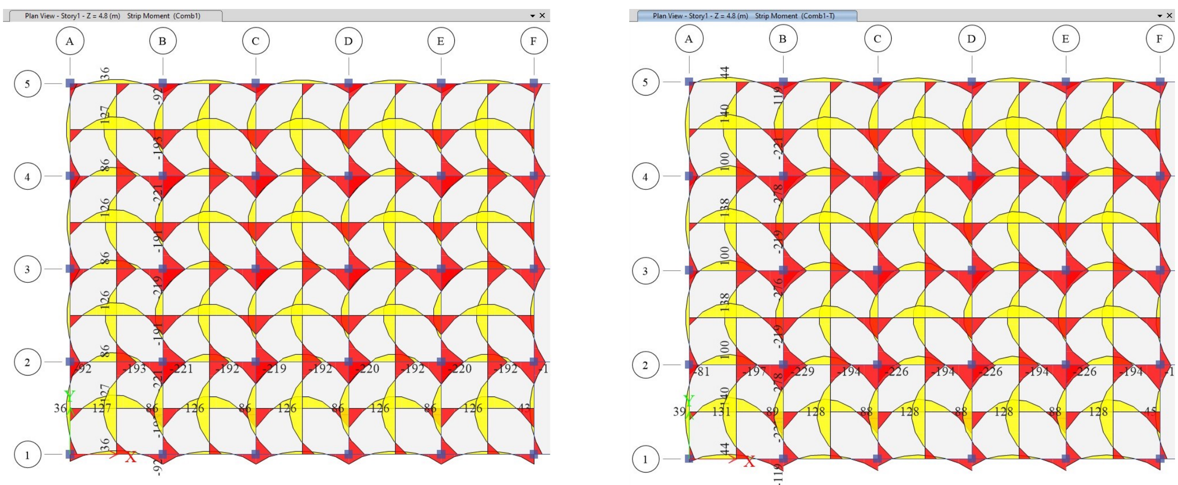
(b) WT – 5 axis

Figure 6. Bending moment of the frame in X direction of model S2

Table 2. The increment of 1st slab moment due temperature load in model S2

Direction	Strip	Position	M (kN.m)			
			WoT	WT	Increment* (%)	Average increment (%)
X	Column strip	1st span	86	94	9.3	8.0
		2nd support	221	251	13.6	
		Internal spans	74	79	6.8	
		Internal supports	215	239	11.2	
	Middle strip	1st span	127	135	6.3	
		2nd support	193	208	7.8	
		Internal spans	111	115	3.6	
		Internal supports	189	200	5.8	
Y	Column strip	1st span	86	89	3.5	2.5
		2nd support	221	228	3.2	
		Internal spans	74	75	1.4	
		Internal supports	219	228	4.1	
	Middle strip	1st span	127	131	3.1	
		2nd support	193	197	2.1	
		Internal spans	111	113	1.8	
		Internal supports	189	190	0.5	

*Increment = (WT-WoT)/WoT



(a) WoT (b) WT

Figure 7. Strip moment of 1st RC slab of model S3

Fig. 7 shows the strip moments of 1st RC slab in both direction X and Y of model S3, which is representative for long building. The same changing trend with model S2 is observed in this model.

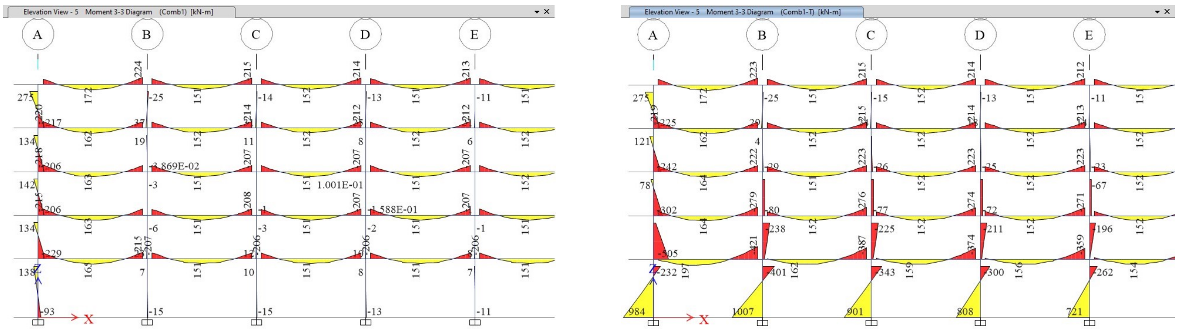
Table 3. The increment of 1st slab moment due temperature load in model S3

Direction	Strip	Position	M (kN.m)			
			WoT	WT	Increment* (%)	Average increment (%)
X	Column strip	1st span	86	100	16.3	15.4
		2nd support	221	278	25.8	
		Internal spans	74	84	13.5	
		Internal supports	215	263	22.3	
	Middle strip	1st span	127	140	10.2	
		2nd support	193	221	14.5	
		Internal spans	111	120	8.1	
		Internal supports	189	212	12.2	
Y	Column strip	1st span	86	89	3.5	2.4
		2nd support	221	229	3.6	
		Internal spans	74	76	2.7	
		Internal supports	215	218	1.4	
	Middle strip	1st span	127	131	3.1	
		2nd support	193	197	2.1	
		Internal spans	111	113	1.8	
		Internal supports	189	191	1.1	

*Increment = (WT-WoT)/WoT

The bending moments of representative column and middle strips in X and Y direction of 1st slab obtained from model S3 in the cases of without and with temperature load are presented in Table 3. Similar average increment of bending moment in Y direction (i.e. in the short direction) with model S2 of 2.4% is obtained. For X direction, the slab moments of middle strips due to the temperature load increase from 8.1 to 10.2% at the mid-spans and from 12.2 to 14.5% at the supports. The greater increments of slab moments are observed for column strips of from 13.5 to 16.3% at the mid-spans and from 22.3 to 25.8% at the supports. An average increment of slab moment in X direction of 15.4% due to the temperature load must be absolutely taken into account in slab design.

The bending moments of beams in Y direction at storey 1 are kept almost unchanged, while the bending moments of beams in X direction at storey 1 are changed due to the temperature load (Fig. 8). In this direction, the increment of positive moments of 19.4% at first mid-span, 7.2% at second mid-span, and less than 3.3% for the other mid-spans are observed, while the most of negative moment portion at the left support is shifted to the right support at each span in X direction (Fig. 8(b)). Thus, the beam design in X direction (i.e. the long direction of building) should consider the effect of temperature load. The bending moments of columns in both X and Y direction at storey 1 are significantly increased due to the temperature load, as can be seen in Figs. 8(a) and 8(b).



(a) WoT – 5 axis

(b) WT – 5 axis

Figure 8. Bending moment of the frame in X and Y direction of model S3

4.2. *Effect of temperature load on design of long RC members*

In order to evaluate the effect of temperature load on the design of long RC structures, structural elements of medium-length and long building models showing the increasing major internal forces due to temperature load are selected to design. It is worthy to note that the presented reinforcement design is intended to emphasize how uniform temperature load affect RC structural design rather than being an actual design result. In addition, it is also to make notes for designers about the positions that need to pay attention in the design process.

Table 4. Design reinforcement in X direction for 1st RC slab of model S2

Direction	Strip	Position	Reinforcement area (cm^2)			
			WoT	WT	Increment* (%)	Average increment (%)
X	Column strip	1st span	12.8	18.8	46.9	33.4
		2nd support	28.8	36.6	27.1	
		Internal spans	12.8	18.8	46.9	
		Internal supports	27.9	36.4	30.5	
	Middle strip	1st span	17.7	22.1	24.9	
		2nd support	24.9	28.9	16.1	
		Internal spans	17.7	22.1	24.9	
		Internal supports	24.3	36.4	49.8	

*Increment = (WT-WoT)/WoT

For slab design, the 1st floor slabs of model S2 and S3 are selected and automatically designed according to TCVN 5574:2012 [18] by using Etabs [14]. It is noted that TCVN 5574:2012 is chosen since it is available in the used Etabs software version. Table 4 lists the design reinforcement in

X direction for 1st floor slab of model S2 in cases of without and with temperature load, together with the increment of reinforcement due to the introduction of temperature load. It is seen from this table that the reinforcement for slab strips design due to the temperature load increases from 16.1 to 49.8% depending on locations, leading to an average increment of slab reinforcement in X direction of 33.4%. Some positions at column strips need special attention during design, where the increments of reinforcement are significant.

Table 5 presents the design reinforcement in X direction for 1st floor slab of model S3 in cases of without and with temperature load, together with the increment of reinforcement due to the introduction of temperature load. It is seen from this table that the reinforcement for slab strips design due to the temperature load increases from 29.7 to 68.4%, depending on locations, leading to an average increment of slab reinforcement in X direction of 48.2%. Some positions at column strips need special attention during design, where the increments of reinforcement are significant. The design slab reinforcement results in X direction of building models S2 and S3 indicates that temperature load strongly effects on the design of slab of long RC structures without expansion joints.

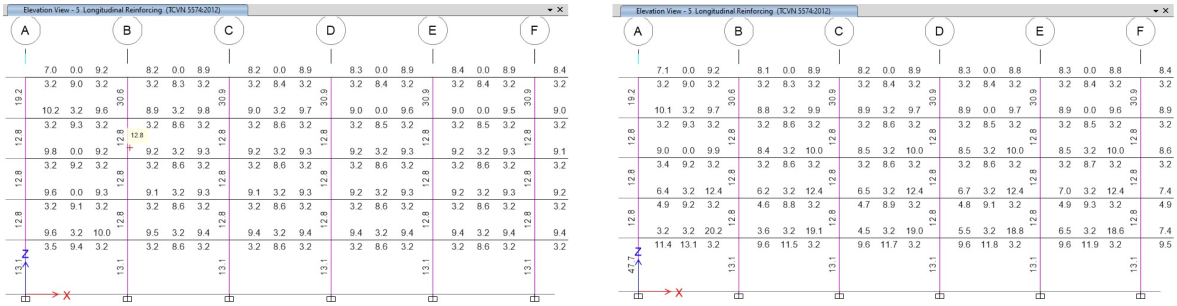
Table 5. Design reinforcement in X direction for 1st RC slab of model S3

Direction	Strip	Position	Reinforcement area (cm^2)			
			WoT	WT	Increment* (%)	Average increment (%)
X	Column strip	1st span	11.7	19.7	68.4	48.2
		2nd support	28.5	40.0	40.4	
		Internal spans	11.7	19.7	68.4	
		Internal supports	27.6	39.5	43.1	
	Middle strip	1st span	16.8	24.6	46.4	
		2nd support	24.6	31.9	29.7	
		Internal spans	16.8	24.6	46.4	
		Internal supports	24.0	34.2	42.5	

*Increment = (WT-WoT)/WoT

The beams and columns design is automatically carried out according to TCVN 5574:2012 [18] by using Etabs [14]. It is noted that only model S3 is selected to be designed owing to the larger number of beams and columns in each model as well as the dependence of the column design result on both bending moments and axial force. Therefore, the beam and column design in this study only aims to show that temperature load must be taken into account in design of beams and columns of long RC structures, as well as to point out particular beam and column positions that should be noticed during design. For that purpose, an example of design beam reinforcement in a part of 5-axis is presented in Fig. 9.

As is seen from Fig. 9, most of beams in X direction at storey 1 need more reinforcement when temperature load is introduced. For instances, the required reinforcement for positive moment at mid-span of beams increases from 33.7 to 39.4%, whereas the required reinforcement for negative moment at the right support of beams increases of about twice due to temperature load. However, the required reinforcement for negative moment at the left support of beams decreases, leading to an increment of



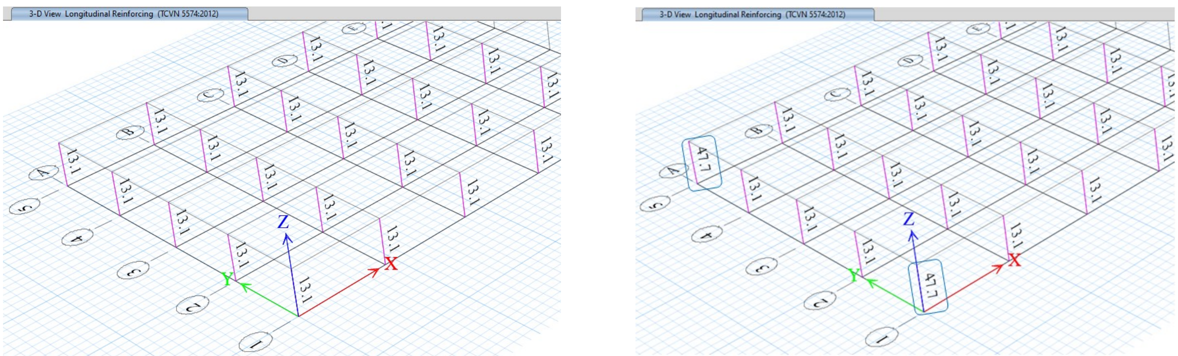
(a) WoT – 5 axis

(b) WT – 5 axis

Figure 9. Design reinforcement (cm^2) for beams and columns of model S3

about 19.4 to 34.9% for total required reinforcement for negative moment at the supports of beams in X direction due to temperature load. This design result indicates that temperature load strongly effects on the design of beams in long direction of long RC structures without expansion joints.

As aforementioned, the column design result depends on both bending moments and axial force, as well as the close relationship between these internal forces and the column cross section, the comparison of design result in this case may be meaningless. However, it should be noted that the columns at storey 1 exhibits much greater bending moment in both directions X and Y due to temperature load. In the case of model S3, this increment of bending moments only effects on the design result of columns at the corners, while the other columns are not affected, as shown in Fig. 10. The reason may be owing to the quite big cross-section size of the columns in this study. Though, column design of long RC structures without expansion joints under temperature load must be concerned, especially for columns in the corners.



(a) WoT

(b) WT

Figure 10. Design reinforcement (cm^2) for columns showing the critical column positions in model S3

5. Conclusions

In this study, the design of long RC structures subjected to temperature load is investigated by considering three RC frame building models with different lengths of 45 m, 135 m, and 270 m. The following conclusions can be withdrawn:

- It is possible to consider uniform temperature load being the difference between the annual average highest and lowest air temperature at the construction site in the case of unavailable temperature data of concrete.

- The temperature load mainly influences on the internal forces of RC members at storey 1 and slightly effects on the internal forces of RC members at storey 2. For short-length RC structures, the effect of temperature load can be ignored in the design of RC elements, whereas it must be taken into account in design of slab, beams and some column positions at storey 1 of medium-length and long RC structures without expansion joints.

- For the presented design example, the required slab reinforcement due to uniform temperature load in long direction increases about 33.4% for medium-length RC structures (135 m) and about 48.2% for long RC structures (270 m) without expansion joints.

- For the presented design example, the required reinforcement due to uniform temperature load for positive moment at mid-span increases from 33.7 to 39.4%, whereas the total required reinforcement for negative moment at the supports of beams increases from 19.4 to 34.9% in long direction of 270 m long RC structures without expansion joints. Column design of long RC structures without expansion joints under uniform temperature load must be concerned, especially for columns in the corners.

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