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THERMAL EFFECT ON THE DESIGN LOADS OF MULTI-STOREY RC BUILDINGS ON SLOPED TERRAIN IN SAUDI ARABIA

M. Y. Laissy [a,] *, A. E. Alluqmani [b]

[a*] Department of Civil Engineering, College of Engineering, University of Prince Mugrin, Madinah, Saudi Arabia,
E-mail: m.laissy@upm.edu.sa / laissy99@gmail.com
[b] Department of Civil Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia,
E-mail: dr.ayed@iu.edu.sa / eng.ayed@gmail.com

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ABSTRACT:

This research investigates the impact of thermal loads on reinforced concrete (RC) buildings in Saudi Arabia and how they behave on sloped terrain. The study analyzed the effects of different types of support systems (hinged and fixed supports) and strengthening systems (with and without bracings) using the software ETABS-V20. Ground + 9 typical floors frame RC models on sloped terrain subjected to seismic loads were used for the investigation. The dynamic analysis of the ETABS models was performed to evaluate the lateral displacement, storey drift, column shear forces, and base shear forces of the buildings. The study found that using a bracing system and fixed supports under seismic loads increases the model's displacement and storey drift compared to models with hinged supports and no bracing system. The maximum shear forces values were also higher for models with bracing systems and fixed supports, while the minimum values were for models without bracing systems and with hinged supports.

1. INTRODUCTION

Understanding the behaviour of reinforced concrete during the early construction stages and throughout its lifespan is crucial in the design process, as the properties of concrete change over time due to the hydration process. This includes the modulus of elasticity, strength, creep, and shrinkage, which are not constant (Delsaute, Torrenti et al. 2017). In addition to live and dead loads, reinforced concrete structures are subjected to temperature changes and resulting thermal loads, which can lead to thermal stresses that exceed stresses from other loads if not properly considered in the design. This is particularly important in cases where there is insufficient thermal insulation (Delsaute, Torrenti et al. 2017).

Concrete structural elements can experience volume changes depending on the concrete environment, configuration, and materials, with unconfined elements experiencing uniform volume change without cracking. The contraction or expansion of concrete is the sum of its volume changes, with the main concern for reinforced concrete members being the volume change resulting from thermal and moisture changes (Cope, Cannon et al. 2002), (Abeka, Agyeman et al. 2017).

The properties of concrete change with time and affect the structural behavior of concrete structures during their lifespan. The CEP FIP,1999 code (CEB 1991) provides a time-dependent process for the concrete properties, including the effect of creep and coefficients with varying strength values. Researchers have conducted studies on the effectiveness of expansion joints and concluded that increasing their numbers and decreasing their spacing improves their effectiveness (Sydnaoui, Mohamed et al.), (Sydnaoui, Mohamed et al. 2019).The changing climate in Saudi Arabia poses a serious threat to human well-being by affecting various aspects of the environment, including weather conditions. Over the last decade, the country has experienced extreme climate changes that have had a negative impact on thermal loads (Almazroui 2020).

Thermal loads affecting concrete structures are due to seasonal climate changes as well as shrinkage and equivalent thermal effects(Sydnaoui, Mohamed et al.), (Badrah and Jadid 2013). There are code requirements for expansion joint spacing in modern or unique buildings, with Dubai municipalities allowing up to 60 m spacing while other standards like ACI 350R have reduced it to a maximum of 36 m. Finite element modeling (FEM) is a recommended methodology for analyzing and drawing conclusions about unique modern buildings, and it has shown that expansion joint spacing can be increased based on these models (Riding, Poole et al. 2006).

The Climate Change Knowledge Portal (CCKP) states that Saudi Arabia has a desert climate with a semi-arid climate in the southwestern part of the country. The summer season in the central region is very dry and hot, While coastal locations has temperatures between 27°C and 38°C, inland areas has temperatures between 27°C and 43°C. Inland regions have wintertime temperatures between 8°C and 20°C, whereas

* Corresponding author: M. Y. Laissy, Department of Civil Engineering, College of Engineering, University of Prince Mugrin, Madinah, KSA, E-mail: m.laissy@upm.edu.sa or laissy99@gmail.com.

coastal areas experience temperatures between 19°C and 29°C. were recorded in the Red Sea coastal areas (Riding, Poole et al. 2006).

The volume of concrete structural elements can change due to various factors such as configuration, makeup, and environment, which can lead to cracks if the elements are not free to change uniformly. Moisture and thermal changes are the main factors for changes in RC elements. The elements can be volume-restrained by different parts or supporting elements, which can lead to compressive, flexural, or tensile stresses in the structure. However, the concrete can withstand compressive stresses, and the main concern is with tensile stresses that can cause cracks. These stresses can result from internal or external restraints, which exist in all concrete structural elements according to the BS Code. The high temperature does not necessarily promote cracks, but rather the lack of freedom of contraction due to restraints can lead to cracks (Riding, Poole et al. 2006).

Another study investigated how steel and reinforced concrete buildings react to heat loading. The findings indicated that the reinforced concrete buildings remained intact and did not fail, while the steel building failed and collapsed within an hour of exposure to fire (Kültür, Al-Masri et al. 2022).

Only a few research studies have focused on investigating the behavior of reinforced concrete flat plates when exposed to compartment fires. These studies involved exposing flat slab models to fire at various locations and revealed that the flexural capacity of the flat plates decreases with increased duration of fire exposure, which in turn affects the shear demand on columns (Abouleiwun, Elbakry et al. 2022). Another study explored the long reinforced concrete structures design subjected to uniform temperature loads based on annual temperature changes at construction sites. It concluded that medium to large span RC structures require increased reinforcement of slabs, beams, and certain columns compared to structural elements with expansion joints. Additionally, the study found that thermal loads can be disregarded for short length RC structures but should be considered for medium and long length RC structures without expansion joints (Hoan and Tuan 2021).

Based on the literature review, there has been limited research conducted to study the impact of thermal loads on reinforced concrete buildings resulting from temperature changes, as most studies have focused on fire thermal loads. Therefore, this study ~~the~~ objective ~~of~~ is to analyze and evaluate the impact of thermal loads on reinforced concrete buildings constructed on sloped terrain by comparing the response of buildings in terms of displacement, drift, deformations, and base shear due to thermal loads.

2. OBJECTIVE

The study aims to examine how thermal loads affect a building's structure on sloped terrain when subjected to seismic loads. The focus is on analyzing and presenting the impact of thermal loads, with an emphasis on displacement, drift, deformations, and base shear.

3. THERMAL BEHAVIOUR ON RC BUILDINGS

For the structural elements of a reinforced concrete (RC) building, a change in temperature will result in the addition of thermal strain. The calculation of strain values is based on the following equation:

$$\varepsilon T = \alpha . \Delta T . L \quad (1)$$

Where: α = thermal expansion coefficient for concrete,
ΔT = temperature change,
L = structural element length.

These thermal strains are due to the thermal stresses induced in the structural elements due to its restraint conditions calculated from the following equation:

$$\sigma T = \alpha . \Delta T . L . E \quad (2)$$

where: σ = The normal stress of concrete,
ΔT = The change in temperature,
L = The length of structural element,
E = The modulus of elasticity of concrete.

The temperature change impact on RC structures is evident; however, there is a need for clarification on the value used for a load of uniform temperature during the design process. The RC concrete structural elements generate heat during the hydration process at the curing stage, which begins from the day of pouring the concrete. This initial temperature in the structural elements must be taken into account. Furthermore, the temperature change (ΔT) value is determined by the variation of the concrete temperature during the loading process relative to the temperature when the structural elements begin their loading and not the change in air temperature surrounding the concrete. Understanding the temperature variation principle for R.C. structural elements during the curing process is crucial in determining the temperature value when the structure commences its loading process. The addition of water to the concrete mixture generates heat through the chemical reaction between water and cement, known as the hydration process.

The exothermic process of hydration between water and cement generates heat during the curing process (Tan, Yu et al. 2021). As the concrete temperature increases due to hydration, cooling occurs, causing a change in the concrete volume and leading to cracking in restrained structural members, similar to drying shrinkage cracking (Gomes, Carvalho et al. 2020). Figure (1) illustrates the heat evolution of cement paste, which shows a rapid heat evolution during the wet phase, followed by a dormant phase with minimal heat generation. The heat evolution rate then increases to a peak due to the hydration process of tricalcium aluminate (C3A) and tricalcium silicate (C3S), after which it gradually declines.

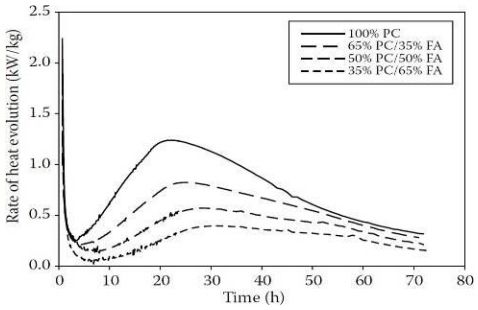


Figure 1. Heat Evolution Typical Plot for Cement Paste

The temperature generated and its spread in concrete is influenced by various factors, including the material's thermal conductivity, concrete composition, formwork materials, and the temperature of the surroundings compared to the concrete temperature during placement. Figure (2) provides an illustration of these factors (Seo, Bae et al. 2020).

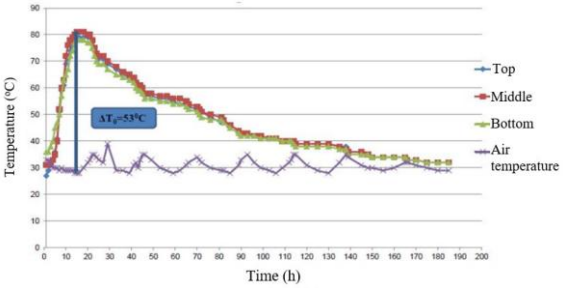


Figure 2. Concrete Process of Temperature Variation

4. ANALYSIS METHOD

The analysis involves modelling a building with nine floors on sloped terrain using ETABS 20 to examine the impact of thermal loads. The frame material for the model is concrete, with a Poisson's ratio of 0.2, modulus of elasticity of 30 KN/mm2 and steel yield stress of 420 MPa. The foundation supporting system for all the models is either hinged or fixed supports and the structural elements are unrestrained.

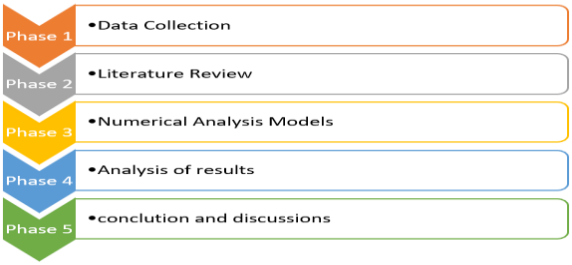


Figure 3. Research Methodology Flowchart

According to the several performed tests on unrestrained concrete components with various cement types, aggregate sizes, and reinforcing compositions, the annual coefficient value for thermal expansion is approximately 1.852, and the average value is 9.5×10^{-6} (Havel, Archilla et al. 2015). The temperature fluctuation between winter and summer used in the study is greater than the variation calculated from daily changes, with a temperature of -17 (C°) for drying shrinkage considered in the design. Figures (4) and (5) show that the temperature used for design from daily variation is -14 (C°) (Sydnaoui, Mohamed et al.). The thermal loads used in the study are ±200C for reinforced concrete elements and ±300C for steel bracing members according to the design codes (Sydnaoui, Mohamed et al.).

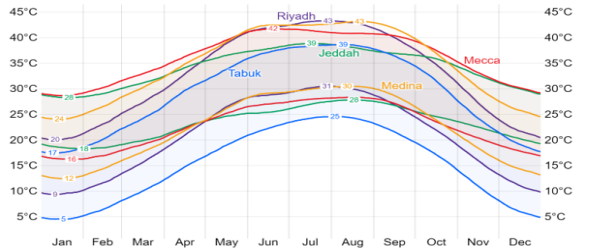


Figure 4. Average reported fluctuations in temperature in 2021 (A.D.I.A.)

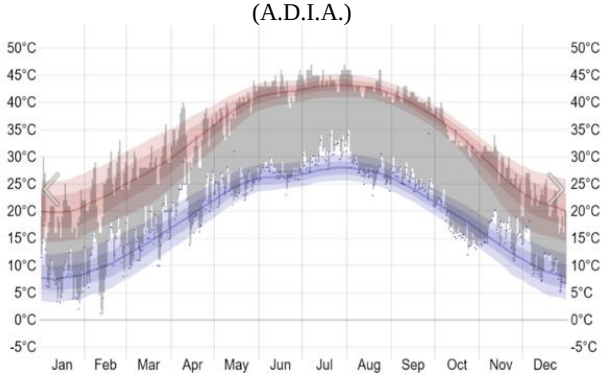


Figure 5. Medina reported fluctuations in temprature in 2021 (A.D.I.A.)

5. STUDIED AREA DATA

Saudi Arabia is the largest country on the Arabian Peninsula and is surrounded by water bodies such as the Red Sea to the west, the Arabian Gulf to the east, and the Arabian Sea to the south. The country has a hot and dry climate, with an average annual rainfall of approximately 93mm. Temperature in the north area of the country ranges from 8.57°C to 28.32°C while in the south area, it ranges from 26.68°C to 33.97°C. Mountains in the southwest of the country, with elevations of approximately 1500m above sea level, play a significant role in controlling the local climate. (Sources: (Almazroui, Nazrul Islam et al. 2012), (Almazroui 2019), Figure 6 (Pandey 2021).

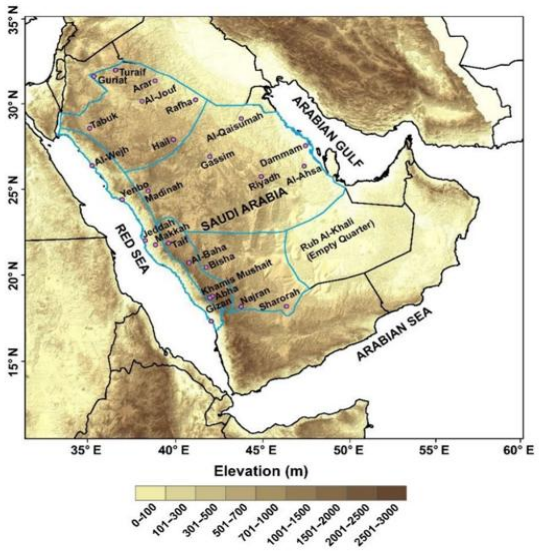


Figure 6. Toppography in Saudi Arabia

6. 3D MODELLING

6.1 Geometry

The 3D-modeling of the building as shown in Figure 7, is a residential building consisting of a ground floor and 9 typical floors with each floor having a height of 3.0m. The building has a symmetrical plan layout with 5 bays in Y direction and 4 bays in X direction, with bay widths of 4m and 5m respectively. To prevent any irregular torsion effects, the building has been designed symmetrically in both directions. The structural elements of the building, including columns, beams, and bracing, have been modeled using ETABS software. The columns have dimensions of 60cm x 60cm, the beam dimensions are 45cm x 60cm, and 20cm x 20cm L-section angles are used for the bracing. The response spectrum analysis method has been used to comply with the Medina zone Saudi building code, considering soil type B.

6.2 Model Properties

The study involved modelling multi-story reinforced concrete buildings with space frames on sloped terrain. Two types of support, fixed and hinged, were used for the models with the same material and geometrical properties. Seismic analysis was performed for the buildings under thermal loads using space frames and bracing. ETABS 20 was used to carry out response spectrum analysis for seismic loading, and various parameters such as displacement and story shear were analyzed.

6.3 Model Specifications

The plan layout of the modelled structures is illustrated in Figure 7, and the specifications of the models are listed in Table 1.

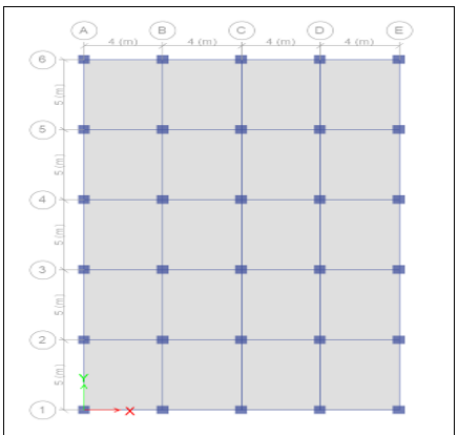


Figure 7. Typical plan layout

Model Parameter	Value
X direction Bayes number	4
Y direction Bayes number	5
Height of story	3
Type of Slab	Flat Slab
Thickness of Slab	200 mm
Importance factor of the building	1
Concrete Grade	M 30

Table 1. Models' Specifications

To investigate the effect of temperature on multi-storey RC buildings, the displacements and reactions were analyzed using ETABS software. As a result, three-dimensional models of multi-storey RC buildings were created.

The use of computers and structural analysis programs has made it easier to consider temperature loads in the design of reinforced concrete structures. Engineers often use popular analysis software, such as ETABS and SAP2000 (Pandey 2021), (Computer and Structures 2004), which enable the incorporation of temperature loads into models.

In order to demonstrate the impact of temperature loads on the design of RC structural elements, particularly in the case of multi-storey buildings, a series of ground + 9 typical floor frame models were analyzed using ETABS software. ETABS software has been widely used in previous studies for structural analysis (Hoan and Tuan 2021), (Khanh, Linh et al. 2019). Specifically, the models used for this analysis were ground + 9 typical floor frames with a grid of columns measuring 4 meters in the X direction and 5 meters in the Y direction, situated on sloped terrain and with and without bracing systems.

Four load combinations were created to consider the effects of temperature change and shrinkage during structural design. The load combinations were based on ULT=0.8(1.4DL + 1.6LL+ 1.4T) and not less than ULT=1.4(DL + T), and the specific value for temperature change can be selected based on the Code used or the calculated value for the area. Two different high-rise reinforced concrete 3D models were used for this study, one without a bracing system and one with a bracing system, and both were located on sloped terrains. Figures 8 and 9 depict these models, respectively. The ETABS software was employed for this study, which is a commonly used software in structural analysis research (Hoan and Tuan 2021), (Khanh, Linh et al. 2019).

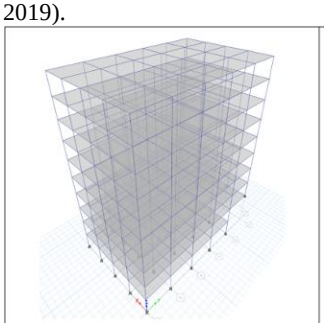


Figure 8. Sloped terrain 3D model without bracing system

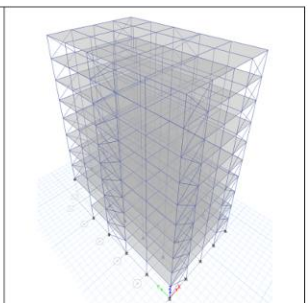


Figure 9. Sloped terrain 3D model with bracing system

6.4 Model Displacement for the Models on Sloped Terrain with and without Bracing System

The joint displacements of models on sloped terrain with and without bracing systems are shown in Figures 10 to 13. These figures depict displacements for models with hinged and fixed supports, as well as models without thermal loads (Figures 10 and 11) and models with thermal loads (Figures 12 and 13).

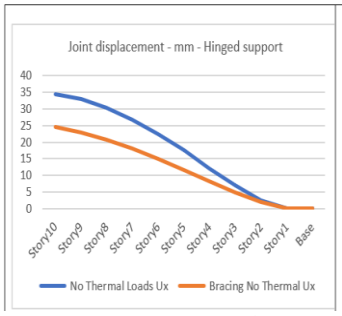


Figure 10. Joint displacement for models with hinged support on sloped terrain with and without bracing system and without thermal loads

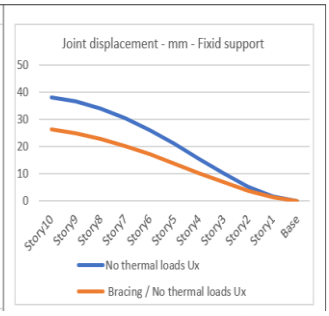


Figure 11. Joint displacement for models with fixed support on sloped terrain with and without bracing system and without thermal loads

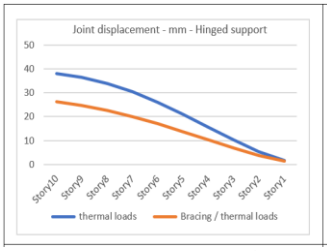


Figure 12. Joint displacement for models with hinged support on sloped terrain with and without bracing system and with thermal loads

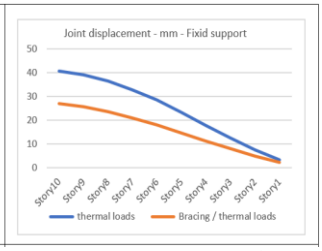


Figure 13. Joint displacement for models with fixed support on sloped terrain with and without bracing system and with thermal loads

6.5 Model Storey-Drift of the Models on Sloped Terrain with and without Bracing System

The storey drifts of the models on sloped terrain, with and without bracing systems and thermal loads, are shown in Figures 16 and 17, while Figures 14 and 15 shows the storey drifts without thermal loads. The models have hinged and fixed supports, and the results are presented for both cases.

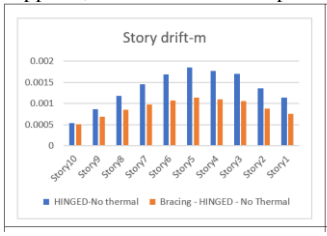


Figure 14. Storey drift for models with hinged support on sloped terrain with and without bracing system and without thermal loads

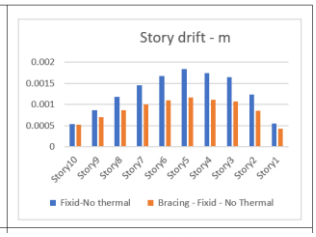


Figure 15. Storey drift for models with hinged support on sloped terrain with and without bracing system and without thermal loads

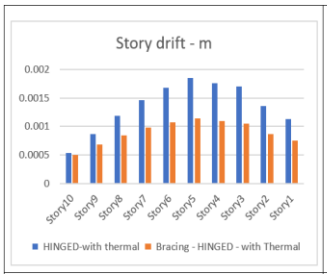


Figure 16. Storey drift for models with hinged support on sloped terrain with and without bracing system and with thermal loads

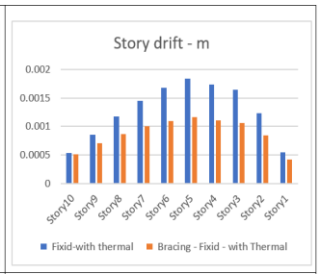


Figure 17. Storey drift for models with hinged support on sloped terrain with and without bracing system and with thermal loads

6.6 Column Shear-Forces of the Models on Sloped Terrain with & without Bracing System

Figures 18 to 21 show the shear forces acting on the columns for the models with and without a bracing system, on sloped terrain with hinged and fixed supports, and under different loading conditions. The results include the cases without thermal loads (Figures 18 and 19) and with thermal loads (Figures 20 and 21).

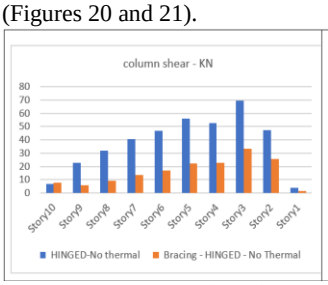


Figure 18. Column shear forces for models with hinged support on sloped terrain with and without bracing system and without thermal loads

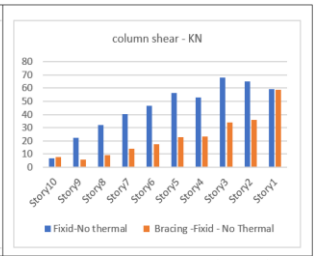


Figure 19. Column shear forces for models with hinged support on sloped terrain with and without bracing system and without thermal loads

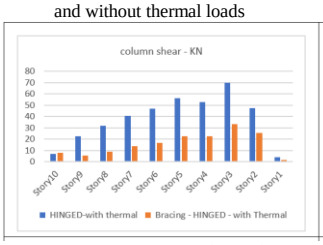


Figure 20. Column shear forces for models with hinged support on sloped terrain with and without bracing system and with thermal loads

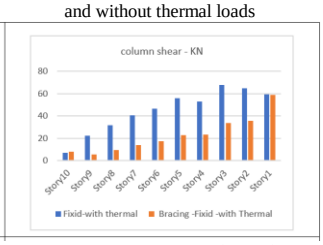


Figure 21. Column shear forces for models with hinged support on sloped terrain with and without bracing system and with thermal loads

6.7 Base Shear-Forces of the Models on Sloped Terrain with and without Bracing System

The base shear forces of the models on sloped terrain were analyzed using both hinged and fixed supports with and without bracing systems and with and without thermal loads. Figures 22 to 25 show the results for each combination, with Figures 22 and 23 representing the models without thermal loads and Figures 24 and 25 representing the models with thermal loads.

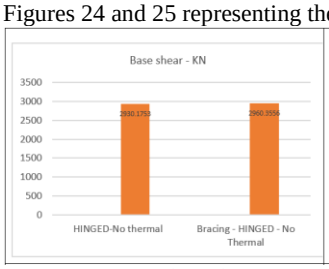


Figure 22. Base shear forces for models with hinged support on sloped terrain with and without bracing system and without thermal loads

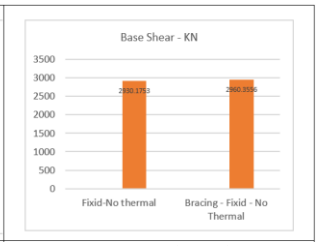


Figure 23. Base shear forces for models with hinged support on sloped terrain with and without bracing system and without thermal loads

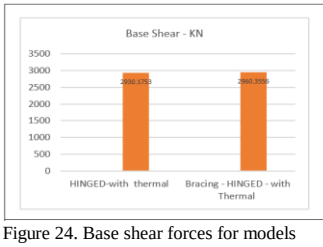


Figure 24. Base shear forces for models with hinged support on sloped terrain with and without bracing system and with thermal loads

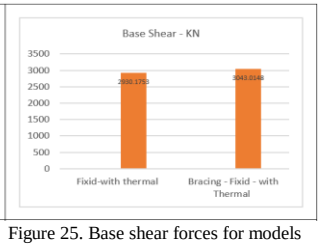


Figure 25. Base shear forces for models with hinged support on sloped terrain with and without bracing system and with thermal loads

7. RESULTS AND DISCISSION

The study investigated the impact of thermal loads on 3D-models of reinforced concrete buildings on sloped terrain with and without a bracing system under seismic loads. The models used two types of supports, hinged and fixed, and compared the effect of thermal loads. Various parameters were analyzed, including displacement, storey drift, column shear, and base shear. The obtained results were compared to draw conclusions.

7.1 Lateral displacement

For the reinforced concrete buildings design on sloped terrain, seismic loads are a crucial factor, and the impact of thermal loads must be taken into account during the design phase to prevent excessive deformation of the building (Oz, Senel et al. 2020). To achieve this, the building's drift and lateral deformation must be carefully considered. The application of restraints to the building will increase the effect of thermal loads, leading to a higher maximum displacement. However, the maximum displacement decreases for models without a bracing system and with hinge supports.

The study conducted dynamic analysis on reinforced concrete 3D models and found that the displacement of the top floors ranged from 40.602 mm to 24.519 mm for the models with fixed supports and bracing system, resulting in a 65.6% increase.

The results of the analysis for various reinforced concrete models are depicted in Figure 26, which reveals that the model without thermal loads and bracing systems has the minimum displacement. The presence of the bracing system and constraints on the support lead to an increase in displacement when compared to other used systems.

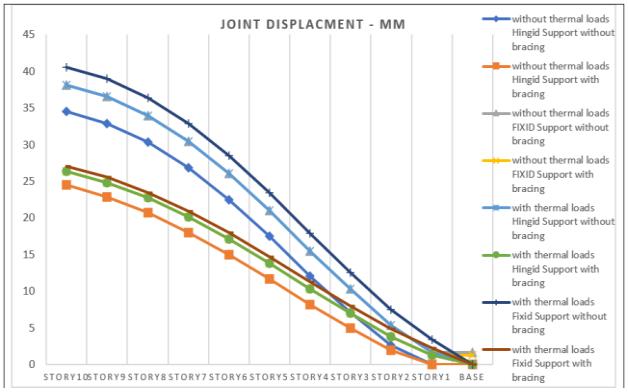


Figure 26. Comparison of joint displacement without thermal loads

7.2 Storey Drift

The parameter of storey drift is crucial in studying the behavior of reinforced concrete buildings and their non-structural damage. It is considered a reliable parameter for assessing the displacement of stories (Rahimi and Maheri 2020). The storey drift of reinforced concrete buildings on sloped terrain with fixed and hinged support types and bracing system due to thermal loads was observed. Figure 27 illustrates the different cases of thermal loads and bracing systems. A significant change in story drift values was observed between models with and without a bracing system. The bracing system significantly increased the story drifts, with an increase in values ranging from 0.001168 m to 0.001838 m, representing a 63.54% increase. Furthermore, high story drift was observed at each level of the model's stories due to the bracing system. Figure 27 shows that the maximum story drift was for the model with bracing systems and thermal loads. It is evident that the bracing system under thermal loads increases story drifts (Rahimi and Maheri 2020).

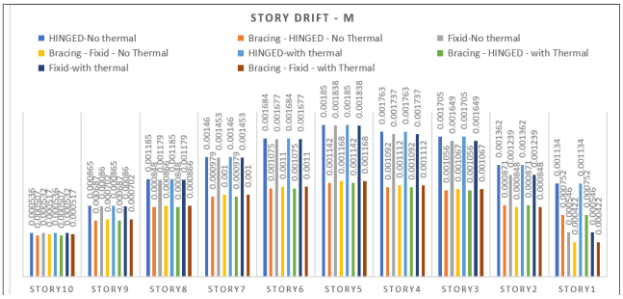


Figure 27. Comparison of storey dift with and without thermal loads for fixed and hinged supports

7.3 Column Shear Forces

The study found that the type of support constraints has a significant effect on the shear forces in the columns. The shear force for the columns with fixed supports was observed to increase significantly, with an increase of 93.34% compared to hinged supports. However, the models with bracing systems and hinged supports showed the minimum shear forces. Figure 28 displays the analysis results of the various models with and without thermal loads and different support types on sloped terrain under seismic loads. The minimum displacement was found for the model without bracing systems and with hinged supports. It is evident that bracing and fixed support constraints increase the design shear forces (Meriam 2018).

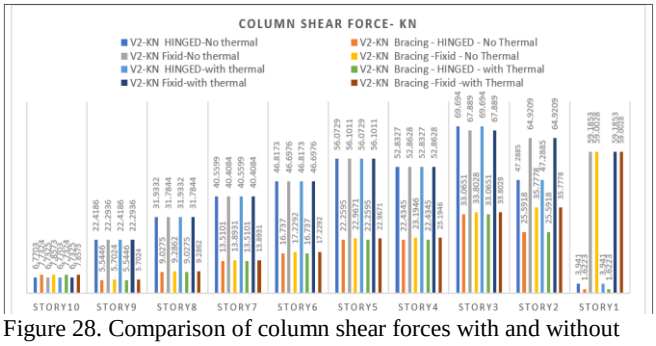


Figure 28. Comparison of column shear forces with and without thermal loads for fixed and hinged supports

7.4 Base Shear

The base shear refers to the total lateral forces caused by seismic loads at the base of reinforced concrete buildings and depends on the building design, soil type, fundamental time period, and seismic weight. This study analyzed the effect of thermal loads on reinforced concrete buildings with and without a bracing system on sloped terrain with hinged and fixed support types. The study found that the effect of these parameters had a minor effect on the base shear values, with an increase of only about 3.85%. The analysis results presented in Figure 29 showed a slight increase in base shear for the

different 3D-models due to thermal loads with bracing systems and fixed supports.

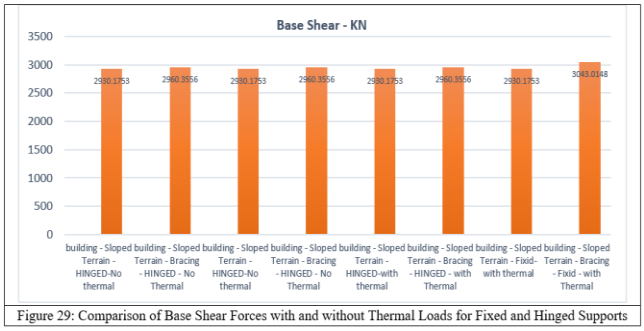


Figure 29: Comparison of Base Shear Forces with and without Thermal Loads for Fixed and Hinged Supports

Figure 29. Comparison of base shear forces with and without thermal loads for fixed and hinged supports

The study examined the impact of thermal loads on reinforced concrete buildings with and without bracing systems and fixed supports on sloped terrain under seismic loads. The analysis revealed that the displacement of the top floors of the models varied from 40.60 mm to 24.52 mm, with an increase of 65.6% in models with fixed supports and bracing systems compared to those without bracing and with hinged supports. A similar trend was observed for story drifts, with a significant increase of 63.54% in models with bracing systems compared to those without. The column shear forces also increased with the use of bracing systems, with an increase of 93.34% for fixed supports compared to hinged supports. Models with fixed supports and bracing systems showed the maximum shear force values, while the minimum values were observed in models without bracing and with hinged supports. However, the effect of these parameters on the base shear values was minimal, with an increase of only about 3.85%. Overall, the study showed that the use of bracing systems and fixed supports can significantly affect the behavior of reinforced concrete buildings under seismic loads with thermal effects.

8. CONCLUSION

In conclusion, buildings located in seismic load-prone places on sloped terrain have uneven and asymmetrical layouts, making them susceptible to severe damage from seismic loads caused by earthquake ground motions. This study examined the effect of thermal loads on reinforced concrete buildings with different support types, including fixed and hinged supports with and without bracing systems, subjected to seismic loads. Dynamic analysis was performed to compare and assess the lateral displacement results, column shear forces, story drift, and base shear for ground + 9 typical floors frame reinforced concrete models on sloped terrain. The results showed that thermal loads have a significant effect on reinforced concrete buildings, potentially leading to severe damage if not considered during the design phase. The use of bracing systems and fixed supports increased displacement by 65.6% and story drift by 63.54%, while the increase in base shear was only 3.85%. Further research is needed to fully understand how actual structures behave when subjected to thermal loads.

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