Thermal Cracks Development Study in Newly Built Reinforced Concrete Residences

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Abstract: Concrete blocks and concrete assemblies are affected by natural physical conditions, which impacts on the durability and service life of the structures. In this paper, site data was gathered, which was used to perform a numerical and a finite element modelling to investigate the impacts of several conditions on thermal cracking in a structure. The field recorded data was used for the numerical modelling, using MATLAB software, and the finite element modelling, using ANSYS Mechanical software. It was observed that among the conditions considered, the wall ratio in the structure and formation of microcracks have significant impacts, while the age of the structure, the compressive strength of the concrete have minimal impacts, as the shifting in the curve is small. Finally, a probabilistic crack development model was made to study the potential crack development in the finite element model, which was seen to tally with observed site data, demonstrating the potential of predicting cracks development.

1. Introduction

Concrete is the most used product in the construction industry, with more than 4300 Mega tonnes being used annually, which amounts to 8% of the annual carbon dioxide emissions in the atmosphere worldwide [1]. Cracking in a concrete structure results in deterioration of the structure, where the latter can no longer fulfil its desired purpose and also suffers a decrease in aesthetic. In many cases, the actions taken include renovation, which increases the investment on the structure and the concrete consumption. Many structures around the world are being subjected to severe cracking as a result of improper considerations during design, resulting in failure before the desired lifespan.

Ever since concrete has been used as a construction material, there has been the problem of crack development. Nowadays, nearly every individual in Mauritius goes for concrete residences, which is highly susceptible to cracking. For this purpose, being able to identify the possibility of crack formation and the location can help take measures against them. Amongst the various crack types which exist, there is thermal cracks which is one of the most common that occur in concrete structures. These cracks will reduce the strength of the structure overtime, resulting in failure after the cracks have accumulated and reached an undesirable degree. The analysis performed in this research concerns mostly unreinforced concrete and masonry units in load bearing reinforced concrete structures, with the aim to investigate thermal crack development probability in newly constructed reinforced concrete residences, based on local conditions, using data gathered on site, numerical modelling and finite element analysis.

1.1. Properties of Concrete

Concrete is a material which is very strong in compression but extremely weak in tension as mentioned by Iflat [2]. Over the years, people started disregarding the tensile properties of concrete, as steel
reinforcements could solve the problems related to the weak tensile properties. The main concerning factor about the concrete has become its compressive properties, as shown by Ashour [3]. However, for this research, in order to be able to model the crack formation, the tensile properties need to be considered. Raphael [4] published a research on the relationship between the tensile properties of concrete and its compressive properties based on 12000 individual tests results. Equation 1 and 2 relates the 2 parameters is:

\[
f_t = 1.7f_c^{2/3}, \text{ in psi} \tag{1}
\]

And,

\[
f_t = 0.7f_c^{2/3}, \text{ in kg/cm}^2 \tag{2}
\]

Where,

- \(f_t\) = Tensile strength of the concrete sample, in psi or kg/cm²
- \(f_c\) = compressive strength of the concrete sample, in psi or kg/cm²

These results were based on the graph:

This was then further refined by Riding A. et al. [5]. The final formula obtained was:

\[
f_t = 0.266f_c^{0.907}, \text{ in psi} \tag{3}
\]

This equation is seen to yield a lognormal distribution for the concrete cracking nearly same as the actual behavior of the concrete in reality, with same mean and standard deviation. This formula will be the one use for modelling purposes.

1.2. Properties of Masonry Units
Masonry walls are vertical members, which can be used for load transfer in certain structures known as load-bearing wall structures. Generally, residential houses are built to be load-bearing, as it reduces the cost of the overall structure, with the blocks being part of load transfer from super structures to the foundation.

In Mauritius, the masonry walls are generally made out of cellular blocks.

Those blocks are of different sizes depending on the need. Cellular blocks in Mauritius are made using a relatively high ratio of aggregate (Rocksand 0-4mm & Coarse Aggregate 4-6mm & 6-10mm) with Portland cement as the bonding agent, following prescriptions of BS 6073 part 1. The properties of the blocks are therefore made in such a way so as to have fulfil the requirements [6]. The properties of masonry unit use for this research is taken as shown in Table 1.

| Table 1. Masonry Parameters. |
|-----------------------------|
| Parameter                  | Compressive strength/ MPa | Tensile strength/ MPa |
| Average                    | 31.9                       | 2.02                   |
| Standard Deviation         | 7.1                        | 0.23                   |

1.3. Size of Cracks
The size of a crack is relative to the severity of the crack. As such, it is very important to give adequate consideration to the types and size of cracks as they give a lot of information about the reason for the existence of the crack and the extent of it.

The crack size can be separated into 2 main categories, which is microcracks and hairline cracks. Microcracks are very tiny cracks which are not visible to the eyes and cannot be measured unless with
special equipment as shown by Dare et al. [7]. Hairline cracks are small but visible to the eyes. Beyond the point of hairline cracks, the tensile strength of that part of the structure has already been compromised severely [8]. Table 2 shows the different types of cracks.

| Damage State | I(slight) | II(Moderate) |
|--------------|-----------|--------------|
| Type of Crack| Micro Crack | Hairline Crack |
| Crack width limit | <0.01mm | 0.01<C<0.1mm |

1.4. Thermal Crack Development
There are two main types conditions which can affect the temperature of concrete structure, which is the heat of hydration released during the hardening of the concrete, and, the external environmental heat which has an impact on the structure. Both of those must be given proper considerations during the design process.

For the environmental temperature variation, that is due to the ambient temperature, the sun radiation, the orientation of the structure, the time of the day and other physical conditions to which the structure is subjected to. The thermal condition is one which has continuously impacts on the structure, whether during the day or night. The changes in temperature will cause differential expansion in the structure, resulting in stress build up and cracking. One example of such effect on an arch dam as discussed by Sheibany and Ghaemian [9].

The impact of thermal conditions was demonstrated by Araújo [10] in his paper where the development of restrained strained is analysed relative to thermal cracking in concrete pile caps. The first factor related to this is the thermal conductivity of concrete, which is taken to be 1.65 W/m°C as a representation of the worst-case scenario. The first step of the analysis is the determination of the strain which the element is to undergo due to the thermal condition. The formula proposed by Araújo is:

\[ \varepsilon_o = \alpha (T - T_o) \]  \hspace{1cm} (4)

Where,
\( \varepsilon_o \) = Free Thermal Strain
\( \alpha \) = Coefficient of Thermal Expansion of concrete = \( 10^{-5}\,\text{C}^{-1} \)
\( (T - T_o) \) = Temperature difference between the point being considered and a reference point

Following this formula and considering the actual strain sustained by the structure, the restrained strain is calculated using the formula \( \Delta \varepsilon = \varepsilon - \varepsilon_o \). The restrained strain is the expansion which the element should have sustained, but due to the restriction on the structure was unable to.

The stress in the concrete can then be determined using the stress-strain diagram. Figure 1. shows the tensile and compressive relationship proposed by Araújo [10].

The change in gradient which occurs in the tensile behaviour graph after \( \varepsilon_{ct1} \), corresponds with formation of microcracks and change in behaviour of the sample.

The value of \( \varepsilon_{ct1} \) can be determined using:

\[ \varepsilon_{ct1} = \frac{0.9f_{ctm}}{E_c} \]  \hspace{1cm} (5)

Where \( f_{ctm} \) = mean tensile strength of the material
\( E_c \) = tangent modulus at age \( t \) days
Figure 1. Stress-Strain diagrams for tensile and compressive behaviour

Based on CEB-FIP Model Code, these values can be determined using the formulae relating them to the age of the concrete:

\[ E_c(t) = \{\beta_{cc}(t)\}^{1/2} E_{28} \]  
\[ f_{ctm}(t) = \beta_{cc}(t)f_{ctm28} \]

Where \( \beta_{cc}(t) \) represents the aging function and, \( E_{28} \) and \( f_{ctm28} \) represents the values of the tangent modulus and the mean tensile strength of the sample at 28 days. The mean tensile strength can be obtained by using the compressive value obtained when testing the sample in direct compressive test and relating it using the formula proposed by Riding et al. [5], given previously., or the relationship proposed by Araújo (2016) can be used, which is given as:

\[ E_{28} = 21500 \left( \frac{f_{ck} + 8}{10} \right)^{1/3}, \text{ in MPa} \]  
\[ f_{ctm28} = 1.40 \left( \frac{f_{ck}}{10} \right)^{2/3}, \text{ in MPa} \]

Where, \( f_{ck} \)compressive characteristic strength, in MPa

The aging function \( \beta_{cc}(t) \) can be obtained by using the following formula:

\[ \beta_{cc}(t) = \exp \left\{ s \left[ 1 - \left( \frac{28}{t/t_1} \right)^{1/2} \right] \right\} \]

Where \( t \) = time, in days
\( t_1 = 1 \text{ day} \)
\( s \) = parameter considering the type of cement [11]

\( s = 0.20 \) for rapid hardening high strength cement, \( s = 0.25 \) for normal and rapid hardening cement N and R, and, \( s = 0.38 \) for Slow hardening cement SL, obtained from CEB-FIP Model Code.

1.5. Probability of Crack Formation

Crack formation is dependent on the stress sustained by the structure as explained by Al-Sanea [12], where the stress-crack relationship was demonstrated. The bigger the stress, the higher the probability of crack formation and the bigger the crack. For the determination of the probability of crack formation relative to the applied stress, a log normal graph was obtained, as shown by Riding et al. [5].

Hordijk [13] analysed the impact of various factors on concrete crack size and formation. Concrete is a material which deforms like a brittle material, followed by microcracks and when the yield strength
is reached, there is the development of a softening zone at the ends of the crack, where the strength of
the element drops gradually. This results in a gradual decrease of the tensile strength of the material with
increase in the crack size, as in Figure 2, which was first brought forward by Hillerborg [14] and then
studied by a few, including Petersson [15].

To simplify the analysis of the sample, the material can be assumed to behave in a linear elastic
fashion before cracking and the stiffness softening occurs after reaching the ultimate tensile strength, as
shown in Figure 2.

![Figure 2. Behavior of Concrete](image)

The two parts of the graph each have an equation relating them. For the first elastic behavior of
concrete, the behavior follows the Young’s Modulus Equation [16]:

\[
\sigma = E \varepsilon
\]

Then, as for the second part of the graph, the proposed equation, by Hillerborg [14], for the analysis is:

\[
\frac{\sigma}{f'_{tef}} = \left(1 + \left(c_1 \frac{w}{w_c}\right)^3\right) \exp\left(-c_2 \frac{w}{w_c}\right) - \frac{w}{w_c} (1 - c_1^2) \exp(-c_2) \tag{11}
\]

Where, \(w\) = crack opening
\(w_c\) = crack opening at complete release
\(f'_{tef}\) = effective tensile strength
\(C_1\) and \(C_2\) = constants, and
\(\sigma\) = Applied Stress in the member

The crack opening at complete release can be calculated using the formula proposed by Hordijk and
Reinhardt [17].

\[
w_c = 5.14 \frac{G_f}{f'_{tef}} \tag{12}
\]

Where \(G_f\) = fracture energy

\[
= \text{Area under graph of the stress against crack opening graph}
\]

This proposed behavior of concrete has been adopted by many and has proven to be really accurate
for the analysis and modelling of the behavior of in various contexts.

In order to assess the probability of failure of the element at different temperature variation, a normal
distribution probability is used. For this, the mean value of the tensile property of the cellular block is
determined and the standard deviation of the results. Then, assuming that the result follows a normal
distribution, which has been proven to be close to the actual behavior by Kyle et al. [5], the determination
of the failure of the probability is calculated.
The probability of the strength of the sample being weaker than the applied stress is calculated, which is \( P(F_t < F) \) where \( F_t \) is the tensile strength and \( F \) is the applied stress. For this, the following principle is used, where the \( F \) is converted into a \( Z \) value, which is a normal distribution case where the mean is 0 and the standard deviation is 1. For this conversion, the following formula is used:

\[
Z_i = \frac{X_i - \bar{X}}{S}
\]  

(13)

Where \( X_i \) = The value being considered

\( \bar{X} \) = Mean

\( S \) = Standard deviation

Then, using the \( Z \) table, the probability of \( P(X<Z_i) \) is determined [18]. This formula is used alongside the probability table to obtain the probability of crack formation.

2. Methodology

2.1. Onsite Data Gathering

For onsite data gathering, a series of site visits were carried out in local houses, at various location on the island. For this, a sampling process is made following the “Small Sample Technique” method, presented by Krejcie et al. in 1970 [19]. Using the following formula:

\[
s = \frac{X^2NP(1 - P)}{d^2(N - 1) + X^2P(1 - P)}
\]  

(14)

\( s \) = required sample size.

\( X^2 \) = the table value of chi-square for 1 degree of freedom at the desired confidence level

\( N \) = the population size.

\( P \) = the population proportion (assumed to be 0.50 since this would provide the maximum sample size).

\( d \) = the degree of accuracy expressed as a proportion (1 - confidence interval)

For this case, a confidence interval of 80% is taken, therefore to get the sample size, the following parameters were used, \( X=1.28 \), \( P=0.5 \) and \( d=0.1 \). The population size is assumed to be 20000 for load bearing residential houses. Solving the equation with those parameters yields to a sample size of 41.

For this research, a total of 55 different samples were taken all around the island for representative data to be obtained.

2.1.1. Observations. On site, it was seen that the location most at risk for crack formation is the window corners. Some houses, however, are not affected by this problem, which is due to the use of reinforcement at the corners of the windows or use of appropriate lintels and sills. It is seen that without the proper considerations, the damage is considerable. That is the result of the differing coefficient of expansion and Young Modulus between the wall and the metals used for the window frames. The window expands by a great extent causing differential movement and tension build up in the masonry unit, resulting in crack formation.

For a structure, there are various conditions which can impact on the probability of crack formation, including excess loading, inadequate reinforcement in slab, thermal conditions and settlement. From the results obtained, another important observation is the relationship between the damage sustained by the structure and the age of the structure. It is observed that as the residential building gets older, the extent of the damage increases, showing that the damages accumulate overtime. Also, as a stress is applied on
a structure, microcracks is formed due to material defects, which overtime, with repeated loading, joins ups to form bigger cracks.

2.1.2. Temperature Profiles. Then, from the houses sample where the site visits were carried out, a newly constructed house (12 months old) was chosen and apparatus installed. The apparatus installed was an Arduino circuit with a DHT 22 module to measure the temperature and moisture content in the house at various location. The temperature was recorded for 127 days in total in Port Louis. Those temperature profile include the internal wall, external wall and ambient temperature.

The temperature recorded is the data used for the modelling. Also, the ambient temperature in Port Louis is recorded at 6 hours interval everyday starting from the 23rd of October 2019 to the 29th of February 2020.

It is seen that the maximum temperature recorded is during the month of December and January, with the maximum being 30 degrees Celsius.

2.2. Modelling

2.2.1. Numerical Modelling. The data obtained from the site visit is used for the numerical modelling in MATLAB. For this, the parameters in Table 2 is used.

2.2.2. Synthetic Temperature Profile. The first step graph generated from the numerical model are synthetic temperature profiles, which is generated from the temperature profiles obtained from site.

2.2.3. Effect of Micro Cracks. The synthetic temperature profile is then input into a model and an actual site condition is modelled. When the sample is loaded, the stress gives rise to microcracks which develops into hairline crack. Figure 3 is a probability curve showing the difference between when microcracks are considered and when it is not. The condition used for the model is concrete strength of 30 MPa, 12 months old and axial load transfer between the elements. It is seen in Figure 3, by the shift in the graph, the sample has a lower probability of hairline crack formation at higher temperature when there is microcrack formation in the structure.

The Model was run using a strength of concrete of 30 MPa for a 12 months old sample with the load being transferred axially for determining the temperature required for achieving the set probability of cracking when microcracks are considered and when it is not.

![Probability of Hairline Crack Formation in Wall](image_url)

**Figure 3.** When Considering Microcracks

Table 3 shows the temperature required to generate different probability of cracking under the applied conditions, which is plotted in Figure 4.
### Table 3. Microcracks Effect on Temperature needed to cause failure

| Conditions | Temperature for Hairline Cracking |
|------------|----------------------------------|
|            | Without Microcracks | With Microcracks |
| Strength of Concrete/ MPa | Age/ Months | Ratio of Walls | Probability | 30 | 12 | axial | 0.1 | 8 | 8 |
| 30 | 12 | axial | 0.2 | 8.7 | 9.5 |
| 30 | 12 | axial | 0.3 | 9.1 | 12.6 |
| 30 | 12 | axial | 0.4 | 9.5 | 15.2 |
| 30 | 12 | axial | 0.5 | 9.9 | 17.6 |
| 30 | 12 | axial | 0.6 | 10.2 | 20.1 |
| 30 | 12 | axial | 0.7 | 10.6 | 22.7 |
| 30 | 12 | axial | 0.8 | 11 | 25.7 |
| 30 | 12 | axial | 0.9 | 11.7 | 30 |
| 30 | 12 | axial | 0.95 | 12.2 | 33.5 |

The graph shows the relationship between the hairline crack probability formation when microcracks are considered and when it is not.

**Figure 4. Effect of Microcracks**

It is seen that when microcracks is formed in the sample, a higher temperature is required to yield the same probability of crack formation. Effect of Strength of Concrete

2.2.4. Effects of Strength of Concrete. The model is run again with varying concrete strength used for the masonry unit each to identify the effect on probability of hairline cracks formation.

The relationship between the compressive strength of concrete is plotted against the tensile strength of concrete using the formula proposed by Araujo [10]. Figure 5 shows the tensile strength variation of the concrete relative to the compressive strength of concrete used.
Figure 5. Effect of Strength of concrete on Temperature required

The data obtained from the variation of the strength of the concrete is plotted and compared. The temperature required to yield a 0.5 probability of crack formation is determined with varying strength of the concrete used. This is done considering scenario with microcracks and without microcracks. The parameters used for the modelling is a strength of concrete of 30 MPa for a 12 months old sample with the load being transferred axially.

Figure 6. Strength of Concrete effect (With microcracks)

From Figure 6, it is seen that when microcracks is formed in the sample, as the strength increases, the temperature required for hairline crack formation diminishes, meaning the probability of hairline cracking increases, whereas without microcracks, the temperature required increases. That is because, when microcracks are considered, when a tensile stress is applied to the sample, small cracks are formed, resulting in a deformation in the sample. This deformation reduces the restrained strain in the structure and thus, reduces the stress in the structure and the probability of cracking. That is why, a higher temperature is required to cause hairline crack formation in the sample, as compared to when there is no microcracks.

One interesting behaviour is the probability of hairline crack formation in the model when microcracks are considered. This can be seen in Figure 6, where the lower the strength of concrete, the
lower the probability of hairline crack formation at bigger temperature differences. That can be attributed to the stiffness of the structure. As the strength of the concrete used is increased, the stiffness of the structure increase and more micro-cracks are formed, reducing the tensile restrained strain in the structure and reduce the risk of cracking.

2.2.5. Effect of Age of Concrete. After modelling the effect of the age of concrete, a new model is made, where the strength of the concrete is related to the age. Then, using the previous relationship obtained from the modelling, the relationship between the age of concrete and the probability of hairline crack formations can be determine.

![Figure 7. Effect of Age on Probability](image)

It is seen, in Figure 7, that when microcracks is formed in the sample, as the age increases, the temperature required for hairline crack formation diminishes, meaning the probability of hairline cracking increases, whereas without microcracks, the temperature required increases. Nonetheless, the difference is minimal.

2.2.6. Effect of Wall Ratio. Then, the next parameter considered is the wall ratio in the structure. For this purpose, a frame is considered, as shown in Figure 8. The position of the wall in the considered Frame is important as it will vary the strain and stress transfer between the various walls in the model.

![Figure 8. Frame Ratio](image)

In the model, the ratio x/y is varied and the impact on the stress and cracking probability in the internal wall is analysed.

It is seen that as the ratio increases, that is as the wall moves further apart, the temperature required to achieve this probability of cracking is decreasing, showing the probability of hairline cracking increases.
2.2.7. Probabilistic Crack Formation Curve. Finally, before moving on to the finite element model, a probabilistic curve is made using data gathered on site and from past researches. This curve will be used to relate the restrained strain and the stress in the sample to the probability of crack formation in the sample. This is done using the parameter: concrete strength 30 MPa, 12 months old, with micro cracks, axial loading and data from Table 2. Also, the behavior of concrete shown in Figure 9 is used for the development of the graph.

![Behaviour of Sample](image)

**Figure 9. Loading and Fracture Curve**

The probability distribution curve obtained is shown in Figure 10, which will be used for the finite element modelling. It is seen that the probability reaches nearly 1 at about 45 °C temperature difference between the walls.

![Probability of Hairline Crack Formation in Internal Wall](image)

**Figure 10. Probability of Crack Formation**
2.3. Finite Element Model Results

Now, onto the finite element modelling. For this, there are a total of 3 models which are made in the software Ansys Mechanical.

2.3.1. Simple Frame. The first model analysed in Ansys Mechanical is a simple frame model, just like the in the numerical model. This is in order to be able to compare the results. For this case, the frame model shown in Figure 8 is analysed, with varying wall distance and temperature profile.

The temperature profile is applied to one of the external walls. The stress developed in the structures is then compared to the probability curve and the probability of cracking is determined.

The frame is made so that the internal wall is exactly in between the 2 external walls, with varying slab length. The data obtained shows that the length of the slab is important. The result is seen to differ with the numerical model, where a stress of 3.63 MPa is obtained, whereas the FEM is at 1.06 MPa.

This difference in the result is due to:

1) the self-weight of the slab which is not considered in the numerical model, and
2) the deflection of the slab which occurs in the finite element model due to self-weight but not in the numerical model.

In this aspect, the result obtained from the finite element is close to onsite behaviour of the model. It is also seen that the maximum stress generated in the middle wall with a slab length of 2 m being 1.06 MPa, but when the slab length is changed to 3m the stress drops to 0.78 MPa. This is due to the self-weight of the slab, which increases as the length increases and rests on the middle wall, countering the tensile stress developing in the middle wall due to the external wall expanding. However, the stress is seen to increase again after, due to compressive stress developing in the wall because of the slab self-weight.

2.3.2. Window Corners. The FEM was then used for the modelling of windows to determine the actual possibility of crack formation in windows due to direct expansion is considered, as mentioned in the methodology. The model shown in Figure 11 is the model used, and the materials used is concrete for the walls, and steel and aluminium for the window. The temperature profile was applied to the window side and the wall, and the Stress is analysed. Figure 11 shows the stress development around the window.

![Figure 11. Window Meshed Model (Front View)](image-url)
Table 4. Stress development in walls due to Window effect

| Temperature | Location | Material | Stress/MPa | Probability |
|-------------|----------|----------|------------|-------------|
| 10          | Bottom   | Steel    | 2.85       | 0.29        |
| 10          | Top      | Steel    | 3.27       | 0.35        |
| 10          | Bottom   | Aluminium| 3.03       | 0.31        |
| 10          | Top      | Aluminium| 3.369      | 0.37        |
| 20          | Bottom   | Steel    | 5.77       | 0.77        |
| 20          | Top      | Steel    | 6.69       | 1           |
| 20          | Bottom   | Aluminium| 6.98       | 0.9         |
| 20          | Top      | Aluminium| 6.1        | 0.81        |
| 30          | Bottom   | Steel    | 8.24       | 0.97        |
| 30          | Top      | Steel    | 10.2       | 1           |
| 30          | Bottom   | Aluminium| 10.96      | 0.99        |
| 30          | Top      | Aluminium| 9.45       | 1           |
| 40          | Bottom   | Steel    | 13.7       | 1           |
| 40          | Top      | Steel    | 10.8       | 1           |
| 40          | Bottom   | Aluminium| 14.7       | 1           |
| 40          | Top      | Aluminium| 12.2       | 1           |
| 50          | Bottom   | Steel    | 16.5       | 1           |
| 50          | Top      | Steel    | 14.4       | 1           |
| 50          | Bottom   | Aluminium| 17.4       | 1           |
| 50          | Top      | Aluminium| 15.8       | 1           |

From Table 4, it can be seen that Aluminium windows have significant impacts on the masonry unit as the resulting stress can lead to failure of member. The probability obtained is very high, considering the other conditions the walls may be subjected to, and the higher probabilities are observed at the corner windows, especially the top part. Between aluminium and steel, it was seen that steel has slightly more impacts because of the stiffness of the materials, which accommodates less deformation.

2.3.3. House Model. Finally, the analysis of an actual surveyed model on site house model is performed. The model analysed is a residential house found in Bois Pignolet, Terre-rouge, which was surveyed appropriately. The model used for the analysis is shown in Figure 12, and was the on input in the Ansys Mechanical Software.

![Figure 12. Plan of house](image)
A temperature profile is applied to the wall which is observed to be the one subjected to the sun in reality. Then, the analysis is carried out with different temperature profiles and the result of the stress development is obtained, which is used for the probability analysis. From the results, it is seen that the corners of the structure are highly susceptible to thermal cracking. The walls perpendicular to the one subjected to the thermal condition are also highly vulnerable to cracking. As we move further from the location where the thermal conditions are applied, the probability of cracking decreases. This model, however, does not allow movement of the sun over the building to identify the cracking probability at different times of the day.

2.4. Comparison of Results
The results obtained from the 3 different analysis, which is numerical analysis, finite element analysis and site visits, are seen to be in line with each other. However, some values differ between the finite element analysis and the numerical analysis, because of the assumption made during the writing of the numerical model.

The location identified to be the most prone to crack formation in the finite element model is seen to be close to the crack observed on site. On site, cracking at window corners was seen to be really significant, especially at the lower corners. Also, the internal wall of room 4 (refer to Figure 12) is seen to have cracks at the top and middle, just like predicted by the model. Several walls were also seen to have cracks at the top, as seen also in the model. The house corners also are location predicted to have high probability of crack formation, which was seen on site, with severe crack forming next to windows at the corner.

However, some cracks were seen on site which could not be predicted in the model. One of such places is the cracking at the top of the wall separating Room 1 and storeroom 1 (refer to Figure 12). However, after inspection, it was seen that this was due to this wall being added after the house has been completed. Another location where cracks were observed is in the slab of room 3 (refer to Figure 12), which though subjected to significant stresses in the model (up to 12 MPa), is a reinforced part of the structure and is not supposed to crack like it did. The possibility is that proper considerations were not given to thermal conditions during the design. Another such location is the staircase in the house which could not be modelled, however this is due to the difficulty of modelling the staircase in the model and due to time constraints.

3. Conclusion
In this research, the thermal loading on a load bearing residential building was investigated, using data gathered on site, numerical modelling and 3D finite element modelling. The conditions affecting the cracks formation were determined using numerical modelling, the locations which are prone to cracking are surveyed on site and determined using finite element modelling and comparison were made between the results.

The various parameters analysed in this paper includes the strength of the concrete used for manufacturing of the masonry units, which is seen to have a slight effect only, the age of the structure, which can be said to have close to no effect after the 28 days point, and the distance between the walls, which is seen to have significant impact. The closer the walls, the more the impact of the thermal loading. From the finite element model, the length of the slab is seen to have quite an impact on the loading on the internal walls, because of its sagging. Microcracking is also a very important factor to consider, as the impact it has is very significant.

Also, the expansion of windows has a very high impact on crack formation, due to the differing properties. This is supported by data on site, where corner windows are seen to be a location where there is severe crack formation. Nonetheless, in places with the proper corner reinforcement or lintels and cills, no cracks were observed.

Then, the finite element model was made for the residential building considered, though with some minor discrepancies in term of staircases, windows and support, the location of high risk of crack formation obtained from the model was seen to be close to the location of the cracks on site. However,
there were some locations where cracks were observed on site which could not have been predicted using the model, which can be associated to conditions other than thermal.

As a conclusion following the research, it can be said that cracks in a load-bearing wall building, especially those related to thermal loading, can be modelled and predicted with relative ease. Following which, measures can be taken to provide reinforcement at those locations to prevent them from forming. Though, there are some which cannot be predicted using the proposed methodology, the overall crack formation in the building can be significantly reduced. However, it may be possible to enhance the analysis if more parameters are considered.

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