Numerical modelling of cracks in façades

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Civil Engineering

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Abstract

The cracking on façades is a well-known phenomenon. The several inspections in buildings conducted over the years enabled the identification of the zones most likely to develop cracks. Numerical models and laboratory tests that study the cracking phenomenon in materials used on façades help understanding the causes of cracking in each material but must be complemented with numerical models that study real façades, which take into account the behaviour of the different materials together. This input is important since cracking is visible on most façades and most of these cracks are avoidable with diligent projects and careful execution on site.

The main objective of this work is to model façades and detect zones where it is more probable for cracks to appear, in order to define zones of reinforcement for integration in details of future projects. This will permit a theoretical improvement of the durability of the façades which can be related to an improvement of the buildings’ durability and in the end, results in better quality of life for the users. With this work surprising and innovative conclusions are not expected as this is a well-known phenomenon. However this work aims to draw attention to the benefits of using numerical models as tools in the design phase, in order to study these phenomena and improve the details in future projects.

Keywords:

Cracking; Façades; Numerical models; Numerical Analysis
Resumo

A fissuração em fachadas é um fenómeno bem conhecido devido às inúmeras inspeções realizadas em edifícios ao longo dos anos, que permitiram identificar as zonas mais propícias a desenvolver fissuras. Os modelos numéricos que estudaram a fissuração em materiais usados nas fachadas bem como os testes de laboratório, permitiram compreender porque e como cada material pode fissurar, tendo esta informação que ser completada com modelos numéricos que estudam fachadas reais e tem em consideração o comportamento de diferentes materiais juntos. Esta informação é importante visto que a fissuração tem um efeito visual na maior parte das fachadas e, maior parte dos casos, podia ser evitada com projetos e execuções em obra mais cuidadosos.

O principal objetivo deste trabalho é modelar elementos de fachadas e detetar as zonas onde é mais provável que apareçam fissuras, de maneira a definir zonas de reforço em futuros projetos. Isto irá permitir um progresso teórico sobre a durabilidade das fachadas que pode ser relacionado com um melhoramento da durabilidade dos edifícios e, finalmente, traduz-se numa melhoria da qualidade de vida dos utilizadores. Com este trabalho não são esperadas conclusões surpreendentes e inovadoras, no entanto pretende-se chamar a atenção acerca dos benefícios da utilização de modelos numéricos como ferramenta na fase de projeto, no intuito de estudar estes fenómenos e melhor os detalhes em futuros projetos.

Palavras-chave:

Fissuração; Fachadas; Modelos numéricos; Análise numérica
1 Introduction

1.1 Background

The cracking on façades is a well-known phenomenon. The several inspections in buildings conducted over the years enabled the identification of the zones most likely to develop cracks. Numerical models and laboratory tests that study the cracking phenomenon in materials used on façades help understanding the causes of cracking in each material but must be complemented with numerical models that study real façades, which take into account the behaviour of the different materials together. This input is important since cracking is visible on most façades and most of these cracks are avoidable with diligent projects and careful execution on site.

This work follows a previous master thesis (Gaspar et al., 2011), where the factors that directly influence the adherence of mortar with interface elements were analysed. In the beginning of this work the introduction of contact elements, a more complete and complex version of the interface elements, in the same conditions were studied given rise to an article in the International Journal of Adhesion & Adhesives (Silva et al., 2014) and a presentation in the 4th National Congress of Construction (Esteves et al., 2012). As there is no information available of detachments due to hygrothermal loads in order to compare and calibrate the numerical models, this work has evolved to the analysis of cracking in façades, using the knowledge of the contact elements to improve the numerical models created.

1.2 Objectives

The main objective of this dissertation is to model façades and detect zones where it is more probable for cracks to appear, in order to define zones of reinforcement to integrate in details of future projects. To achieve this objective, the work will be divided in three major points:

1. A systematization of cracking types divided by load types;
2. The inspection of different buildings in order to identify the most common cracking types, integrate them in the previous category of load type and select some with the intention of modelling;
3. Modelling the selected buildings or part of them so that it is possible to identify the zones where a detailed reinforcement should be prescribed in future projects.

If these detailed zones are prescribed in the design phase of the projects, the projects will be more precise and this will enable a theoretical improvement of the durability of the façades which can be related to an improvement of the buildings’ durability and in the end, results in better quality of life for the users. With this work, surprising and innovative conclusions are not expected as this is a well-known phenomenon. However this work aims to draw attention to the benefits of using
numerical models as tools in the design phase, in order to study these phenomena and improve the details in future projects

1.3 Work structure

This work is organized in four chapters with a first chapter related to the theoretical framework of the phenomenon of cracking and the major causes, namely: hygrothermal loads, chemical reactions and structural and other movements. A summary review of the existing numerical models was also carried out. The second chapter describes the buildings and the inspections performed in those buildings as the experimental basis for the models created and presented in the third chapter. In the third chapter, apart from describing the programs used and the inputs needed, the simulations performed and the results that permit comparing what was observed in the field and the program output are described. The fourth and last chapter, describes the conclusions of this work and makes mention of future works that can be done.
2 Cracking on façades

The façades are the envelope of the buildings, therefore they have an important aesthetical requirement but, even more importantly have a mechanical component that is closely related with the durability of the building components and the appearance of anomalies. The phenomenon of cracking, usually, is the physical reaction in the building to an excessive load (internal or external load) or movement (differential or structural movements) and works as a trigger to the development of other severe anomalies.

This chapter attempts to present a theoretical view of the phenomena of cracking (2.1), its patterns (2.2) and a review of each phenomenon or pattern already modelled (2.3).

2.1 The cracking phenomena

As discussed by Roylance (2001) and Schreurs (2011), three types of cracks can be defined based on three loading modes to wit, Mode I, Mode II and Mode III (Figure 2.1). In Mode I the load is perpendicular and normal to the crack, originating a normal opening; in Mode II and in Mode III the crack is originated by shear stress, with the load parallel to a sliding crack in Mode II and perpendicular in Mode III.

![Figure 2.1 - Three standard loading modes of a crack. (Polaha and Ingraffea, 1994)](image)

The authors (Paiva et al., 2006), (Bonshor and Bonshor, 1995) and (Gaspar et al., 2006) define the mechanism of cracking as a physical process associated with movements originating from different forces or causes transforming into stress and once the stress is greater than what the material or component can withstand, a crack will appear. Following the work of the previously mentioned authors and (Bone et al., 1989), cracks in coatings do not represent danger to the users; they are a first sign that something is not working as it should be and despite their serious appearance, are a natural reaction to occupation and external conditions. Some cracks are inevitable but controllable, such as cracks formed during the early age of the building, caused by the drying process.

As stated by (Bonshor and Bonshor, 1995) and (Bone et al., 1989) the mechanism of cracking affects the global performance of the building. A crack is a privileged entry point for moisture with or without hygroscopic salts and carbon dioxide that accelerates chemical phenomena in cement-based products and a place where seeds can settle and grow inside (Figure 2.2). In summary,
the cracking phenomenon accelerates the processes of degradation in façades and contributes to a decrease in the quality of life in buildings, namely the thermal and acoustic quality.

![Figure 2.2 – Plants growing inside a crack in the façade (Ortonesque, 2010)](image)

In this work the forces and causes associated with cracking on façades, are divided into three major groups, namely hygrothermal loads, chemical reactions and structural and other movements.

2.2 Cracking patterns on façades

2.2.1 Hygrothermal loads

According to (Bonshor and Bonshor, 1995) the most common materials used in construction have a considerable and a continuously size changing when subjected to a variation in temperature. The simplified analysis assumes that the material is homogeneous, which means that all material experiences the same changes in temperature and it has no restraints preventing deforming. Although this is not the correct approach to apply to current materials in a construction system, it is a solid approach to non-restricted material and a reasonable starting point for an analysis of deformation. A building, in most cases, is an aggregation of elements that are built with different, non-homogenous materials and have most of their movements restrained not only by the connections between different materials of the same element but also by the physical restraint imposed by other elements.

The hygrothermal loads are the result of the thermal and moisture variations expressed as a combined load of the elements in the construction. This analysis can be done separately and the effects combined as proposed by (Bonshor and Bonshor, 1995) although, despite the complex calculations, (currently mostly worked out by computer models), it is beneficial as a combined action since there are interdependencies with both properties.

As discussed by (Bonshor and Bonshor, 1995), (Gaspar et al., 2006), (Paiva et al., 2006) and (Silva, 2002), two types of cracking in façades can be defined that depend not only on the load but also depend on the type of material. A first type, common in the early ages of cement base materials (Figure 2.3) is characterized by the shrinkage of the cement base material as a consequence of quick evaporation of the water present in the cement base paste. A second type,
most common in façade walls and flat roofs, is a set of parallel cracks as shown in Figure 2.4. These cracks appear, normally, after a one year cycle (winter and summer), are perpendicular to the longest axis and can appear in a wall subjected to high thermal surface gradient without an expansion joint or similar.

As referred in the work of (Bonshor and Bonshor, 1995), (Kovler and Frosting, 1998) and (Ignatiev and Chatterji, 1992) the individual behaviour of each material, in most cases, is not the main cause for façade cracks but when different materials are interconnected, the forces created by the connection of the materials generate a restraint to the individual movements of each material originating in shear tension between them. When this tension is higher than the internal strength of the material a crack appear.

With the constant and quick evolution of materials, associated with the need to build more and faster, forces a shift away from constructive systems with compatible materials and the disrespect of drying times (Silva, 2002). With the use of different materials and as they have different properties, different materials will react differently to the same solicitations, giving rise to differential movements. In wall systems the most common places for the appearance of render cracks due to differential movements, are in the correspondent zone of transition between the concrete (slabs or pillars) and the brickwork (Figure 2.5).
In these cases, two materials with very distinct behaviours when subjected to changes in hygrothermal load, are covered by a third material, typically a cement base material that does not have the resistance to accommodate the differential movements of support. Currently, despite not being common practise, a fibreglass mesh is sometimes used to prevent the appearance of these cracks in walls of new constructions.

2.2.2 Chemical reactions

Unlike the slight predictability that can occur in the appearance of hygrothermal cracks (Yuan and Wan, 2002), according to (Bonshor and Bonshor, 1995), (Shi et al., 2012) and (Chernin and Val, 2011) it is difficult to estimate if, where or when a crack, induced by a chemical reaction, can appear despite the existing models of the phenomenon. The chemical reactions in construction materials are associated with high damage to them; in some cases due to the chemical reaction by it-self since chemical reactions are expansive, which means that the products of the reaction are bigger than the reagents (as much as seven to eight times the original volume), or the chemical reactions can be the trigger to other reactions. For the first case the most common examples are the presence of hygroscopic salts in porous materials which can crystallize inside or outside the macrostructure (crypto-efflorescence or efflorescence respectively) and the Alkali-silica reaction, a reaction between the highly alkaline cement paste and reactive non-crystalline silica (Haddad and Smadi, 2004) (Figure 2.6); in the second case a good example is the carbonation reaction, which began in the early days of any cement base material leading to a reduction in pH and the consequent depassivation of the steel surface, therefore, the reinforcing steel is no longer protected from corrosion (Chernin and Val, 2011) (Figure 2.7).

These reactions, according to the work of (Bonshor and Bonshor, 1995) and (Cóias, 2006), despite being so destructive, can take years to reveal themselves and most of the time, when a crack shows it is too late for corrective measures. Taking into consideration these difficulties, a way to protect the structure from chemical factors is to prevent the entrance of salts, CO₂ or water inside the structure in order to delay their effect. This prevention begins in the design phase with the prescribed regulations, namely in the Portuguese case, to warrant the durability of concrete structures: the EN 206-1 (NP EN 206-1:2007, 2007) and the LNEC specification E464-2005 (LNEC, 2007), that divides the ambient in levels of aggressiveness and for each level establishes
minimum values that the concrete used in the structure needs to comply with. On the other hand, despite all regulations, the occurrence of these phenomena is fully dependent on other causes. In the design phase a very compact concrete with low permeability which retards the corrosion of reinforcement can be prescribed but if a crack appears due to temperature or a variation in support conditions, the process of corrosion begins earlier than what was idealized in the design process.

2.2.3 Structural and other movements

According to the authors (Paiva et al., 2006) and (Sousa and Silva, 2000), masonry walls with concrete blocks or bricks are the most common construction process in Portugal for façades or partition walls which, typically, lay in a slab or a beam made of reinforced concrete. The walls are built by juxtaposition of bricks and interconnection between them with a cement based mortar. The walls have an assured capacity to resist compression forces; however they have slight resistance to traction actions which lead to the appearance of cracks in walls.

![Figure 2.8 - Trees near foundations (left) and differential variation of moisture content of the foundation soil (right) (Sousa and Silva, 2000)](image)

![Figure 2.9 - Effect of tree roots in construction (Fix Your Water Damage, 2014)](image)

In the work of (Sousa and Silva, 2000), it is determined that cracking due to foundation movements is one of the most common phenomenon. These phenomena depend on the type of soil and structure and mostly how perceptively the foundations were designed. The worst case is the differential movements caused by heterogeneous soils or soils with different compactness (Figure 2.10 and Figure 2.11), different foundation types or different stress distributions in non-homogeneous soils or variations in the moisture content of clay soils (Figure 2.8). A particular case of this type of soils appears following the removal or the planting of trees near the site which tends to introduce under swelling or swelling respectively (Figure 2.9).
The authors (Paiva et al., 2006; Sousa and Silva, 2000) cite the excessive deformation of the support elements subjected to bending loading as another factor to take in consideration in the structural movements. The walls despite their low stiffness tend to oppose the progress of deformation but not enough to resist the deflection imposed by slabs and beams so, in cases of excessive deformation, besides the visible deflection, a crack in the coating and the wall can be noticed. One of the most common cases of cracking is the cantilevered slab, especially when the slab has a big span (Figure 2.12).

These deformations are controlled in the design process by the imposed limits, however these limits do not ensure a crack free wall. Although, as stated by (Paiva et al., 2006), the analysis of the crack configuration provides a hint to determine which mechanism has occurred, in summary the appearance of a crack depends on:

- Relation between span-height of walls;
- Quality and dimension of materials used in walls;
- Presence of openings in walls;
- Interaction between walls and other structural border elements or non-structural border elements.
In the work of (Veiga et al., 2009) there are other situations to take in consideration concerning differential movements related to the rehabilitation of old renders of historical or non-historical buildings. In these cases the difficulty is achieving coherence between the old support and the modern material that will substitute the old mortar that has become detached or disaggregated. These substitutions need to be well thought and carefully designed to prevent incorrect rehabilitation (Figure 2.13). As is referred in the work of (Cotrim et al., 2008; Veiga et al., 2009; Lanas and Alvarez, 2003), when cement base mortars are used in old buildings, a common practice in the early century, due consideration needs to be taken with respect to issues such as the shrinkage of the new mortar that can provoke a crack along the replacement or the low permeability that can induce instability or detachments.

![Figure 2.13 - Cracking of mortar due to bad application (Veiga et al., 2009)](image)

2.3 Numerical modelling of cracks in façades

In recent years, thanks to the development of computer software capable of numerical calculus, modelling a material or a structure with linear or non-linear behaviour became more accessible and a powerful help to save time in the designing process in various areas of engineering namely in mechanical, aerospace and in civil engineering (Terdalkar and Renci, 2006). The most common analysis is related to simple materials or isolated pieces in order to gain a better understanding of their behaviour when subjected to high levels of stress. These simulations can save money and time to the constructors and are an advantage in presenting possible methods of rupture that can normally be validated by experimental inspections which can lead to numerical models very close to reality (Demir et al., 2008; Terdalkar and Renci, 2006). On the other hand the study of real structures or parts thereof are not as developed, since each structure has its story and most of the time it is very difficult, without resorting to destructive tests, to know precisely which materials were applied in the structure. Given this difficulty, the modelling of real structures is limited to historical buildings or constructions of major importance, where the associated costs are worthwhile due to the high value of the structures, as can be seen in the works of (Ramos and Lourenço, 2004), (Betti and Vignoli, 2011), (Romera et al., 2008) and (Augusti et al., 2001).
Concerning the modelling in Civil engineering, concrete and reinforced concrete are the most modelled materials, not only because these are the most used materials in constructions but also because these are the materials of choice for structures subjected to adverse environments (Shi et al., 2012). Other materials with positive behaviour in adverse environments and object of multiple modelling are bricks with or without air gaps (Fathy et al., 2009).

More than modelling the mechanical properties, numerical models are used to predict the potential zones of high stress and deformation and therefore the cracking zones, which will influence the durability of the structure (Tang et al., 2013; Dilrukshi et al., 2010). The study of cracking influence has been simulated from different angles and subjected to different load cases with different models as can be seen in Error! Reference source not found..

Table 2.1 – Examples of numerical models of cracking

<table>
<thead>
<tr>
<th>Cause of cracking</th>
<th>Element</th>
<th>Photo/Illustration</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time varying thermal load</td>
<td>Masonry walls under a concrete slab that is exposed to solar radiation</td>
<td><img src="image" alt="Photo" /></td>
<td>(Dilrukshi et al., 2010)</td>
<td>Objectives: • identify the contribution of factors that cause cracking, such as the structural form of the wall; • the effect of different geometric and structural features such as openings and lintels Methodology: • homogeneous and isotropic masonry • five parameter Williams-Warnke failure criterion</td>
</tr>
<tr>
<td>Heat of hydration</td>
<td>Massive hardening concrete</td>
<td><img src="image" alt="Photo" /></td>
<td>(Schutter, 2002)</td>
<td>• The time dependent material behaviour is implemented by means of a Kelvin chain; • The cracking behaviour is implemented using a smeared cracking approach with non-linear softening behaviour • Hydration process is the driving force in the modelling approach</td>
</tr>
<tr>
<td>Hygrothermal loads</td>
<td>Early-age cement base materials</td>
<td><img src="image" alt="Photo" /></td>
<td>(Yuan and Wan, 2002)</td>
<td>• based on a micromechanical model and empirical formulas on the property development of young concrete; • The numerical model could account for the effects of hydration, moisture transport and creep</td>
</tr>
<tr>
<td>Moisture diffusion and shrinkage cracking</td>
<td>Cement base material (concrete)</td>
<td><img src="image" alt="Photo" /></td>
<td>(Tang et al., 2013)</td>
<td></td>
</tr>
</tbody>
</table>
In general, the simulations were time dependent and focused, as mentioned early, in concrete materials or in bricks. Despite all the simulations referring to situations that condition the service life of the structure, just a few analyse real structures or part of them as per the works of (Fathy et al., 2009) and (Dilrukshi et al., 2010). Other common characteristics between the simulations described were the definition of the location of an initial crack, the definition of failure criterion and

<table>
<thead>
<tr>
<th>Cause of cracking</th>
<th>Element</th>
<th>Photo/illustration</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical reactions</td>
<td>Chemical phenomenon - corrosion-induced</td>
<td>Cover concrete</td>
<td>Chernin and Val, 2011</td>
<td>• critical overview of existing empirical, analytical and numerical models for predicting the time to corrosion-induced cover cracking</td>
</tr>
<tr>
<td>Steel reinforcement corrosion</td>
<td>Reinforced concrete structures</td>
<td>Sanz et al., 2014</td>
<td>• Accelerated corrosion—to generate the cracks—with impregnation under vacuum with resin containing fluorescein—to enhance their visibility under ultraviolet light. • A model was developed to simulate the expansion of the oxide and finite elements with an embedded adaptable cohesive crack were used to describe concrete cracking</td>
<td></td>
</tr>
<tr>
<td>Structural movements</td>
<td>Single masonry element</td>
<td>Fathy et al., 2009</td>
<td>Four different load cases were used: • Case 1: imposed deflection of 10 mm in the mid-span of the beams with fourth degree parabolic distribution; • Case 2: settlement of 16 mm in only one axis of the columns; • Case 3: the settlement is applied to the two column axes coinciding with the expansion joints; • Case 4: is the same as case 3 but the settlement was applied to only one axis coinciding with an expansion joint</td>
<td></td>
</tr>
<tr>
<td>Structural and other movements</td>
<td>Overlaid slab panel under cyclic flexural loading</td>
<td>Slab panel with reinforced concrete</td>
<td>Benzerzour et al., 2014</td>
<td>Objectives: • investigated the origin and magnitude of internal stresses generated at the interface between an overlay and concrete substrate of a reinforced concrete slab subjected to flexural loading; • experimental work to measure the evolution of the structural capacity and the cracking behaviour of the two slab panels.</td>
</tr>
</tbody>
</table>
the definition of a virtual model to simulate the cracks as per the works of (Tang et al., 2013),
(Dilrukshi et al., 2010) and (Sanz et al., 2014) respectively. However, despite all the efforts to
predict the time of the first crack or the crack development, it was necessary to make
simplifications and assumptions in order to run these simulations.

2.4 Chapter conclusions

The phenomenon of cracking is one of the most influential parameters in the durability of structures
and therefore is the subject of several studies in order to better understand the phenomenon. It
is a complex process and normally it is an entanglement of different phenomena which makes
the modeling process difficult. The causes are normally connected to each other and only in a
controlled process it is possible to see each effect separately, sometimes with accelerated tests
(when possible) or for more accurate knowledge, real tests that can take months or years to
achieve a result.

Facing the difficulty to study each phenomenon separately, the numerical modeling becomes an
important tool to improve the knowledge that we have about these phenomena. It is cheaper and
quicker to obtain the results, but on the other hand each model needs to be experimentally
validated before conclusions can be obtained. Is very difficult to create a model that closely
resembles reality, it is necessary to make some assumptions and some simplifications as referred
early where the previously cited works just modeled one effect or load case with the necessary
simplifications.
3 Case studies

In order to have a term of comparison with the numerical models, five inspections were conducted in different types of buildings with different cracking causes. The inspections were performed with experts responsible for the construction project in collaboration with the supervising professors. The buildings were chosen in a project of cooperation between industry and university which will result in a master's thesis with the systematization of cracking in buildings running in parallel to this dissertation.

3.1 Office building – Oriente

3.1.1 Building characterization

This is an abandoned building located near Parque das Nações, Oriente (Figure 3.1). It was an office building attached to a mechanical workshop, abandoned few years ago and it is foreseen that it will be demolished.

![Location of the building](image)

*Figure 3.1 – Location of the building (Google, 2014)*

This building has two elevated floors with a ground floor with high ceiling when it was in use it was an auto dealer in one part and a workshop in the other connected with the main workshop in the back of the main building with a double ceiling. The main building can be divided in three modules (Figure 3.2) separated by expansion joints and with north orientation for the main façade of module one and east orientation for the main façade of module three. The main façades used to have a high percentage of glazed areas as shown in Figure 3.3 (left), but for unknown reasons, the windows have disappeared and some of the spans are filled with masonry as shown in Figure 3.3 (right).

It is a concrete gantry framing structure with voided slabs 40 cm thick (estimated) and pillars up to 50cm thick (average value estimated). The measures of the building are all estimations based on observation or comparisons based on photographs; the location of the pillars is also an estimation based in the analyses of photographs, thermal imagery and structural knowledge.
3.1.2 Building inspection

The inspection was carried out alone with a camera and an infrared thermal camera, just on the outside of the building as building is sealed to prevent inappropriate occupation. The infrared thermal camera were used to confirm the location of the pillars as no project are available.

During the inspection it has been observed that module 1 is where most of the cracks appear. In the other modules, the cracks appear in specific places and in the same places as in module 1 namely the platband. This way, in module 1 cracks were detected in the platband, above and below the roof slab of the first floor, two cracks aligned with the window sill of the first and the second floor, some cracks in the corner between the main façade and the west façade and some in the corner between the west façade and the back façade. In the Figure 3.4 the cracks are illustrated.
The most likely cause for the appearance of cracks in render is the transition of materials in the support (concrete to masonry) allied to stress concentrations in the corners of windows frames. In the corners of the façades, cracking is possibly the result of a stress concentration in the corners or a possible settlement in the rear corner.

3.2 “Pinhal da Charneca” - Cascais

3.2.1 Building Characterization

“Pinhal da Charneca” is a private condominium of fifty twin-houses divided in two blocks (Figure 3.5 - right), located in Aldeia de Juzo near Cascais, 2 km away from the ocean (Figure 3.5 - left).

Each house has an elevated floor and a pitch-roof and façades with variable orientation, depending on each house. In structural terms, the houses have a gantry framing structure, with
variations of the roof height and step-down areas in the façade (Figure 3.6 left). Close to each house there is a parking spot for one car without soil reinforcement (Figure 3.6 right).

![Figure 3.6 – Twin houses (left); parking spot near the house (right)](image)

3.2.2 Building inspection

The inspection was conducted in the presence of the two teachers responsible for this dissertation, a co-worker which is developing a master thesis in patterns of cracking and three engineers from PTCP. To help the comprehension of the on-site inspection an infrared thermal camera, a camera and a crack ruler were used. The use of these tools was a complement to the on-site inspection, with the crack ruler and the camera as the most used and the infrared thermal camera used only to clarify some doubts, not always with success.

The cracking patterns vary, depending on the orientation of the façade, the type of façade and the surrounding conditions, however there are a few that are constant in almost every house. The most common are in the connection zone between different materials (especially near the roof) (Figure 3.7) and multiple cracks due to ground settlements (Figure 3.8). Some of this has given rise to new and disorder patterns of cracks caused by the intense hygrothermal variations and the proximity to the ocean.
The largest cracks measured have 4mm width, located in a corner of a house and may have appeared due to ground settlement (Figure 3.9 left); and a 3mm width in a general settlement located in the entrance of a house (Figure 3.9 right). The width of the remaining cracks varies between 0.2mm and 1.4mm.
3.3 Social housing quarter of Adroana – Cascais

3.3.1 Building characterization

The social housing quarter of Adroana is a complex of forty buildings, near the Estoril Racing Circuit, which were concluded in 2005 (Figure 3.10).

All the buildings have the same architecture with a dominant North-South orientation (twenty-nine of forty) to the main and posterior façades and the remaining eleven of forty have a West-East orientation (Figure 3.10 right).

Each building has a gantry framing structure with four elevated floors and a plane non-accessible rooftop. Each floor has two fractions, a T3 and a T2 and a stairwell in the middle. The walls are double-twine masonry of ceramic hollow bricks with eleven centimetres (cm) width and an air gap of five centimetres, and render in both sides (1.5x11x5x11x1.5 cm).
3.3.2 Building inspection

The inspection was conducted in the presence of a co-worker which is developing a master thesis in patterns of cracking, and a representative of the construction company. To help the comprehension of the in site inspection, a hygrometer, an infrared thermal camera and a crack ruler were used.

As the buildings are similar, the cracking patterns tend to be similar too. Most of the cracks are located in the corners of the windows frames (Figure 3.11a), wall-corners (Figure 3.11b), the upper part of the transitions of cladding materials (Figure 3.11c) and in the balconies and walls above (Figure 3.11d).

![Cracking patterns: (a) windows frames, (b) wall-corners, (c) transitions of coating material, (d) balcony and wall above](image)

Other than the cracking due to the changing of cladding materials which may be caused by the difference in thermal stress due to different materials with a large difference in thermal conductivity, all others are originated by structural forces; stress concentration occurs in the
corners of windows frames, in the wall-corners and gravitational forces and large deformations occur in the balconies.

During the inspection it was also verified that all the façades with north orientation have problems with moisture, presenting larges areas on the façade with green or black stains (Figure 3.12). This, in combination with cracks, accelerates the degradation of the structure and degradation of the quality of life for the residents.

![Humidity stains in north façades](image)

**Figure 3.12 – Humidity stains in north façades**

### 3.4 “Quinta de Santo António” - Miraflores

#### 3.4.1 Building characterization

The complex of buildings “Quinta de Santo António” is a group of four-twin buildings next to the redesigned urban park with the same name in Miraflores. The complex consists of four buildings with West-East orientation for the main façades with a gantry structure of eight elevated floors in the west façade and eleven elevated floors in the east façade with one parking floor underground and another at ground level from the east side (Figure 3.13). The construction was concluded in 2005 and the first cracks began to appear at the date of conclusion of the construction.

![Location of “Quinta de Santo António”](image)

**Figure 3.13 – Location of “Quinta de Santo António” (Google, 2014)**
3.4.2 Building inspection

The inspection was conducted in the presence of a co-worker and two representatives of the construction company. To help the comprehension of the in site inspection, an infrared thermal camera, a crack ruler and the maps of cracks of previously inspections carried out by the construction company were used (Figure 3.14). In these maps the cracks that appear since the end of the construction are illustrated and, in the course of this inspection some updates were performed.

During the inspection two blocks and three fractions in each block were visited. The inspection reveals that the cracks are almost recurrent and do not depend on the fraction despite there being some cracks appearing only in some fractions. In general, there are cracks in all divisions; we will focus on the cracks in the kitchens and living rooms.

In the kitchens the most common cracks are near the microwave and oven (Figure 3.16a) and above the kitchen worktops repeated for each fraction visited, but we also observed in some kitchens, cracks that pass through different materials (Figure 3.16a), cracks in the connection between different materials (Figure 3.16b) and in the corners where there are possibly changes in the brick alignment (Figure 3.16b).
Figure 3.15 - Common cracks in kitchen: a) next to microwave and oven; b) in the connection between materials;

Figure 3.16 – Common cracks in kitchen: a) through different materials; b) transitions of brick alignments

In the living room, the recurrent cracks found are in the wall corners (Figure 3.17a) and near windows frames, corners and under the window (Figure 3.17b). The first type of cracks appear, possibly, due to a deficient change in brick alignment or a bad connection with different materials and the second type is caused by the large deflection of the structure.

Figure 3.17 – cracks in living room: a) wall corners; b) windows frame, corner (above), below the parapet (below)
As mentioned above all the fractions visited show multiple cracks, although most of them are stabilized some new cracks will appear as time goes by. The construction company requested a study to understand the principal causes; the study concluded that the slabs are too thin leading to excessive deformation of the structure and inducing the appearance of most of the cracks.

3.5 High school *Dr Solano Abreu* - Abrantes

3.5.1 Building characterization

The high school *Dr. Solano Abreu* located in *Abrantes* is a renovated school with the works being concluded in 2011 (Figure 3.18).

![Figure 3.18 – Location of the high school Dr Solano Abreu: a) before renovation b) after renovation (Google, 2014)](image)

This is a continuous building, after the renovation work, with three elevated floors and two underground floors. Before (Figure 3.18a), the school had two separated buildings but nowadays these buildings are connected and have been expanded in height on the right side and a new block was added to the main façade (Figure 3.18 and 3.18). These parts are separated by structural joints, which guarantee an isolated function of each part by itself.
3.5.2 Building inspection

The inspection was conducted in the presence of a co-worker and a representative of the construction company. To help the comprehension of the on-site inspection a crack ruler was used. The atmospheric conditions made it inviable to make perfect use of the infrared thermal camera.

In general, the cracks appear mostly in the new buildings and in the connection between the new and the previously existing buildings. In the new buildings the cracks appear due to settlements (Figure 3.20a), excessive loads, incompatibility between materials (Figure 3.20c) or bad application of materials (Figure 3.20b) whilst in the connection between parts, the incompatibility of materials or bad design of the expansion joints are the most probable causes.
It should be noted that the most cracked zones are the newest ones, particularly a new part in the main building that is all new and has the biggest problems. The cracks in this part follow a pattern that leads to excessive deformations in the structure due to loads (library overload) that were not appropriately defined in the design (most probable cause) (Figure 3.21).
3.6 Cases to model

After the inspections it was chose to model the buildings described in 3.1 (Office building) and 3.3 (Social housing quarter of Adroana). These choices were made based on the possibility of, in the first instance, model the building or part of it and to introduce in the model actions similar to those which caused cracks in the buildings; secondly, the possibility to compare the results vs. the reality and afterwards provide feedback based on this comparison.

The buildings in chapter 3.2 (Pinhal da Charneca) were not chosen to be modelled, in the first case because some of the cracks developed after the appearance of a first crack and are due to the interaction of hygroscopic salts in structure; other cracks appear due to ground settlement which involves modelling the behaviour of the soil or to quantify this settlement in an equivalent way. The second building, described in 3.4 (“Quinta de Santo António”), has already been modelled and our work will not introduce additionally relevant information. The building described in 3.5 was not model due to a lack of the design project, despite have an interesting part to model concerning variations in the overload.

In Table 3.1 a synthesis of this chapter is made with the major cracks described, principal reason, framing in a category and if it will be model or not and why.
Table 3.1 - Synthesis of the major cracks observed in the inspected buildings

<table>
<thead>
<tr>
<th>Building</th>
<th>Major cracks</th>
<th>Cause(s)</th>
<th>picture</th>
<th>Category¹</th>
<th>Modelled</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Building – Oriente</td>
<td>Connection between platband and slab</td>
<td>Differential movements of the substrate</td>
<td>SM HL</td>
<td>Yes</td>
<td>A well-known phenomenon which frequently occurs.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corner of the façade</td>
<td>Different temperatures on perpendicular façades</td>
<td>SM HL</td>
<td>Yes</td>
<td>The analysis of these cracks was tested in a global three-dimensional building.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical cracks</td>
<td>Differential movements of the substrate</td>
<td>SM HL</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Pinhal da Charneca” – Cascais</td>
<td>Connection zone between different materials</td>
<td>Differential movements of the substrate</td>
<td>SM HL CR</td>
<td>No</td>
<td>This problem was evaluated in another model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlements</td>
<td>Ground settlements locally and sometimes in large scale</td>
<td>SM</td>
<td>No</td>
<td>It is necessary to introduce the behaviour of the soil and there is no information available</td>
<td></td>
</tr>
<tr>
<td>Social housing quarter of Adroana - Cascais</td>
<td>Corner of windows frames</td>
<td>Stress concentration</td>
<td>SM</td>
<td>Yes</td>
<td>Common situation majorly influenced by stress which can be easily introduced in a numerical model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wall-corners</td>
<td>Stress concentration</td>
<td>SM AP</td>
<td>No</td>
<td>This situation is majorly influenced by the mode of application of the coating material</td>
<td></td>
</tr>
</tbody>
</table>

HL: Hygrothermal Loads; SM: Structural and other Movements; CR – Chemical Reactions; AP: Application Problems
Table 3.1 - Synthesis of the major cracks observed in the inspected buildings (cont.)

<table>
<thead>
<tr>
<th>Building</th>
<th>Major cracks</th>
<th>Cause(s)</th>
<th>picture</th>
<th>Category</th>
<th>Modelled</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social housing quarter of Adroana - Cascais</td>
<td>Transition of cladding material</td>
<td>Differential heat transfer; Transition of floors;</td>
<td></td>
<td>HL SM</td>
<td>No</td>
<td>This problem (partially) was evaluated in another model.</td>
</tr>
<tr>
<td></td>
<td>Balconies and wall above</td>
<td>Deformation due to self-weight; excessive loads in balconies</td>
<td></td>
<td>SM</td>
<td>Yes</td>
<td>This phenomenon was analysed indirectly by introducing a different overload in the balconies</td>
</tr>
<tr>
<td>“Quinta de Santo António” - Miraflores</td>
<td>Kitchen – vertical cracks</td>
<td>Deficient connection between materials; Large deformation of the structure</td>
<td></td>
<td>SM</td>
<td>No</td>
<td>This building already has a numerical model and this work will not introduce additional relevant information</td>
</tr>
<tr>
<td></td>
<td>Living room – near Window frames</td>
<td>Large deflection of the structure</td>
<td></td>
<td>SM</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Living room – wall corners</td>
<td>Deficient change in brick alignment; Bad connection between materials</td>
<td></td>
<td>SM</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>High school Dr Solano Abreu - Abrantes</td>
<td>Bad application of the materials</td>
<td></td>
<td></td>
<td>AP SM HL</td>
<td>No</td>
<td>Due to the lack of design project it was not possible to model some of these situations.</td>
</tr>
<tr>
<td></td>
<td>Incompatibility between materials</td>
<td></td>
<td></td>
<td>SM HL</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Excessive deformations due to overloads</td>
<td></td>
<td></td>
<td>SM</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
4 Numerical modelling

Described in this chapter are the numerical models of the buildings mentioned in Chapter 3 using the programs described in chapter 4.1 and the methodology described in the chapters 4.2 to 4.6. This Chapter establishes the relation between what was seen in the inspections and the results presented by the simulations in the chapters 4.7, 4.8 and 4.9. Whenever possible a repair solution or suggestions for mitigation of the cracking phenomenon are presented.

4.1 The software used

A commercial software of finite elements modelling, Ansys Workbench 14.5® (Figure 4.1), the most visual interface of the Ansys package, was used to perform the simulations. This interface enables the user to get a better control of the systems used, in the definition of the mesh, forces and supports and quickly retrieves the results. Other interfaces of the Ansys package are not so user friendly and require a mastery of the command line language in order to obtain fast results.

The geometric models were created in a commercial software of solid creation, Solidworks 2013, as the drawing in Ansys interface is very complex and limited when compared with the software used.

Before starting the simulations it is necessary to prepare the ambient of simulation where the geometric models are included, the types of simulation intended and the materials used. Described in the next sub-sections are the steps needed to perform the simulations.

![Figure 4.1 – Main window of Ansys Workbench 14.5](image)

4.2 Types of analysis

The first step of a simulation is defining the different types of the simulations which are intended. In the main window of the program, Figure 4.1, there is a list of analysis systems (Figure 4.2), each one for a specific analysis, from where the wanted systems can be selected by double click
or just click and drag to the “Project Scheme” (Figure 4.1ii). The number of stand-alone systems will depend on the intended types and when load combinations are introduced, the number of stand-alone systems depends on the number of variables of the load combinations. During a structural analysis with more than one load, not all loads contribute in the same way so it is necessary to combine the loads with load combinations defined in rules and regulations such as the NP EN 1990:2009 (Eurocódigo 0 - Bases para o projecto de estruturas, 2002). In order to later introduce load combinations in the model it is necessary to previously create a stand-alone system for each structural load which guarantees that firstly each load is analysed separately and only combined at the end.

Figure 4.3 shows the global look of the Project Schematic with a system for steady-state thermal analysis and three static structural analysis; thermal stress, self-weight and variable actions. The blue arrows represent the sharing of information between the different stand-alone systems.

4.3 Engineering Data

After defining the types of simulation it is necessary to define the materials to apply to each part of the model by entering the Engineering Data menu of the stand-alone system A. This is where all the materials selected for the project are listed and, if necessary, it is possible to perform a quick edition of the properties without interfering with the global library or obtain a quick view of the properties of the selected materials.
When a new project starts, the list of project materials has a default material that can be deleted before new materials are added. To add materials it is necessary to go to the global library, by clicking on the bookshelf icon as shown in Figure 4.4. This is a set of materials available to add to the project, major materials that come programmed by the developer which can be edited and saved; however the program enables the user to create new materials with the desired properties and save them to the global library for future use.

Figure 4.4 – Main window of Engineering Data

For this work new materials were created based on experimental works or product specification catalogues in order to have more control over the properties and the behaviour of the materials. The properties of the materials were chosen in such a way as to guarantee an elastic linear behaviour of each material, with thermal behaviour and the making it possible for the program to calculate the self-weight of the materials. This way the properties introduced are:

1. Density;
2. Isotropic secant coefficient of thermal expansion:
   a. Coefficient of thermal expansion;
   b. Reference temperature.
3. Isotropic elasticity:
   a. Derive from: Young’s modulus and Poisson Ration;
   b. Young’s Modulus;
   c. Poisson ratio;
   d. *Bulk modulus;
   e. *Shear modulus.
4. Tensile yield strength;
5. Compressive yield strength;
6. Tensile ultimate strength;
7. Compressive ultimate strength;
8. Isotropic thermal conductivity.

After defining all the materials and saving them in the global library for further projects, it is necessary to add the desired materials to the project materials list. In order to do this it is only necessary to click in the “+” sign in front of each material and when all the materials are added click the “Return to project” icon to return to the main window.

4.4 Geometry

As mentioned earlier, the program Solidworks 2013® was selected to build the geometries as it is a powerful tool and a reference where creation of tridimensional geometry is concerned.

The model is made in separate parts, thus guaranteeing the interdependency between the different parts of the building. The final model is an assembly of the parts (Figure 4.5) that can be exported directly to Ansys Workbench or exported to a file (STEP 2014 in this work) which is compatible with Ansys and results in less computer memory requirement during the simulation.

![Figure 4.5 – An assembly in Solidworks®](image)

Returning to the main window of Ansys Workbench to import the geometry file, right click in the sub-menu “Geometry” of box A, pass above “Import Geometry” select “Browse…” and select the file previously created if this is the first simulation with that geometry otherwise when using a previously used geometry just select from the recently used geometries that appear in the box (Figure 4.6a); if the selection is a valid geometry file, a green check appears indicating that the field of geometry is ready for simulation (Figure 4.6b).
4.5 Model

With the materials defined and the geometry imported it is necessary to assign the materials to the parts, define the boundary conditions and assign the loads to the model. After double clicking on the Model menu, a new window will open (Figure 4.7a) where these last steps will be carried out. As the Ansys Workbench is more visual it is easy to know what is missing or what requires attention. So, as shown in Figure 4.7b (Outline), the sub-menus that have a blue question mark mean that some information is missing; for example in the sub-menu Geometry, the linking between the materials and the parts is missing. The yellow thunder appears when a context needs to be solved or updated; e.g. the sub-menu Mesh that needs to be created before the simulation starts.

The boundaries and loads are created on each submenu related to each subsystem. The first submenu TEMP (A5) relates to the thermal loads, three convection environments: inside the building except in the roof slab, outside the building and in the inner side of the roof slab (when applied). The output of this analysis (A6) is the temperature distribution in the building that will be the input to the structural subsystem TEMP (B5).

In the three structural subsystems (B5, C5 and D5) all the supports are equal: in the pillars, bottom of the walls (when applied) and in the side of the building that connects with the rest of the building. The inputs vary, depending on the subsystem; in the TEMP structural subsystem (B5) the input is the body temperature that comes from A6 as previously mentioned; in the self-weight subsystem (C5) the input is the Standard Earth Gravity which combined with the defined Density of each material, will calculate the weight of the structure. In certain models, for each pillar, a vertical force representing the structural weight of the structure above the pillar was introduced.

In the subsystem of the variable actions (D5) a vertical distributed load in each slab, depending on the use of the structure where the values vary from $2 \text{ kN/m}^2$ for the residential buildings, $3 \text{ kN/m}^2$ for the office buildings and $5 \text{ kN/m}^2$ to the balconies, in accordance with Eurocode 1 (Eurocódigo 1 - Acções em estruturas, 2002), was introduced. In terms of outputs of the three
structural systems (B6, C6 and D6) and in the load combinations, the Total Deformation of each isolated system was analysed. With the load combinations the Total Elastic Strain Intensity and Vector Principal Elastic Strain was also analysed in order to determine the zones more propitious to crack.

![Figure 4.7 – Multiple: a) Main window; b) Outline detail before simulation c) – Outline detail after simulation](image)

4.6 Load combinations

As referred early in section 4.2 the quantification of each action is made by load combinations defined in international regulations (namely the Eurocode 0 (Eurocódigo 0 - Bases para o projeto de estruturas, 2002)) and based on the relevance of each action in a certain load combination which is reflected in the probability of some action acting at the same time as the others. As the main objective of this work is the study of the cracking phenomenon, the characteristic (rare) combination was selected, taking into account that a crack is a permanent (irreversible) local damage. This combination can be written according Equation (4.1):

$$
\sum_{i} G_{i} + Q_{k,1} + \sum_{j>1} \psi_{0,j} Q_{k,j} \quad (4.1)
$$

where:

- $G_{i}$ – permanent actions;
- $Q_{k,1}$ – leading variable action (VA) with characteristic value;
- $\psi_{0,j} Q_{k,j}$ – other variable action with combination value

and $\psi_{0,j}$ can vary according to Table 4.1:

<table>
<thead>
<tr>
<th>temperature</th>
<th>vertical forces in slabs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In order to study the influence of the actions in the appearance of cracks, two load combination types were created, one with the temperature and the other with the distributed force in the slabs as the leading variable actions.

To create a load combination just right click on Model, Insert and select Solution Combination (Figure 4.8a); a new submenu will appear where the structural subsystems and the coefficient of combination according to Equation (4.1) and Table 4.1 (Figure 4.8b) are added. The output solution, as previously mentioned, were the same of each structural subsystem plus the Elastic Strain Intensity and the Vector Principal Elastic Strain in order to make it possible to compare the results against the inspections that were carried out.

![Solution Combinations](image)

Figure 4.8 – Solution Combinations: a) Procedure to add a new load combination; b) global aspect of each Solution Combination

In the next sub-sections, four simulations that encompass the cracking problems described in Chapter 2 except the cracks due to chemical reactions are detailed. The results will be presented following the order of the subsystems created and modelled: thermal analysis, thermal structural analysis, self-weight analysis and variable action on slabs analysis.

### 4.7 General example of a connection between the platband and the structure

In this example a part of a structure, common amongst the constructed buildings in Portugal and seen in the building inspected at Oriente, is illustrated, as can be seen in Figure 4.9, where a crack in the transition of materials usually appears.

As a common structure and there is no project available for the building inspected, a part of a rooftop corner with a parapet of seventy five centimetres height and an equal length of four meters in both directions and a floor-to-ceiling of two point six meters was adopted. As the main objective of this model is to study the appearance of cracks in the transition of materials the structure is without openings in the façade. The model is comprised of a slab of fifteen centimetres thickness, a corner square pillar of twenty centimetres, brickwork of fifteen centimetres thickness and an external layer of mortar of one point five centimetres thickness.
Figure 4.9 – Model of a rooftop corner

For this model, as no project is available, a concrete C20/25 in the structural part, a masonry of ceramic hollow bricks and a dry-mortar Fassa Bortolo KC1 (Fassalusa Lda., 2011) composed by hydrated lime, Portland cement, selected sands and additives to improve workability and adherence, was adopted. The properties of all the materials are described in Table 4.2.

<table>
<thead>
<tr>
<th>properties</th>
<th>units</th>
<th>concrete (C20/25)</th>
<th>render</th>
<th>masonry</th>
</tr>
</thead>
<tbody>
<tr>
<td>density [kg/m³]</td>
<td></td>
<td>2500</td>
<td>1600</td>
<td>900</td>
</tr>
<tr>
<td>young’s modulus [GPa]</td>
<td></td>
<td>30</td>
<td>3</td>
<td>6.2</td>
</tr>
<tr>
<td>poisson’s ratio [-]</td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>coefficient of thermal expansion [1/°C]</td>
<td>1.00E-05</td>
<td>1.35E-05</td>
<td>5.50E-06</td>
<td></td>
</tr>
<tr>
<td>isotropic thermal conductivity [W/m·°C]</td>
<td>0.7</td>
<td>0.55</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>reference temperature [°C]</td>
<td></td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>tensile yield strength [MPa]</td>
<td></td>
<td>2.2</td>
<td>1</td>
<td>0.04</td>
</tr>
<tr>
<td>compressive yield strength [MPa]</td>
<td></td>
<td>13.3</td>
<td>2.5</td>
<td>3</td>
</tr>
</tbody>
</table>

As the main objective was to study the effect of a thermal load in the structure, in this model only a thermal load introduced by a convection heat transfer was applied and the effect of the self-weight was taken into account as it is a permanent load in every structure. Both loads were analysed separately and combined in a single load combination where both loads contribute equally and without mitigation.

The parameters introduced to calculate the convection heat transfer on the façades and slabs, air temperature and film coefficient (inverse value of thermal resistance), are described in Table 4.3.

<table>
<thead>
<tr>
<th>ambient</th>
<th>film coefficient [W/m²·°C]</th>
<th>air temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>outside walls and roof</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>inside walls</td>
<td>7.6923</td>
<td>25</td>
</tr>
<tr>
<td>inside - roof</td>
<td>5.8824</td>
<td>25</td>
</tr>
</tbody>
</table>
Finally, to perform the structural analyses the following support conditions were applied: two sliding restraints in both sides of the model and a simple support in the bottom as shown in Figure 4.10.

![Figure 4.10 – Supports of the model](image)

In this simulation two different types of contact were introduced: between the masonry and the structure a “Frictionless contact” was introduced enabling the surfaces to slide freely and, depending on the loads, open or close contact between surfaces. The remaining contacts between the mortar and the brickwork and the mortar and the concrete were defined as “Bonded contact” which means that the elements are not allowed to separate or slide (Figure 4.11). In the next sub-sections the results for each separate analysis and the load combination are illustrated.

![Figure 4.11 – Illustration of the different types of contact](image)
4.7.1 Thermal analysis

In the Figure 4.12 the distribution of the temperature for the structure in the conditions previously referred is illustrated.

It is important to notice that the maximum temperature calculated in the model is higher than the one introduced, however, it is possible to see in Figure 4.12 that this value corresponds to a single point with no interference in the global results arising from a miscalculation of the numerical model.

![Temperature distribution](image)

**Figure 4.12 – Temperature distribution**

4.7.2 Thermal structural analysis

In this analysis, the structural response for the temperature distribution Figure 4.12 and with the restraints mentioned previously is illustrated. Figure 4.13 illustrates the “Total deformation” with an amplification of the deformed shape and the undeformed wireframe.

Analysing the results it is possible to see the symmetry of the deformed shape and the rotation of the masonry with regard to the slab. The maximum value occurs in the bottom of the masonry with a deformation of 8.87 millimetres.
4.7.3 Self-weight analysis

In this sub-section the effects of the self-weight only were analysed; the deformation illustrated in Figure 4.14 is similar to the deformation illustrated in Figure 4.13 even the maximum value occurs in the same place although the value is higher (11.65 millimetres) than the previous value (8.87 millimetres). The deformed shape is also symmetric and has a deflection on the farther slab corner, about 4 millimetres.

4.7.4 Load combination

In this simulation the load combination is a particular example of equation (4.1) where $Q_{k.1} = T$ and there are no other variable actions. So it can be written as Equation (4.2):
\[ \sum_{i} G_i + T \]  

(4.2)  

As both deformed shapes illustrated in sub-sections 4.7.2 and 4.7.3 are similar, the deformed shape of the load combination have the same configurations with the rotation of the masonry and the maximum deformation occurring in the bottom of the masonry with the value of 20.38 millimetres.

![Figure 4.15 – Total deformation for the load combination](image)

It is interesting and significant to notice that the deformation due to the self-weight is approximately 57% of the total deformation. In other words, self-weight has an important contribution to the deformation and the consequent appearance of cracks. In the next sub-section an analysis in order to identify the zones more prone to crack was carried out.

### 4.7.5 Cracking analysis

The identification of the zones prone to crack was made based on the evaluation of the “Elastic Strain Intensity” (Figure 4.16) and the “Vector Principal Elastic Strain” (Figure 4.17). In the first figure it is possible to detect the zones where the strain is higher which is associated with higher deformations whilst in the second figure it is possible to detect the zones tensioned and the compressed zones (red arrows and blue arrows respectively). Figure 4.18 it is illustrated an overlapping of a photo with the cracks highlighted and the vector principal elastic strain, being visible the cracks align with the tensioned zones.
Analysing the figures, it is possible to define traction zones and disregarding the values near the sliding restraint where the results are affected by the support, it is possible to define a zone where
the occurrence of a crack is highly probable. This zone extends over the edge of the pillar and the slab with a higher probability in the interception of the pillar and the slab.

Taking into account the symmetry, a façade was analysed and four zones where the render should be reinforced with a glass fibre net (or similar) were defined (Figure 4.19). The most critical zone, the intersection between the pillar and the slab (orange box), extends by fifty five centimetres centred in the slab axis with a length of one point seven metres. The green box aligns with the slab with a height of thirty centimetres centred in the axis of the slab. The yellow box is aligned with the axis of the pillar and has a width of thirty five centimetres, fifteen over the pillar and the other twenty over the masonry. The blue box relates to the change of direction of the tensions (slab to pillar) and usually it is a zone without reinforcement; however, as can be seen in Figure 4.16, Figure 4.17 and Figure 4.19 it is a traction zone. This zone is a square shape of seventy centimetres.

![Figure 4.19 – Reinforcement zones of the render](image)

### 4.8 Office building – Oriente

The dimensions of the building were estimated based on photos and comparison to other buildings and other elements. In general the model seeks to translate what the building was during its use although it is not possible to determine exactly the back of the building and due to the doubt a conservative approach was adopted. Figure 4.20 illustrates the geometrical model used in the numerical model.
In order to model a voided slab without introducing all the single moulds, which would make the simulation longer and heavier, zones of solid concrete near the pillars and all around the slab with softened up zones in the middle, were defined. The softened up zones have an equivalent height \( h_{e,cal} \) given by Equation (4.3) (Araújo, 2006):

\[
h_{e,cal} = \left( \frac{12I}{S} \right)^{1/3}
\]  

(4.3)

where \( I \) stands for the inertia of the softened zone and \( S \) the distance between the ribbings. In this case a mould of FERCA 800 (FERCA, 2014) to a total height of four hundred millimetres was used which leads to an equivalent height of two hundred and sixty millimetres.

As only a visual inspection was carried out and as there is no project information available, the properties of the materials for this building were adopted as a concrete C20/25, a Fassa Bortolo render KC1 (Fassalusa Lda., 2011) and a masonry of fifteen centimetres thickness. These properties are listed in Table 4.4.

<table>
<thead>
<tr>
<th>properties</th>
<th>units</th>
<th>concrete (c20/25)</th>
<th>render</th>
<th>masonry</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>( [kg/m^3] )</td>
<td>2500</td>
<td>1600</td>
<td>900</td>
</tr>
<tr>
<td>young's modulus</td>
<td>( [GPa] )</td>
<td>30</td>
<td>3</td>
<td>6.2</td>
</tr>
<tr>
<td>poisson's ratio</td>
<td>([-)]</td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>coefficient of thermal expansion</td>
<td>( [1/°C] )</td>
<td>1.00E-05</td>
<td>1.35E-05</td>
<td>5.50E-06</td>
</tr>
<tr>
<td>isotropic thermal conductivity</td>
<td>( [W/m°C] )</td>
<td>0.7</td>
<td>0.55</td>
<td>0.34</td>
</tr>
<tr>
<td>reference temperature</td>
<td>([°C] )</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>tensile yield strength</td>
<td>( [MPa] )</td>
<td>2.2</td>
<td>1</td>
<td>0.04</td>
</tr>
<tr>
<td>compressive yield strength</td>
<td>( [MPa] )</td>
<td>13.3</td>
<td>2.5</td>
<td>3</td>
</tr>
</tbody>
</table>

As in the first case study, thermal loads as convection effects were applied, with the following properties described in Table 4.5.
As supports for the structural analyses the pillars were fixed by a *Fixed Support* and the walls simply supported by a *Remote displacement* equal to zero. In the zone of connection with the remaining building a sliding restraining was adopted, applied to the model by a *Frictionless Support*. Regarding the connection between the different elements the same strategy as described in sub-section 4.8, was applied; *Frictionless Contact* between masonry and concrete and the other contacts as *Bonded*.

In this model a simulation of a full tridimensional building with a refined mesh was attempted, however, the simulation was taking too long to process. This partially invalidates the possibility of introducing singularities or the test of different solutions in a short time. Thus a mid-term refinement was adopted, making it possible to obtain reliable results and within reasonable simulation time. The results are presented in the next sub-sections with a comparison of results between the individual and the load combinations in Table 4.6.

### 4.8.1 Thermal analysis

The Figure 4.21 illustrates the temperature distribution to the previously mentioned conditions. The difference of 2°C from the maximum temperature applied by convection effects and the temperature calculated by the program stem from numerical miscalculations in the mesh, solved by refinement of the mesh; however, as referred, this solution introduces a time lag which does not translate into improved results. The points where these values occur are a minority, appearing in some edges and do not have an interference in the global results due to their one-off nature.

![Figure 4.21 – Temperature distribution (Oriente)](image-url)
4.8.2 Thermal structural analysis

Figure 4.22 illustrates the deformation due to the distribution of temperature as shown in Figure 4.21. An enlarged view of the deformed shape helps to have a better understanding of the deformation due to temperature. From the illustration it is possible to see that the maximum deformation occurs in the platband and despite all of the platband having the same temperature, the zones near the support have a lower deformation than the farther zones.

![Image of thermal structural analysis](image)

*Figure 4.22 – Total deformation due to temperature (Oriente)*

4.8.3 Self-weight analysis

The Figure 4.23 illustrates the deformed shape due to self-weight. As expected the maximum deformation occurs in the middle of the larger span, whilst the walls near the bottom have zero deformation and in the top there is little deformation due to the deformation of the slabs.

Comparing the maximum values, despite occurring in different places, the maximum deformation due to self-weight (8.323e-4 m) is nearly forty percent (40%) of the maximum deformation due to temperature (2.069e-3 m).
4.8.4 Variable actions on slabs analysis

In Figure 4.24 the total deformation due to the variable action in slabs defined in sub-section 4.5 is illustrated. The deformed shape is similar to the previous (Figure 4.23) with the maximum value occurring near the same place. However, the maximum value of deformation is a third of the maximum deformation calculated for the self-weight and an eighth of the deformation due to temperature.

4.8.5 Load combinations

As defined in sub-section 4.6, two different load combinations were selected, one with the temperature as the leading action (LC1) and the other with the variable action in slabs as the leading action (LC2). In Figure 4.25 and 4.26 the deformed shapes for these two load combinations with the location of the maximum value are illustrated.

At first sight, the location of the maximum value in both of the load combinations is approximately the same as the one for the deformation due to self-weight and variable actions in slabs although these maximum values are lower than the thermal deformation. Still, the load combination with the temperature as leading action is the most severe combination with a maximum value to the total deformation of two point twenty four millimetres (2.24mm) whilst in the load combination LC2 the maximum value is one point seventy four millimetres (1.74mm).
Analysing the deformation in the building and comparing the figures 4.25 and 4.26, it can be seen that for LC1 the deformations are high throughout the façade whilst in LC2 they are located nearest the platband which leads to the identification of LC1 as the most severe and the load combination requiring further analyses.

4.8.6 Results summary

Summarized in the following table (Table 4.6) are the results illustrated in the sub-sections above and the location of the maximum and the minimum values. As seen in the previous sub-section, the LC1 has the highest deformation and a global behaviour compatible with the cracks in the building (Figure 3.4). In the next sub-section this analysis was complemented with other results and illustrations to confirm this conclusion.
Table 4.6 – Results summary for the office building at Oriente

<table>
<thead>
<tr>
<th>analysis</th>
<th>Total Deformation (m)</th>
<th>Min</th>
<th>Where</th>
<th>Max</th>
<th>Where</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal stress analysis</td>
<td></td>
<td>0</td>
<td>Concrete</td>
<td>2.069E-3</td>
<td>Render</td>
</tr>
<tr>
<td>Self-weight stress analysis</td>
<td></td>
<td>0</td>
<td>Concrete</td>
<td>8.323E-4</td>
<td>Render</td>
</tr>
<tr>
<td>Variable action in slabs analysis</td>
<td></td>
<td>0</td>
<td>Concrete</td>
<td>2.656E-4</td>
<td>Concrete</td>
</tr>
<tr>
<td>LC1</td>
<td></td>
<td>0</td>
<td>Concrete</td>
<td>2.240E-3</td>
<td>Masonry</td>
</tr>
<tr>
<td>LC2</td>
<td></td>
<td>0</td>
<td>Concrete</td>
<td>1.739E-3</td>
<td>Masonry</td>
</tr>
</tbody>
</table>

LC1 – Load combination 1 – temperature as leading action; LC2 - Load combination 2 – variable action in slabs as loading action

4.8.7 Cracking analysis

Contrary to the first analysis (sub-section 4.7.5) in this analysis the zones prone to cracking are not so easily detected with the analysis of the Vector Principal Elastic Strain (Figure 4.27) as was done in the chapter previously mentioned.

In Figure 4.27 it is possible to detect some tensioned zones and confirm them comparing with the Elastic Strain Intensity (Figure 4.28) but without the accuracy previously obtained.

Comparing the Figure 4.28 and the Figure 3.4 it is possible to detect some zones of high strain (the light blue) that are located in the same zone of the cracks identified in the building inspection but nothing certain.
4.9 Social housing quarter of Adroana – Cascais

The study of these buildings was made in cooperation between the university and the constructors which guaranteed the access to the structural project (Figure 4.29). The models created and the properties introduced in the numerical modelling are those defined in the project and in the case of omissions, common materials were adopted.

![Figure 4.29 – Project of Social quarter of Adroana (ElevoGroup, 2005)](image)

In the first place a three-dimensional model of the building was created (Figure 4.30) however the simulation takes too much time to achieve one result which led to the decision to model just two parts of the building, representing a large part of the building and where a higher concentration of cracks is visible.

![Figure 4.30 – Social Quarter of Adroana: a) three-dimensional model; b) photo of the building](image)

The selected parts cover the most critical parts of the building and the majority of the cracks identified during the inspection. Figure 4.31 illustrates the location of these two parts of the façade on the third floor, selected to be modelled; the part of the front façade with a big window near a corner and a balcony – Façade type 1 (FT1) (Figure 4.32a); and the part of the back façade with two windows near each other – Façade type 2 (FT2) (Figure 4.32b).
In the project document supplied by the construction company, the concrete was defined as C20/25 whilst the properties of the render and a masonry of hollow bricks with two layers were based on technical catalogues of Portuguese suppliers.

<table>
<thead>
<tr>
<th>properties</th>
<th>units</th>
<th>concrete (c20/25)</th>
<th>render</th>
<th>masonry</th>
<th>air</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>[kg/m³]</td>
<td>2500</td>
<td>1600</td>
<td>900</td>
<td>0</td>
</tr>
<tr>
<td>young's modulus</td>
<td>[GPa]</td>
<td>30</td>
<td>3</td>
<td>6.2</td>
<td>6</td>
</tr>
<tr>
<td>poisson’s ratio</td>
<td>[-]</td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>coefficient of thermal expansion</td>
<td>[°C⁻¹]</td>
<td>1.00e-05</td>
<td>1.35e-05</td>
<td>5.50e-06</td>
<td>0</td>
</tr>
<tr>
<td>isotropic thermal conductivity</td>
<td>[W/m°C]</td>
<td>2.2</td>
<td>1</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>reference temperature</td>
<td>°C</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>tensile yield strength</td>
<td>[MPa]</td>
<td>13.3</td>
<td>2.5</td>
<td>3</td>
<td>0</td>
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<tr>
<td>compressive yield strength</td>
<td>[MPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to perform a structural analysis and maintain the correct thermal and structural functioning it was necessary to add a fourth material with the same thermal properties as an air gap of five

$R_{air} = 0.18 \text{ m}^2\text{C}/\text{W}$ (value defined in REH to thermal resistivity)
centimetres defined in the Portuguese Regulation of Energy Performance for Residential Buildings (REH) (DL118/2013, 2013) and structural functioning similar to the masonry in order not to influence the global performance of the models.

Concerning the structural supports several tests were made in order to choose the correct type of support. Various pillar supports were tested, specifically: sliding restrains, elastic linear supports, combinations of elastic linear supports and rotations in the top/bottom of pillars and with fixed supports in the bottom and a simple support in the top. After all simulations and comparing all the results it was concluded that the maximum variation in the maximum deformation varies only one millimetre and the global behaviour of the façade remained constant despite the changing in the support conditions. Thus, selected as support conditions were: the fixed supports in the bottom pillars that fix all the movements in the three planes XYZ and the simple supports in the top pillars that fix the displacement in the normal plane to the pillar axis (section plane of the pillar). Finally a sliding restraint in the connection of the slab with the rest of the structure was applied. These supports are the same for the two façade types and are schematically displayed in Error! Reference source not found..

![Figure 4.33 – Scheme of the supports applied in both façades of Adroana](image)

The connections between the elements in both models remained the same as in the previously described two other models: Frictionless Contact between masonry and concrete and the other contacts as Bonded. In Table 4.9 and 4.10 the results for each model are summarized with maximum and minimum values and where each value occurs.

### 4.9.1 Thermal analyses

As thermal loads, the temperatures are the same as the previous models but only with two zones of convection, inside and outside. The values inserted in the model are described in Table 4.8.
Table 4.8 – Thermal loads applied to the model (Adroana)

<table>
<thead>
<tr>
<th>ambient</th>
<th>film coefficient [W/m².°C]</th>
<th>air temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>outside</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>inside</td>
<td>7.6923</td>
<td>25</td>
</tr>
</tbody>
</table>

In these conditions the results for the temperature distribution in both façades are illustrated in Figure 4.34 and 4.35. Noticing again that the value higher than the maximum air temperature applied is due to mesh problems and does not affect the values as in this case they occur only in one or two elements.

Figure 4.34 – Temperature distribution at FT1

Figure 4.35 – Temperature distribution at FT2

4.9.2 Thermal structural analyses

Figure 4.36 and 4.37 illustrate the deformation for both façade types due to the respective temperatures illustrated in Figure 4.34 and 4.35.

The maximum deformation due to temperature in FT1 occurs in the plaster in the window zone while in FT2 the maximum value occurs between windows but in the render, with similar values between FT1 and FT2.
4.9.3 Self-weight analyses

In this model additionally to the standard calculation of self-weight, vertical forces in each pillar were added in order to take into account the self-weight of the structure above. A distributed load over a twenty-seven centimetres strip in the edge of the slab above the wall was added, related to the weight of the wall above and with a value of 2.6 kN/m². The calculations for the vertical forces were made manually and take into consideration the influence zone of each pillar. The deformation for Façade Type 1 and Façade Type 2 are illustrated in Figure 4.38 and 4.39 respectively.

In both cases the maximum deformation occurs in the slab in the support zone with a relative displacement from the centre. The maximum values in these two different models are similar (vary approximately 0.5 millimetres) since they are closely related.
Variable actions on slabs analyses

Figure 4.40 and 4.41 illustrate the deformation of the models (FT1 and FT2) subjected to the loading defined in 4.5, namely the variable action in slabs for residential buildings and variable action on balconies.

The maximum values are similar but located in different places. For FT1 the maximum value is 1.114 millimetres and is located in the render while for FT2 the maximum value is 1.445 millimetres and is located in the slab near the support.
4.9.5 Load combinations

Applying the methodology described in 4.6 and analysing both models separately, the most severe load combination in each model (sub-sections 4.9.5.1 and 4.9.5.2) was defined in order to apply to further analyses, specifically the cracking analysis.

4.9.5.1 Façade type 1

Analysing the deformation of both load combinations (Figure 4.42 and 4.44) it is possible to see that both deformed shapes are similar and the maximum values occur in the same place too although the value of maximum deformation is slightly greater (0.18 millimetres) for the load combination 1. Despite this marginal difference combination 1 was selected for the cracking analysis.
4.9.5.2 Façade type 2

In this case the deformed shapes are almost the same as can be seen in Figure 4.44 and 4.45 where the difference between maximum values is 0.025 millimetres. The only major difference between these two deformed shapes is the location of the maximum value that for the load combination 1 is in render whilst in the load combination 2 it is in the slab near the support. Despite this tiny difference the load combination 1 was selected for further analyses.
4.9.6 Results summary

In Table 4.9 and 4.10 the summarized results for the two façade types and for the different analysis type are illustrated. To notice that the final results (LC1 and LC2) are very similar when comparing the results for LC1 and LC2 but also when comparing the results between the FT1 and FT2. Other aspect to observe is that the maximum deformation due to self-weight is the higher deformation when comparing the individual results.

Table 4.9 – Results summary for the Façade Type 1

<table>
<thead>
<tr>
<th>analysis</th>
<th>Min</th>
<th>Where</th>
<th>Max</th>
<th>Where</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal stress analysis</td>
<td>0</td>
<td>Concrete</td>
<td>1.428E-3</td>
<td>Plaster (ins)</td>
</tr>
<tr>
<td>Self-weight stress analysis</td>
<td>0</td>
<td>Concrete</td>
<td>1.547E-3</td>
<td>Concrete</td>
</tr>
<tr>
<td>Variable action in slabs analysis</td>
<td>0</td>
<td>Concrete</td>
<td>1.144E-3</td>
<td>Plaster (ins)</td>
</tr>
<tr>
<td>LC1</td>
<td>0</td>
<td>Concrete</td>
<td>3.242E-3</td>
<td>Render (out)</td>
</tr>
<tr>
<td>LC2</td>
<td>0</td>
<td>Concrete</td>
<td>3.058E-3</td>
<td>Render (out)</td>
</tr>
</tbody>
</table>

LC1 – Load combination 1 – temperature as leading action; LC2 – Load combination 2 – variable action in slabs as lading action

Table 4.10 – Results summary for the Façade Type 2

<table>
<thead>
<tr>
<th>analysis</th>
<th>Min</th>
<th>Where</th>
<th>Max</th>
<th>Where</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal stress analysis</td>
<td>4.952E-8</td>
<td>Concrete</td>
<td>1.573E-3</td>
<td>Render (out)</td>
</tr>
<tr>
<td>Self-weight stress analysis</td>
<td>3.342E-8</td>
<td>Concrete</td>
<td>2.045E-3</td>
<td>Concrete</td>
</tr>
<tr>
<td>Variable action in slabs analysis</td>
<td>2.919E-8</td>
<td>Concrete</td>
<td>1.445E-3</td>
<td>Concrete</td>
</tr>
<tr>
<td>LC1</td>
<td>1.209E-7</td>
<td>Concrete</td>
<td>3.894E-3</td>
<td>Render (out)</td>
</tr>
<tr>
<td>LC2</td>
<td>1.018E-7</td>
<td>Concrete</td>
<td>3.869E-3</td>
<td>Concrete</td>
</tr>
</tbody>
</table>

LC1 – Load combination 1 – temperature as leading action; LC2 – Load combination 2 – variable action in slabs as lading action

4.9.7 Cracking analysis

As in the analysis described in sub-section 4.9.5, a separate analysis to each model (FT1 and FT2) was made following the scheme previously used to determine the zones prone to cracking.
4.9.7.1 Façade type 1

Analysing the Figure 4.46 it is possible to detect zones prone to cracking which are associated with the zones where the tractions are higher than the compressions. These zones, highlighted on Figure 4.46 and in detail on Figure 4.48, are zones where it is necessary to introduce some reinforcements in the render, specifically the corners of the window frames, a strip on the left jamb connecting the corner reinforcements and the zone near the corner between the slab and the pillar plus the corner of the window frame. Additionally to these zones, traction zones were observed in the façade, near the balcony slab (the lower part of the upper balcony and the upper part of the lower balcony). Beyond the zones detected in the façade, it is possible to see in Figure 4.46 some vertical red arrows which correspond to cracks in the slabs, specifically in the intersection zone of the slab and the wall and in the connection between the balcony slab and the façade as shown in Figure 4.47 which will be sustained by the reinforcement bars of the slabs.

![Image](image1)

*Figure 4.46 – Vector principal elastic strain – façade view (FT1)*

![Image](image2)

*Figure 4.47 – Vector principal elastic strain – upper view (FT1)*
4.9.7.2 Façade type 2

In Figure 4.49 the vector principal elastic strain, which helps to identify the zones prone to cracking, is illustrated. In contrast with some cracking analyses previously made, in this analysis the zones where it is probable for cracks to occur are easily defined.

Defined are five zones on the façade, where the appearance of cracks is probable, relating to mortar areas that need reinforcement namely: the corner of window frames (i), the zone between the two windows next to each other (ii), the left jamb of the first window (iii), both jambs in the third window (iv) and the corners between pillars and slabs extended through the slab axis (v). As in the analysis of the first façade type, in this analysis a zone in the slabs, prone to cracking was detected, right after the wall in the top slab and in the bottom slab, however these deformations are sustained by the reinforcement bars of the slabs.

To confirm these zones, the result illustrated in Figure 4.49 and a photo taken in the social housing quarter, with the cracks highlighted, were overlapped with the result shown in Figure 4.50. Most of the cracks existing in the building are located in the tensioned zones, which is a good contribution to validate the model and the selected load combination.
4.10 Chapter conclusions

The use of numerical models reveals itself to be a useful tool where analysis of cracking is concerned especially when comparing the cracking patterns that this work proposed to model and that are summarized in the sub-section 3.6 with the results obtained listed in sub-sections 4.7.5, 4.8.7 and 4.9.7. Most of the cracking patterns were reproduced in numerical models except for the global model of the office building at Oriente where it was difficult to determine zones prone to cracking.

The zones prone to cracking are located in the places where cracking is expected, such as the corners of window frames, in the transitions on render substrate between concrete and masonry and in the corners of the concrete structure(between pillar and slab). However, the jambs are zones identified, by the simulations, as prone to cracking and where it is not common to see
references concerning cracking and reinforcement of render. This information was complemented by the photos taken in the social housing quarter of Adroana where the appearance of cracks in these zones is common.

One of the limitations of the numerical models is related to the need to adopt simplifications. In the last models (sub-section 4.9) a crack appears in the slab due to the wall and the bending of the balcony for FT1 and in the slab for FT2. These cracks are controlled by the reinforcement bars in slabs although in the models a uniform material was adopted and can induce in error if this information is not take into consideration.

Other interesting point to note is that the deformation due to the self-weight tends to be greater than or equal to 50% of the total deformation and the deformation due to thermal actions are slightly larger than the deformation due to variable actions on slabs.
5 Conclusions and future works

5.1 Conclusions

The main objective of this work was to create a model making it possible to detect the zones where cracking is probable and, whenever possible, compare the results to real examples. To achieve this objective firstly the types of cracking were divided by load type, namely: hygrothermal loads, chemical reactions and structural and other movements. Numerical models that simulate the phenomenon, directly and indirectly, were searched and it was observed that the majority of simulations are performed based on the most common materials used in construction; the remaining, use parts of the building whilst the largest and more complex models concern with historical buildings or buildings with great value. The majority of the simulations found are time dependent signifying good contribution to the results of these simulations as the variations over time can accelerate the cracking phenomenon or introduce more differential movements that induce cracking. In this dissertation, time variations were not applied, this can be pointed as a limitation of this work but needs to be seen as a point to improve in future works.

With the cracks organized by load type, five inspections were held in order to have experimental data to use in the numerical models and to compare the results with what was seen in the field. Four of these inspections were held in collaboration with the University and PTPC, a Portuguese technology platform for construction that enabled the opportunity of inspecting the buildings and, in some cases, facilitated the access to the design projects. From the inspected buildings the most common cracks found are caused by structural and other movements with some of these movements induced by hygrothermal loads. At “Pinhal da Charneca” cracks were seen that appear due to the appearance of other cracks, most of them due to chemical reactions as the buildings are located near the ocean.

From the five buildings inspected to model, two were selected based firstly on the types of cracks and secondly on the availability of the design project. The buildings of “Pinhal da Charneca” were not modelled due to the presence of chemical reactions and soil-structure interaction whilst the buildings of “Quinta de Santo António” already have numerical analyses of the buildings and the high school Dr Solano Abreu no project information was available. For the two building selected for modelling, two different situations were selected on each building in order to model. In the office building at Oriente, as no project information was available, a part of the structure was adopted to study the connection between platband and the structure and a full part of the building was modelled in order to study the global behaviour. In the second building, the social housing quarter of Adroana, two parts of the façade were selected and modelled covering approximately 50% of the main façades.

Regarding all the models created and the results obtained there are three principal conclusions to note:
Firstly, to obtain better results it is necessary to introduce a more refined mesh, achieving better results in smaller models than in larger models (like the model created for the office building in Oriente). The larger model, with too much detail, is difficult to simulate with high definition, requiring computers specifically designed for this purpose and these, usually, are used for simulating historical buildings or buildings of great value. To counter this difficulty, equivalent models were created, leading to acceptable results but with some assumed mistakes, this in order to enable the simulation to be performed. In addition, the analysis of the results is more detailed in smaller than in larger models and it is easier to compare with photos. Thus, it is possible to conclude that, when dealing with the phenomenon of cracking in façades, smaller models are better choices for the study of this phenomenon.

Secondly, whenever it was possible to compare results to photos, the results obtained are compatible with what was observed in the field and compatible to what is known about cracking on façades. In some cases the results indicate places where it is not common to suggest the reinforcement, however, from the comparison between results and photos, it is possible to say that the jambs are zones to take into consideration when reinforcing the render. This, leads to the conclusion that numerical models are a good tool to predict the possible location of cracks when subjected to service loads.

Thirdly, taking into account what was studied in the beginning of this dissertation, variations on the connection between the different materials were introduced such as: the introduction of Frictionless contact between the masonry and concrete enabling the surfaces to slide freely and, depending on the loads, open or close contact between surfaces while the other contacts (render to masonry and render to concrete) were defined as bonded i.e. the elements are not allowed to separate or slide. The bonded connection type was defined by default whilst the frictionless contact was defined in order to allow a relative movement in the render substrate although it is incorrect to admit that the surface between concrete and masonry has no friction forces. To improve the quality of the numerical models there are works that should be done in order to give experimental support to the models. When this dissertation started, with the study of the contact elements, it felt as if, where connection between materials is concerned, nothing is concretely known just a few values without any experimental validation. Thus, it is important to improve the knowledge about the connection between materials in order to improve the numerical models.

As referred to in the beginning of this work the cracking phenomenon is a relevant issue that affects the durability of the building and the quality of life of the users. This phenomenon, despite being well-known, continues to affect a great number of buildings, irrespective of their age. This reality was observed during the inspections conducted in the buildings previously cited in this work. These inspections made it possible to see that the use of reinforcement in mortars is not a common practice, if it was common practice then some of the cracks could have been avoided. Another common error that leads to cracking and was also detected during the inspections was miscalculation in the design phase which leads to cracks of difficult and expensive correction. With all the knowledge and preventive measures known the question is why these cracks continue...
to appear? Is it cheaper to correct them during the warranty period than to construct it well from
the beginning? Are the design projects incorrect or is the building construction careless or rushed?
Considerations that should be answered by the proper entities and that remain after this work has ended.

On the whole, the objectives were achieved with the numerical models showing themselves to be
useful tools in order to predict the cracking zones and a tool for making future projects more
precise and more demanding in order to improve the quality of the construction. The numerical
models are growing in relevance, they are a quicker and cheaper way to predict some phenomena
that influence the durability of the buildings. In fact, in times of fast developing of new materials
the evaluation techniques need to follow this evolution and the numerical models, despite the
need of making assumptions, reveals to be a good alternative.

5.2 Future works

As referred previously in this work and, despite the favourable results, some parts need
improvement in order to make the numerical models as close as possible to reality. Summarizing
the future works shall be target to:

- Improving the knowledge about the connection between materials with laboratory tests;
- Introduce time variations in loads and material properties.
Bibliography


