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NON-LINEAR ANALYSIS OF CONCRETE STRUCTURES SUBJECTED TO TEMPERATURE LOADS

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ملخص البحث

الهدف الأساسي من هذا البحث هو استخدام التحليل اللاخطي بطريقة العناصر المحددة لدراسة سلوك المنشآت الخرسانية المعرضة لأحمال الحرارة. لإدراك هذا الهدف، تم عمل نموذج حسابي ثلاثي الأبعاد بطريقة العناصر المحددة لكمرة خرسانية مسلحة وتم إضافة التفاصيل الخاصة بالحديد الطولي وحديد الكانات. النموذج يأخذ في الاعتبار تشرخ الخرسانة في حالة اجهادات الشد أو وصولها للحد الأقصى في حالة اجهادات الضغط. في البداية تم عمل نموذج يحاكي أبعاد وتفاصيل أحد التجارب المعملية السابقة لكمرة محملة بحمل رأسي إستاتيكي، وتم عمل تطابق للنتائج للتأكد من صلاحية هذا النموذج الحسابي. بعد التأكد من صلاحية هذا النموذج تم استخدامه في دراسة تأثير أحمال الحرارة على سلوك الكمرة. تم تحليل الكمرة بتعريضها لأحمال رأسية متزايدة وأحمال حرارية مختلفة تتراوح من +55° حتى -55°. لكل درجة حرارة تم دراسة حمل الكسر، الإجهادات، الانفعالات، الإزاحة الرأسية. كما تم حساب القوة الأفقية المتولدة من الحرارة في كل حالة. النتائج أوضحت أهمية أخذ السلوك اللاخطي في الاعتبار عند تحليل المنشآت الخرسانية المعرضة لأحمال الحرارة.

ABSTRACT

The main objective of this research is to use nonlinear finite element analysis to study the behavior of concrete structures subjected to temperature loads. To realize this goal, a three-dimensional numerical finite element model was built to represent a reinforced concrete beam. Details of longitudinal and transverse reinforcement was included in the model. The model considers cracking of concrete in tension and ultimate capacity in compression. In the beginning, a model was constructed using the dimensions and details of a previous laboratory experiment consisting of a beam subjected to monotonic vertical load to verify the validity of the model. After confirming the validity of the model, it was used to study the effect of temperature loads on the behavior of the beam. The beam was analyzed by subjecting it to an increasing vertical load coexistent with various temperature loads ranging from +55 ° to -55 °. For each temperature, the ultimate vertical load, stresses, strains and vertical displacement were studied. The horizontal force generated by temperature was calculated in each case. The results showed the importance of taking nonlinear behavior into consideration when analyzing concrete structures exposed to temperature loads.

INTRODUCTION

The change in temperature causes considerable strains that in turn can cause large stresses in restrained structures. The strain and the corresponding stress due to temperature load can be easily calculated in linear problems. However, in reinforced concrete structures where cracking is dependent on the stress level and considerably affects the stiffness, the calculation of the stresses arising from temperature loads is not straightforward. Vecchio[1] published a study of reinforced concrete plane frames subjected to thermal and mechanical loads. The study proposed an analytical method to incorporate the effect of cracking and reinforcement in the linear finite element analysis by proposing an effective stiffness that can be adjusted in an iterative process to emulate the non-linear behavior of the structure. The results obtained were compared to preliminary tests and were considered acceptable. Other theoretical models for evaluating thermal stresses in reinforced concrete structures were developed by Priestley[2], Thurston el. al.[3] and Pajuhesh[4]. Vecchio and Sato[5] experimentally investigated three large-scale reinforced concrete portal frame models subjected to combinations of thermal and mechanical loads. This research showed that thermal loads imposed on a reinforced concrete structure can induce significant levels of deformation, stressing, and cracking. Other experimental research conducted on the effect of thermal loads on concrete structures were conducted by Aboumoussa and Iskander[6], and Ndon and Bergeson[7]. Despite the considerable research done in this area, there is still no standard way of evaluating the effect of temperature stresses that takes into effect the non-linear behavior of concrete structures. As a step in attaining this goal, 3D non-linear finite element model of concrete was used to analyze the effect of temperature loads on concrete structures. This approach allowed the effect of the detailed reinforcement as well as the cracking and non-linear behavior of the concrete material to be taken into consideration.

THE FINITE ELEMENT MODEL

A 3D finite element model for a simple beam was constructed using ANSYS[8] finite element package. The concrete dimensions and details of the steel reinforcement are shown in **Fig. 1**. The beam was loaded by two vertical loads near mid span up to failure.

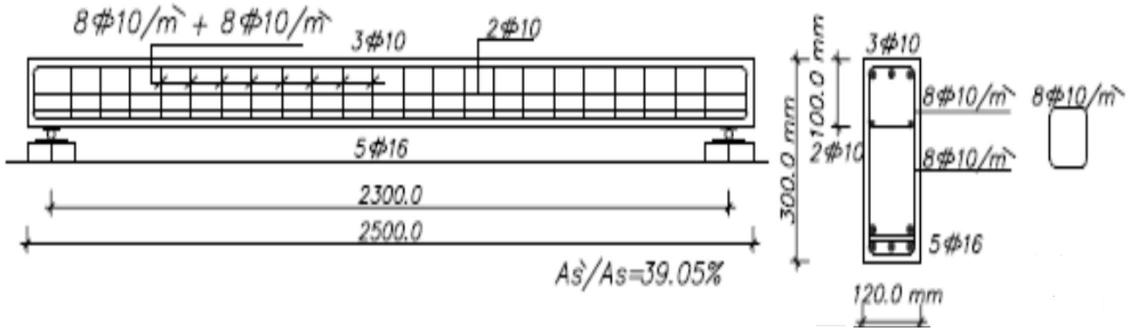

Fig. 1–Details of the experimental model by Abd-Alkhalik[8]

The finite element model was constructed using 3D solid elements to represent concrete and line truss elements to represent reinforcement as shown in Fig. 2. Only one quarter of the beam was modelled in Ansys by taking into consideration the symmetry conditions. This is done by applying special boundary conditions at the symmetry interface. By using symmetry, the model is considerably reduced leading to a large decrease in computational needs.

In order to eliminate numerical problems due to stress concentration near the supports and concentrated loads, strong elements were introduced at these locations to help in distributing the concentrated loads on a larger area as shown in Fig.2.

The concrete and steel stress-strain curves were modelled using non-linear curves as shown in Fig. 3. Cracking of concrete was also considered in the model by using the

Solid65 3D solid element. In this element cracking is handled using the smeared crack approach. When the stress at an integration point in the element reaches the concrete cracking stress, a plane of weakness is introduced in the direction normal to the crack face at that integration point.

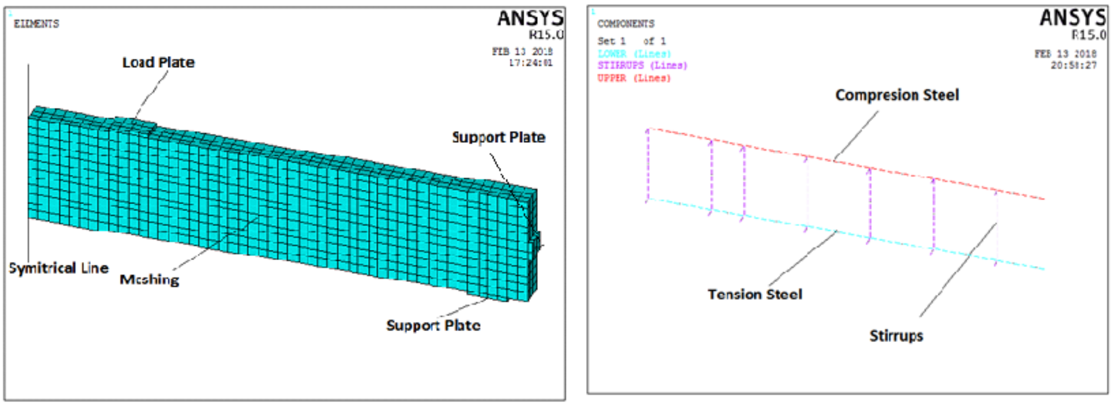

Fig. 2– 3D Finite Element Model

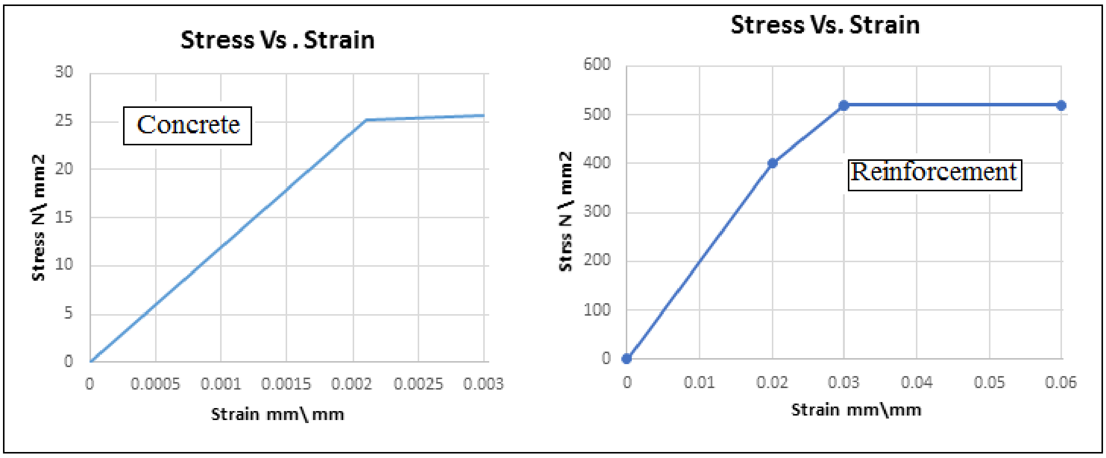

Fig.3 – Concrete and Reinforcement Stress-Strain Curves

EXPERIMENTAL VERIFICATION

In order to verify the finite element model, the results of the finite element model were compared to that of previous experimental work performed by Abd-Alkhalik[9]. The dimensions and reinforcement of the model were adjusted to match that in the experimental model. The loading in the finite element was also similar to the experimental setting shown in Fig.4. The material properties were modeled in the same manner described earlier, with the ultimate strength matching the experimental program. The failure load of the experimental specimen was reported to be 155 KN compared to 167 KN obtained by the ANSYS model, about 7.7% increase. Fig. 5 shows a comparison of the load-deflection curve between the experimental and finite element model. The curves for both models were very near, except that the experimental model experienced a higher final deflection. The difference in the deflection however was in the post failure phase and therefore is considered insignificant. Both curves were nearly horizontal at failure indicating the yielding of the steel reinforcement, confirming that both models experienced the same mode of ductile failure. This result is also confirmed by comparison of the stress-strain curve of the tension reinforcement near the middle of the beam shown in Fig. 6. Both models showed similar behavior. The strain was nearly identical up to a load of 60 KN nearly 40% of the failure load then the strain in the experimental specimen started to be considerably large. This may be attributed to the slippage that could have occurred in the experimental model. Slippage was not considered in the finite element model.

Fig. 4- Experimental Setting for Specimen Testing by Abd-Alkhalik[9]

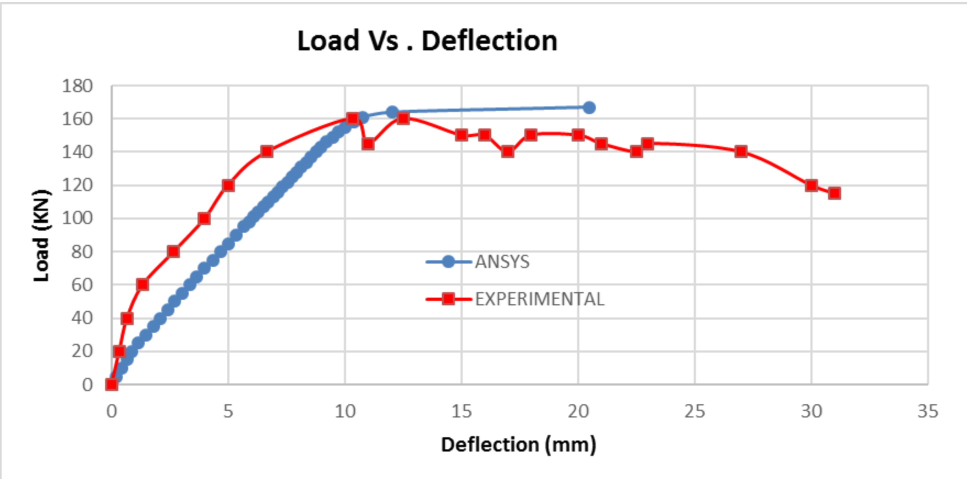

Fig. 5- Comparison between Experimental and Finite Element Load-Deflection

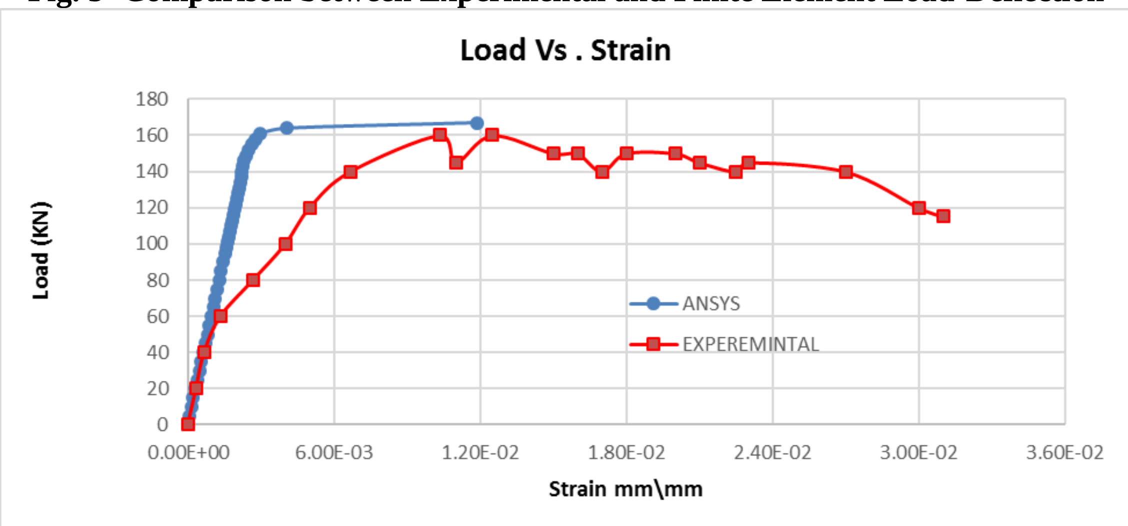

Fig. 6- Experimental vs. Finite Element Reinforcement Strain

Fig.7 shows a comparison of the cracking in both the finite element and the experimental model. As shown in the figure, cracking was similar for both models. Overall, the comparison between the finite element results and the experimental results showed that the results were very near giving confidence in the reliability of the finite element results.

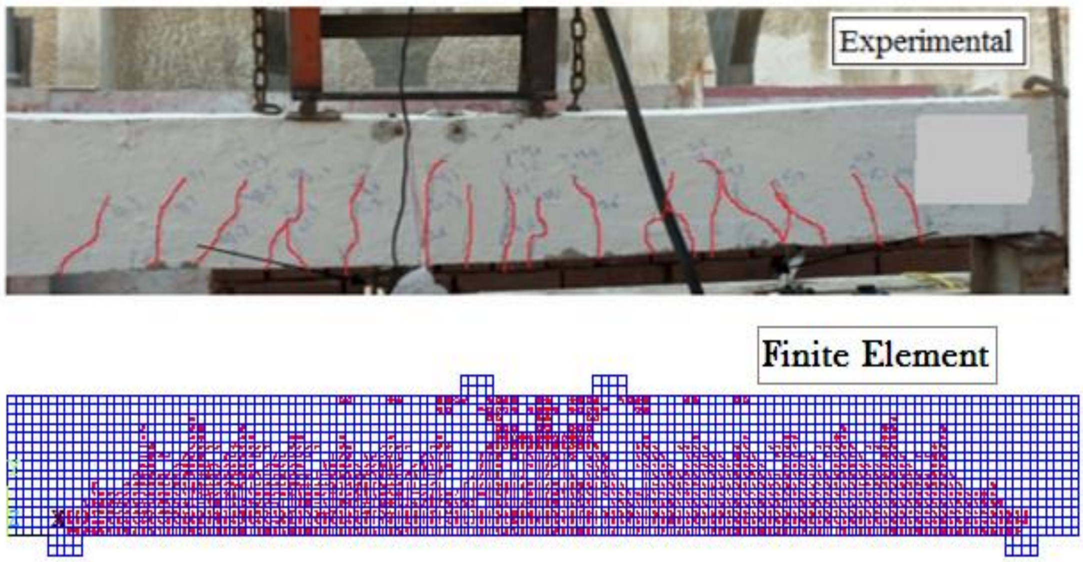

Fig. 7- Comparison between Experimental and Finite Element Cracking

EFFECT OF TEMPERATURE

In order to investigate the effect of temperature change on concrete structures, the finite element model of the beam was subjected to a temperature change in addition to the vertical load. The temperature load used the same ramped function as the vertical load, i.e. it started at zero and increased linearly as the vertical load increased. Since the failure always occurred before the maximum load imposed on the beam has been reached, the same was true for the temperature change. For example, when a temperature change of +55°C was imposed on the beam, this value was never reached because failure occurred before reaching the maximum value. Only a fraction of this value was reached in the analysis. To avoid confusion, two temperature values will be referred to, the maximum nominal temperature, T_N, which is the maximum temperature change imposed in the analysis, and the maximum actual temperature, T_a, which is the maximum temperature change attained.

To study the effect of temperature change on a range of values the maximum nominal temperature imposed on the beam model was varied form -55°C to +55°C. The non-linear behavior of the beam was studied under this variation of temperatures to evaluate the effect of the temperature change on the reinforced concrete beam. The effect on maximum capacity, deflection, axial force and reinforcement strain was studied.

Ultimate Capacity

As shown in Fig. 8, the failure load increased with an increase in the temperature probably due to compression strains. A decrease in temperature, however, produced tension strains and led to a decrease in the ultimate load. It was also noted that the ultimate load varied linearly with the change in the temperature. The maximum change in the value of the failure load, however, was not very big. It ranged from 14 t for the lowest temperature to about 15 t for the highest temperature, a change value of about 7%.

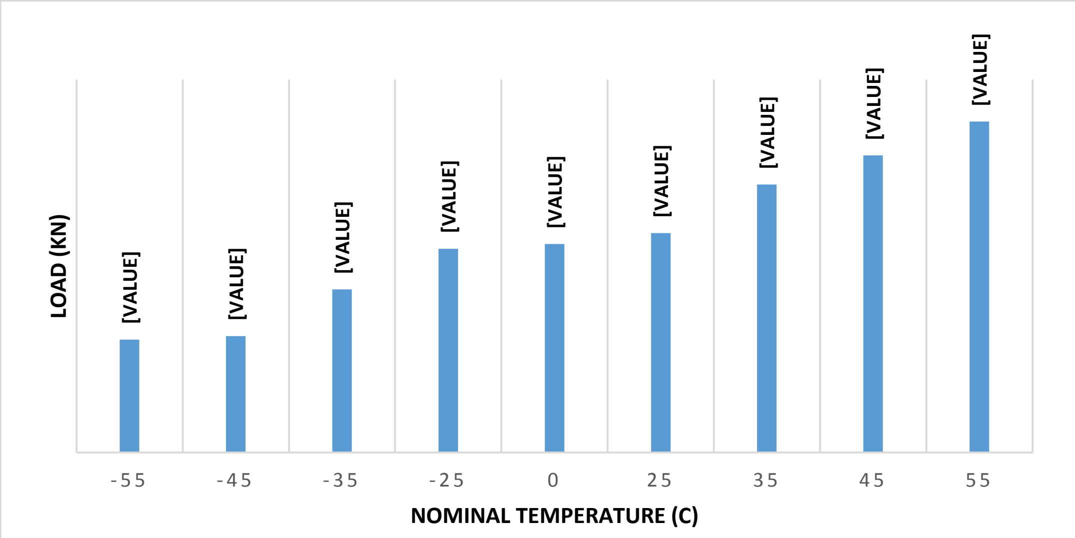

Fig. 8 – Failure Load Vs Temperature Change

Mid Span Deflection

A comparison of the mid-span deflection for three beams subjected to different temperature loads is shown in Fig. 9. The three compared beams were: 1- a beam with vertical load only, 2- a beam with vertical load subjected to nominal temperature +55°C, and 3- a beam with vertical load subjected to nominal temperature -55°C. It can be shown from the figure that the deflection for three cases showed similar behavior with a linear straight curve at the beginning changing to non-linear behavior at a certain load followed by a nearly horizontal relation indicating failure. The linear portion was largest in the case of +55°C (increase in temperature causing compression strains), while it was smallest in the case of -55°C (decrease in temperature causing tension strains). Case 1 of the vertical load was intermediate between the other two cases. It is evident from the figure that a decrease in temperature caused the non-linear behavior to start earlier and the vertical stiffness in general to decrease.

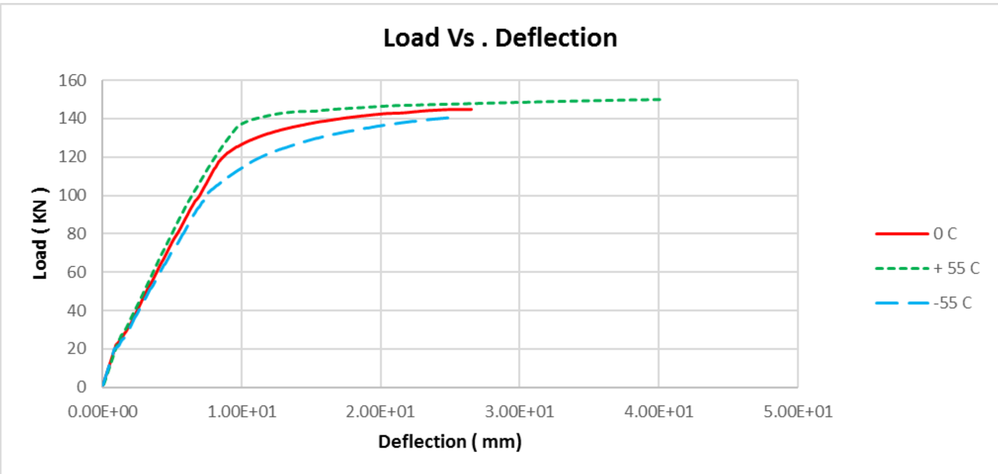

Fig. 9 – Mid Span Deflection

Bottom Reinforcement Strain

Fig. 10 shows the strain in the bottom reinforcement vs load for the three beams explored at the previous section, at nominal temperature +55°C, 0 and -55°C. All beams experienced the same behavior with a starting linear branch followed by a flat near horizontal branch. As noticed earlier, the load at which the relation turned to the flat branch was smaller as the temperature decreased.

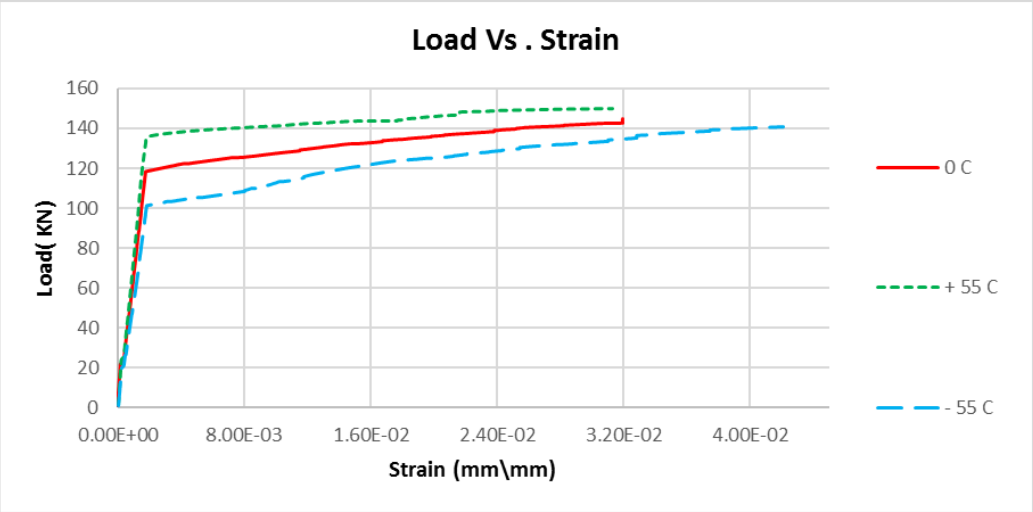

Fig. 10 – Strain in Bottom Reinforcement

Axial Force

Fig. 11 shows how the axial force in the beams changed as the vertical load increased. The three cases of nominal temperatures 0, -55 and +55°C were compared. As stated earlier, the nominal temperature is the temperature limit that was input to the program. The temperature was increased gradually from zero to that nominal temperature as the vertical load was increased to reach the maximum load. Because failure occurred before reaching the maximum load, the nominal temperature load was not reached. An actual value around 60% of the nominal temperature load was reached.

The figure illustrates how the rate of change of normal force is affected by the temperature change especially when comparing positive vs. negative temperature changes. Comparing this figure with the load strain curves in Fig. 10 shows that the non-linear behavior in both figures starts nearly at the same vertical load values. This also illustrates how the normal force increased exponentially as the tension steel started to yield.

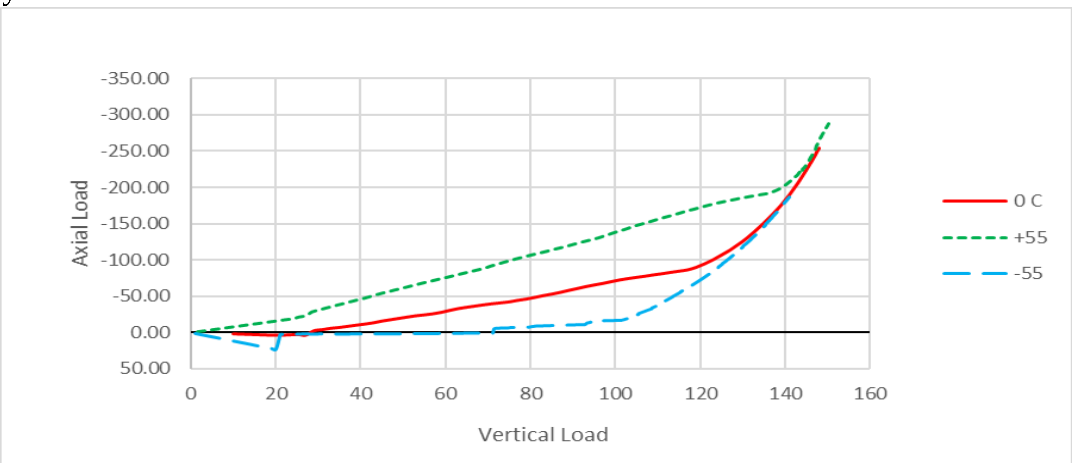

Fig. 11 – Axial Force Generated for Different Temperatures

In order to isolate the axial load generated in the beam due to temperature effect, the absolute difference between the axial load obtained in the case subjected to the combined effect of vertical load and temperature load and that load generated in the case of zero temperature load was evaluated. The result of this operation is shown in Fig. 12 for the case of nominal temperature changes of +55°C and -55°C. The figure shows that the axial load generated due to positive temperature change (causing compression) was higher than that generated due to negative temperature change (causing tension) probably due to the increased cracking in the second case. Fig. 12 also contains the expected axial force that should have been generated due to temperature based on two different assumptions. The first assumption using the linear modulus of elasticity of concrete based on code equations. The second assumptions using the modulus of elasticity used in the analytical model which is the secant modulus of elasticity obtained from the theoretical stress-strain curve of concrete. In both cases, it is clear that in the non-linear behavior of the concrete beam, the axial force generated was considerably smaller than the expected theoretical value. It is also noticed that the generated force is considerably decreased approaching zero as the beam reinforcement is yielding.

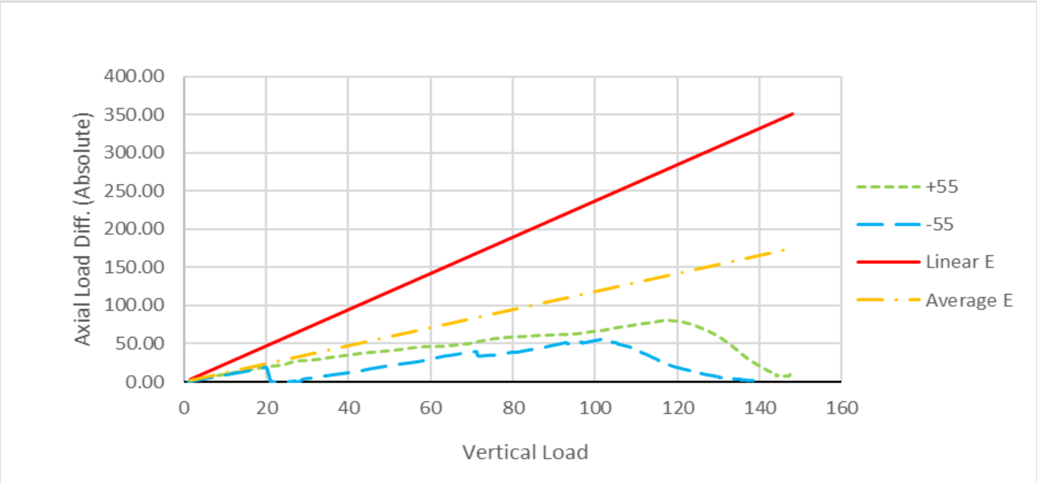

Fig. 12 – Axial Load Difference due to Temperature

SUMMARY AND CONCLUSIONS

In this research, a 3D finite element model was constructed for a simple hinged-hinged beam subjected to combined effect of vertical load and temperature. The model considered the cracking and non-linear behavior that can occur in reinforced concrete structures. The details of reinforcement were included in the model, as well as, non-linear material behavior of the reinforcing steel. The finite element model was analyzed using ANSYS[8] finite element program. The model was validated using previous experimental work performed by Abd-Alkhalik[9]. The model was used to explore the effect of temperature loads on the behavior of the reinforced concrete beam. Ultimate capacity, mid-span deflection, reinforcement strain and axial force generated due to temperature were explored.

The analysis showed that the ultimate capacity was slightly affected by the temperature load. The capacity slightly increased as the temperature increased. The difference between the maximum and minimum ultimate capacities was about 7%.

The mid-span deflection curves showed that the beams subjected to lower temperature loads where generally less stiff in the vertical direction and yielding of the bottom reinforcement started at a lower load as the temperature load was decreased.
The magnitude of the axial force generated due to temperature was generally lower for the case of negative temperature changes generating tension, than that of the positive temperature changes generating compression. It was also noted that the magnitude of the axial force obtained in the non-linear analysis is considerably lower than that expected using theoretical linear models indicating the importance of considering the effect of non-linearity when studying the effect of temperature changes on reinforced concrete structures.

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