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MODERN MATERIALS USEFUL IN REHABILITATION OF BUILDINGS: UHPC AND FRP

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To me and to my family

Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning

Albert Einstein

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RESUMO

A reabilitação de edificios é actualmente vista em Portugal como uma solução para a crise que o sector da construção atravessa. O mercado associado a este sector tem vindo a evoluir favoravelmente ao longo dos anos no nosso país, devido à consciencia das entidades componentes de uma elevada necessidade de intervir num parque habitacional bastante deteriorado, bem como a existência de uma politica que visa estimular o mercado da reabilitação, tendo em conta o seu elevado potencial de crecimento e impactos favoráveis que poderá adver no sector da construção.

As intervenções de reabilitação podem passar por vários níveis, podendo ir de uma primeira fase que corresponde a uma simples reparação até a uma intervenção profunda na estrutura que visa a reposição de condições de segurança ou outras medidas com o objectivo de cumprir os níveis de exigencia actuais, bem como, a função a que a estrutura se designa.

No parque habitacional Português existe o predominio de três principais materiais de construção, a madeira, a alvenaria e o betão, sendo que este último tem vindo a ser objecto de variadas investigações e estudos, no domínio de novas tecnologias para reparação e reabilitação de estruturas degradadas bem como para improviso do seu comportamento estrutural.

Desta forma as intervenções de reabilitação em estruturas de betão armado devem ser precedidas por um conhecimento prévio das causas de degradação do betão e também os métodos de avaliação dessa mesma degradação. Após essa fase poderão ser definidas as etapas a ter em consideração na reabilitação da estrutura e também as técnicas de reparação e reforço.

Atendendo ao referido nos paragrafos anteriores, procurou-se abordar neste trabalho as principais causas de degradação de elementos constituintes de uma estrutura de betão armado e também as técnicas e materiais normalmente associados á sua reparação. Como referido anteriormente, este tema tem sido objecto de várias investigações e portanto ser referido no presente trabalho alguns materiais modernos que poderão ser utilizados na reabilitação de edificios, bem como técnicas associadas aos mesmos. Com o intuito de perceber as possiveis diferentes formas de aplicação destes 'novos' materiais no sector da reabilitação de edificios, realizou-se uma sintese de vantagens e principais factores atractivos ao uso destes materiais, referindo-se a sua possivel aplicação em intervenções de reabilitação em diferentes elementos constituintes de uma estrutura de betão armado.

PALAVRAS-CHAVE: REABILITAÇÃO DE EDIFICIOS, ESTRUTURAS DE BETÃO ARMADO, REPARAÇÃO E REFORÇO, UHPC, FRP

ABSTRACT

Rehabilitation of Buildings is these days seen in Portugal as a solution to current crisis that building sector is passing through. The market associated to this sector has shown some favorable evolution through the years in our country, due to the conscience of competent authorities of the growing awareness of the need to intervene in many degraded buildings, but also as a result of structuring policy aimed at stimulating the rehabilitation market, taking into account its high growth potential and the economic benefit it would bring to the construction industry.

A rehabilitation intervention can go through different levels, as a simple repair or, in a deeper perspective, an intervention in the structure that needs other measures aimed at raise the safety terms of the structures towards the current requirements.

In the Portuguese Building stock there is the predominance of three main construction materials, wood, masonry and concrete, being the last one object of different research and studies, in the domain of new technologies to repair and rehabilitation of degraded structures, as well as, the improvement of structural behavior.

Thus, the rehabilitation of reinforced concrete structures has some peculiarities and must be proceed by a previous knowledge about degradation causes and also the knowledge of different evaluation methods. In a later stage it will be possible to define the steps to take into account in the structure rehabilitation and associated reinforcement and repair techniques.

Given the above paragraphs, this work tries to address the main subjects to the main causes of deterioration of concrete elements and the common materials and techniques associated and usually practiced. The research and studies done in this field allows the appearance of modern materials useful in the rehabilitation of buildings. The main purpose of this work is to present some of this materials. With the goal of understanding the application possibilities of this materials in building rehabilitation, is presented an overview of the possible applications of rehabilitation materials in the different elements of a structure, presenting their advantages and techniques associated to the implementation in real cases.

KEYWORDS: BUILDING REHABILITATION, REINFORCED CONCRETE STRUCTURES, REPAIR AND STRENGTHENING, UHPC, FRP

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1
INTRODUCTION

The sector of Rehabilitation has become an issue of great importance around the world, particularly in the most developed societies. The need to improve existing buildings for new conditions of use and also the recognition of the importance of conservation of the architectural heritage are two of the most important points to the growth of this sector.

Existing heritage buildings are subjected to different processes of degradation with time and many times it leads to a situation in which they became not able to fulfil the purposes for which they were built. The adaption of old buildings to new functions is sometimes a reason to rehabilitate.

Rehabilitation of heritage buildings can be considered a way of sustainable development and also an act of culture. The most sensitive aspect of the rehabilitation of existing buildings is structural rehabilitation, it means, their structural safety. Sometimes, the eventual strengthening of existing buildings can conflict with their cultural value.

In previous centuries wood and masonry were the main materials in building construction. However, in the 60's to 80's, concrete became the most used material and most structures were built with reinforced concrete, of which some of the important structures are nowadays considered as heritages. These concrete structures show nowadays problems related with their exposure to different agents which cause deterioration and distress.

Due to this deterioration of concrete heritage structures, their repair and maintenance in becoming indispensable to prolong the service life of these structures. It is a common practice the use of traditional materials and techniques and based on past experience.

In the last years a considerably amount of research, development and innovations are carried out in construction and particularly in rehabilitation sector. For example products or techniques that can lower the cost of maintenance and prolong the life time of the structure do not only save some of heritage to the future as can save a lot of money. It's based on this that a research and development of high performance and multifunctional construction materials have been improved. Advanced technologies have been focused on repair or upgrading of existing structures.

Based on these facts, there are some modern materials with high potential to be used in building rehabilitation. Fiber reinforced polymer matrix composites are increasingly being considered for use in this construction sector, due to its efficacy, range of applications and facility of application. Ultra High Performance Concrete is other material suitable to use in rehabilitation due to the its excellent performance under severe environmental conditions.

Nonetheless, for a good performance of the repair materials, the bond between concrete layers needs to be assessed and its essential that the bond offers enough strength to resist the stress due to mechanical loading or thermal effects, while also maintaining an extended service-life performance.

1.1 Motivations and Objectives

The development of this dissertation results by the interest to know in detail the area of building rehabilitation and the notion that it's needed an improvement in this area to the process of rehabilitation be the adequate, valuing the pre-existing heritage.

For the development of this theme will be done various studies and analyses, being the main objectives described below:

- Analysis of the construction sector in the rehabilitation of buildings in Portugal;
- Characterization of old buildings and their constructive system and materials;
- Collection and synthesis of available information about concrete and causes associated to it's degradation, as well as, techniques and materials for rehabilitation and strengthening;
- Collection and synthesis of information on modern materials useful in rehabilitation of buildings, in particular with concrete in their structure;
- Assess the potential use of these materials in the rehabilitation and reinforcement of reinforced concrete elements, referring application techniques and suitable elements to application of different materials.

1.2 Structural Organization

The aim of this thesis is to shown the potential of some modern materials as repair materials in the sector of rehabilitation of buildings. The organization of the work is as follows:

- Chapter 2 is a literature review about the sector of Rehabilitation in Portugal, some important concepts, the characterization of the Portuguese building stock and the evolution of some constructive techniques in the last decades;
- Chapter 3 is a description more detailed of the three main types of old buildings, wood, masonry and concrete, including a historical framework and a complete characterization of these kind of buildings;
- Chapter 4 focuses on material concrete, referring it's causes of deterioration and the associated techniques of reparation and strengthening of different building elements;
- Chapter 5 presents the two modern materials in study on this work, UHPC and FRP, referring the main characteristics of each one, as well as, potential applications in the field of building rehabilitation;
- Chapter 6 refers the bond strength that has to exist between the repair material and concrete substrate to ensure the success of the rehabilitation interventions;
- Chapter 7 closes with the conclusions and proposal for further research.

2
OLD BUILDING REHABILITATION

2.1 Basics of Rehabilitation
2.1.1 Definition of Old Building

It's understood that old buildings are those which construction is based on the use of traditional technologies, including the use of wood on the roof and floors and bulkheads for partition walls. Generally the structure of the building consists on sturdy walls of stone masonry with mortar. Normally, these distinguished by building technology, which remained without major change until the advent of reinforced concrete, which began in the late of 19th century and became common practice in the second half of the 20th century.

The old buildings can be classified in three categories:

- Monumental heritage;
- Built heritage classified;
- Current built heritage.

Fig. 2.1: Example of Monumental heritage (Belem Tower, Lisbon) [1]

Fig. 2.2: Example of Built Heritage Classified (House Barbot, Vila Nova de Gaia) [2]

Fig 2.3: Example of Current Built Heritage (House Granado, Porto) [3]

2.1.2 Definition of Rehabilitation

The rehabilitation term designates the entire series of actions undertaken with a view to recovery and improvement of a building, making it fit for its current usage. Generally, rehabilitate is the action to redesign a reality.

The most important goal is to resolve the physical and constructive environmental anomalies and accumulated over the functional years. At the same time seeks to modernize and a general improvement of the property on which it focuses, improving their functional performance through upgrading of its facilities and equipment and organization of existing spaces. [4]

2.1.3 Definition of different intervention concepts

The level of degradation of the building and the objectives underlying the intervention fall into the same in differentiated processes identified as: Maintenance, Conservation, Rehabilitation and Reconstruction. The concepts here adopted for these types of intervention have basis on the International Council on Monuments and Sites (ICOMOS) [5].

- Maintenance

Maintenance refers to the routine work necessary to maintain the building in a state close to the original, including all its components, whether gardens, equipment or other elements. Must also take preventive action against the potential damage, knowing also decay processes of structures and durability of the materials. At base must have a work plan, with identification of actions and their periodicity, as well as an estimate of the associated costs. It’s the combination of technical actions and administrative procedures during the lifetime of the building intended to ensure that it carries out the functions that was scaled for. [6]

- Restoration

Restoration refers to the action in a building, or in a part of I, which is degraded, in disrepair or that was inappropriately repaired in the past, being their ‘change’/action taken with the aim of putting it in accordance with the design or appearance of a prior specific date recognized as having the greatest value of authenticity. It’s intended to recover the environment and architectural logic and should exist a deep knowledge of its constructive technique, but also of its insertion in the architectural or aesthetic currents of the time. The respect for the past and the techniques that requires assumes that prior to the execution of the project and choice of intervention solutions is needed to proceed a broad study documenting it, an investigation and selection of solutions most appropriate to each case. [6]

- Conservation

Conservation refers only to safeguard actions on historical accidents with the combination of protection and active rehabilitation. Conservation is a State or an objective and not, in technical sense, an activity. [6]

- Reparation

Considering that represents all the work necessary to fix defects, significant damage or degradation caused deliberately or by accident, neglect, weather conditions, social disorders, in order to put the building in good condition, without changes or restoration. Seeks to return to the element damaged their mechanical characteristics, their functional capacity and its original durability. It is in the nature of the irregularity of temporal action repair being beyond simple maintenance and having in mind avoid the reappearance of problems in the future. Must be performed with the minimum of intrusion possible. [6]

- Alteration

An alteration in a building refers to the work produced in the construction that does not fit in the maintenance or repair and which aim is to modify or change the functioning or modify its appearance. [6]

- Conversion

Conversion is the changing produced in the building to change its function to another different than the original. [6]

- Reconstruction

Reconstruction is understood more as an operation associated with the drawing/design than the built subject. In this sense, it’s possible understand that the design can be reconstructed based on evidence, or documents, or both, making the partial or total replacement of the elements following the original design. Used usually to bridge the disappearance of significant parts of the original building and becomes important their replenishment.

- Reinforcement

Reinforcement refers to the interventions to increase the load capacity of a building, mainly in its structural elements such as slabs, columns, walls and foundations.

- Reversibility

Reversibility is the concept of pursuing a job in a building or part this, in order to this can return to the previous state, in some future time, with only minimal changes produced in construction, without modifying any of the elements which give it authenticity.

2.2 Historical Framework

For many years, the concerns for the conservation of the architectural heritage, tended only to be applied to monuments, which were assigned important historical values, such as being the only objects to conserve and protect.

The rehabilitation is therefore a concern that already feels for centuries. Initially, with Camillo Boito (1836-1914) and later with Cesare Brandi (1906-1988). The ‘Conservation Theory’ came to counter somewhat the concept of rehabilitation and so claim the minimum intervention and the safeguarding of the original materials. Only from the 19th Century, due to ‘ Heritage Letters ‘, it was possible to begin defining the concepts of conservation and restoration of built heritage, having been defined the first entities targeted for rehabilitation.

In May 1964, is drafted the ‘Charter of Venice’, as known as International Charter on the Conservation and Restoration of Monuments and Sites. After eleven years, in 1975, in the city of Amsterdam, arises the ‘Amsterdam Declaration’ [7] being possible to highlight at this time the growing concern for a new policy of protection and conservation of the built.
It was concluded on the date, that the conservation of the buildings allows for better economy of resources and requires skilled professionals. To the elaboration of the Charter of Krakow, in 2000, there are still other documents relating to heritage and its conservation, as the letter from Washington - International Charter for the safeguarding of the historic towns in 1987, and also the letter from Village Vigoni [8] – on the conservation of cultural ecclesiastical assets in 1994.

2.2.1 Principles for the conservation and restoration of the Built Heritage

2.2.1.1 The Venice Charter 1964

The Venice Charter was approved in the 2nd International Congress of Architects and Technicians of Historic Monuments, which took place in Venice on May 25th to 31st 1964. [9]

According to this charter, that is one of the most important references in the area of recovery and valorization of the architectural and urban heritage, it is essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions.

The practice of restoration and current improvement adopted a methodology for intervention based on the preservation of the existing element and adaptation functions required by society without significant alteration of the original element. Only when the development of the uses and customs warrant amendments considered necessary, these can be authorized.

The conservation of monuments undergoes a permanent maintenance of the same, as well as of the elements that constitute it. The notion of ' historical monument ' shall encompass the urban or rural ensembles in which the isolated building falls, representing a culture specifies or an historical event, as well as more modest works with relevant patrimonial significance.

The elements of sculpture, painting or decoration cannot be separated from the monument, unless it is the only way to ensure its preservation.

Venice's Charter suggests that the practice of restoration of monuments has a exceptionally character, being its goal to preserve and reveal the aesthetic values of the monument, always respecting the original materials. An archaeological and historical study should always precede and accompany any restoration activity.

Conservation and modern construction techniques may always be used whenever traditional techniques prove inadequate and since the effectiveness of the first has been proven through scientific data and guaranteed by the experience.

2.3.1.2 The Krakow charter 2000

The Krakow Charter, approved the October 26 following “International Conference on conservation" held in Krakow, has as its fundamental basis the Charter of Venice and the whole doctrinal documentation within the international cultural heritage. It’s a primary objective of conserving the architectural, urban and landscape heritage and the elements that make up that depict various historical moments, cultures and traditions throughout different eras. It’s also a readjust and upgrade outdated practices, aligning some of the standards, International Conventions and letters produced since the Venice Charter (1964). [10]

According to this letter, the process of heritage conservation is based on their maintenance and repair. These actions must be punctual, but continuous, in order to avoid more intrusive operations that may damage or alter the original element. Thus, intervention projects should be established that include long-term strategies, which are based on a set of appropriate techniques and options must be made using a cognitive process that integrates the collection of information and understanding of the building or place in which it inserts.

The Krakow Charter establishes different types of built heritage, which are associated with different approach methods. This differentiation is due to the need for individualize each intervention depending on the features the first type is the heritage archaeological, characterized by their vulnerability and relationship with the territory and surrounding landscape. Secondly there are the monuments and historic buildings, characterized by the location in which they find themselves, whose authenticity and integrity must be preserved. The third type is the architectural decoration, sculptures and artistic elements that form an integral part of the built heritage. These must be preserved in accordance with a specific project associated with the General project of restoration, carried out by specialists. Type four is related to the cities and the historical villages that represent a fundamental part in the universal heritage. Finally are distinguished landscapes, recognized as cultural heritage, which are the result and reflection of prolonged interaction between man and nature.

This document also defines principles for proper management of cultural heritage, measures legal and administrative provisions which shall ensure that the execution of the maintenance work is performed by specialists in the subject or under its supervision.

2.3 Levels of Rehabilitation

The rehabilitation of buildings is based on the execution of several interventions in the building to be rehabilitated. Rehabilitation interventions can be divided into shares of repair, which derive from a careful analysis and evaluation of the anomalies in the various functional elements and improvement actions, which are intended to, provide the building, previously non-existent features or increase their performance at the level of minimum conditions of habitability, structural safety, organization of spaces or changes due to needs of residents. The degree of intervention of the repairs will be bigger greater severe is the anomaly.

The type of intervention is also dependent the location of the building, their classification as preserve heritage and their architectural typology. [11]

The table below presents the different levels of rehabilitation, conjugated with the different levels of intervention:

Table 2.1 – Levels of Rehabilitation

Level	**Description**
I - Slight Rehabilitation  Fig 2.4 – Rooftop cleaning [12]	Execution of minor repairs and improvements of existing facilities and equipment: ─Improving the Interior conditions of ventilation and exhaustion; ─Cleaning and maintenance of coverage and the storm water drainage system; ─Non-recurring repair plaster and paintings, interiors and exteriors of the building; ─Improvement of electrical installation and lighting.
II – Medium Rehabilitation  Fig. 2.5 – Replacement of floor covering [13]	In addition to the works included in level I, includes further: ─Partial repair or replacement of carpentry; ─Repair and eventual strengthening of structural elements, usually from floors and coverage; ─General repair coatings in interior and exterior vestments; ─Improvement of functional and environmental conditions of spaces (Reorganization) and equipment.
III – Intense Rehabilitation  Fig 2.6 – Coating repair needs [14]	In addition to the works referred to in previous levels, comprises: ─Introduction of profound changes in the distribution and organization of interior spaces of buildings; ─Repair of deteriorated constructive elements that can endanger the safety of users (stairs, partition walls, coverage); ─Introduction or adaptation of spaces to create installations and equipment missing in accommodation.
IV – Exceptional Rehabilitation  Fig. 2.7 – Reinforcement with laminated wood [15]	Exceptional nature operations with deep development degree, that cost may approach or exceed the cost of a new building if similar features. May require: ─The rehabilitation and/or reinforcement of structural elements; ─The rehabilitation for standards much higher than the preexisting.

2.4 Rehabilitation in Portugal

2.4.1 The Portuguese Residential Building Stock

According to the last known results of 2011 Census, the Portuguese Building stock is divided into two categories, namely, buildings and lodging [16]. There is differences between these two concepts, because the first one correspond to an independent construction that comprehends one or more lodgings, divisions or spaces, which can be destined for housing and its first goal can be commercial, industrial, cultural or other. By other way, the second one correspond to a distinct place that is intended to be a human habitation. It’s estimated that in Portugal exist around 3.544.389 buildings and 5.878.756 lodging, from which 5.859.540 are classic ones [17].

The lodging can be subdivided into collective or family lodging, being that the first one include buildings that were designed or constructed for housing several families, while the other one refers to buildings that were designed or constructed to accommodate one single family.

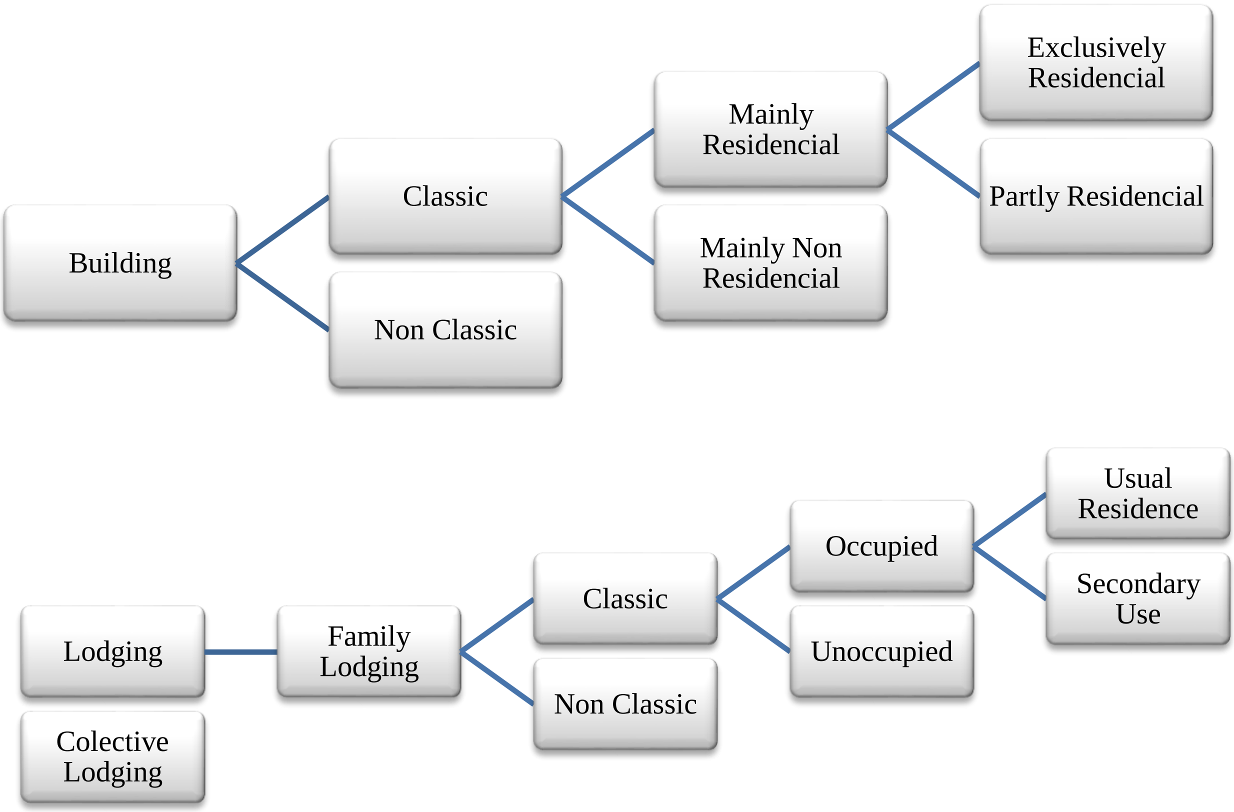


FIG 2.8 - Characterization of the Statistical Unit Lodging and Building [18]

The percentage of collective accommodation in the Portuguese building stock was almost negligible, representing only 0,21%. Almost the entire national territory (99,78%) correspond to a single family housing (including classical and non-classical housing).

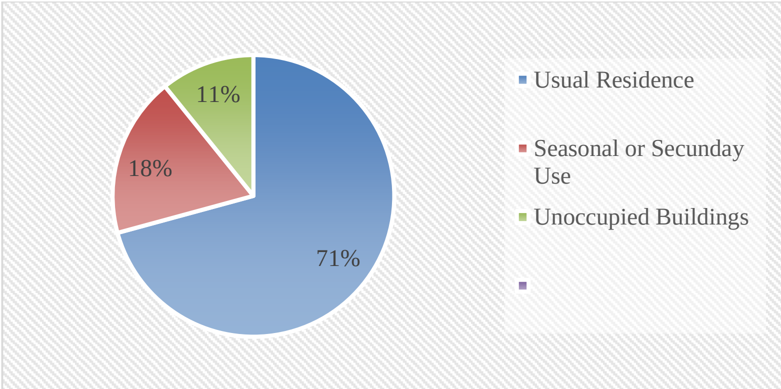


FIG. 2.9 - Percentage of Residence Buildings According with their sate of Occupation [18]

The great majority of buildings in Portugal are used as an ordinary residence (about 68,10%), more than in the generality of Europeans Countries, where about 50% of buildings are occupied by the owner.

The high rates of growth of Portuguese housing stock over the past few decades have meant that, in 2011, a significant part of the existing buildings were relatively recent. Of the total of classic buildings existing in 2011 (3.544.389), the constructed from 1971 constituted 63.1% of the housing stock. These buildings were distributed to approximately uniform form for each of the decades, being however noted a trend of slight reduction in the number of buildings in recent decades. The buildings built between 1946 and 1970 accounted for 22.5% of Portuguese housing stock and buildings with more than 65 years (i.e., prior to 1946) represented the remaining 14.4% [19].

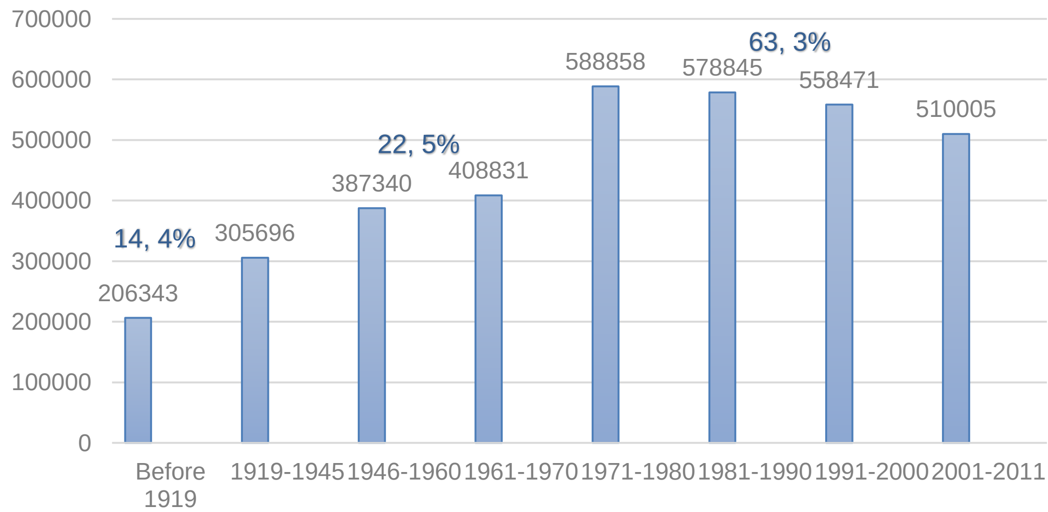


Fig. 2.10 – Number of classis buildings according to their date of construction [18]

While in Portugal the residential stock has an average 33 years old, in Europe great part of the stock is older than 50 years and is still in use today [20].

The North and Central Europe countries, like the United Kingdom (U.K.), Denmark, Sweden, France or Czech Republic are some of the countries with the biggest percentage of older buildings in their building stock.

2.4.2 Constructive Characterization

2.4.2.1 Structure

According to the last Census (2011) almost half of the buildings of the country had structure of reinforced concrete (48.6 %) and approximately 1/3 of the buildings had structure composed of masonry walls with plate (31.7 %). The remaining buildings were types of structure less representative: masonry walls without plate (13.6 %), masonry walls of loose stone or adobe (5.3 %) and other types of structure (0.8 %) (Fig. 2.11).

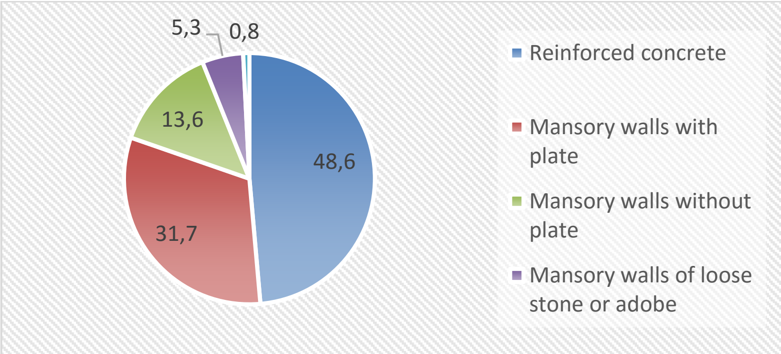


Fig. 2.11 - Number of classic buildings according to the type of structure construction – 2011 [18]

2.4.2.2 Cladding of Walls

In 2011, the majority of the buildings of the country had outer coating of walls in traditional plaster or cement (84.0 %). The proportion of the remaining types of exterior coating was reduced: 11.6% in stone, 3.8% in ceramic tile or mosaic and 0.6% in other coatings (Fig. 2.12).

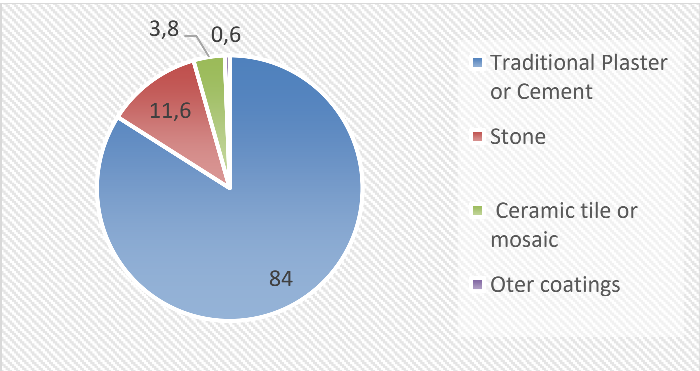


Fig. 2.12 – Number of Classic Buildings According to the type of Cladding of Walls – 2011 [18]

2.4.2.3 Coverage

In 2011, almost all of the buildings of the country had sloped cover coated with ceramic tiles or concrete (93.1 %). The coverage of the remaining buildings was divided to form approximately balanced between sloped cover coated with other materials (1.8 %), mixed coverage (sloped and terrace) (2.1 %) and coverage in the terrace (3.0 %) (Fig.2.13).

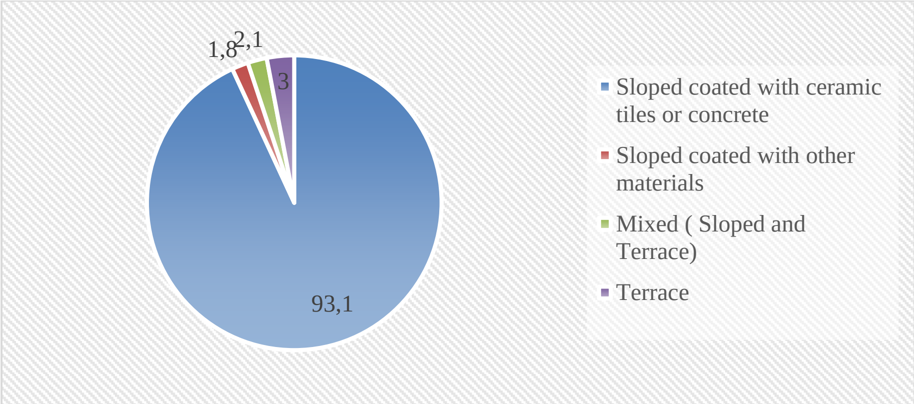


Fig. 2.13 - Number of classic buildings according to the type of coverage – 2011 [18]

2.4.3 Intervention and Rehabilitation Needs – Portugal Vs Europe

As mentioned before, during the last decades, Portugal experienced a period of expansion of the building stock which had as consequence an almost total absence of investment in rehabilitation and conservation of the already existing building stock.

The strong investment in new constructions and lately, the reduction in the loans to private investors granted by the banks due to the economic crisis are the most significant features that lead to the current poor state of repair and rehabilitate the Portuguese Building stock.

Fig 2.14 – Portuguese Traditional Building Needing Reparations [21]

Nowadays, there are many families still paying their houses due to the favorable taxes conditions conceded during many years by the Portuguese banks to private investors. Some of these houses need major repairs but there is no money to pay for that.

According to recent studies, there are in Portugal about 1.000.000 of buildings that require intervention. In 2011, a large part of the Portuguese buildings did not present needs of reparation (71.1%). As increased the degree of necessary repairs, the percentage of buildings diminished (17.6% needed minor repairs, 6.9% medium repairs and 2.7% major repairs) and the remaining 1.7% correspond to very degraded buildings (Figure 2.15).

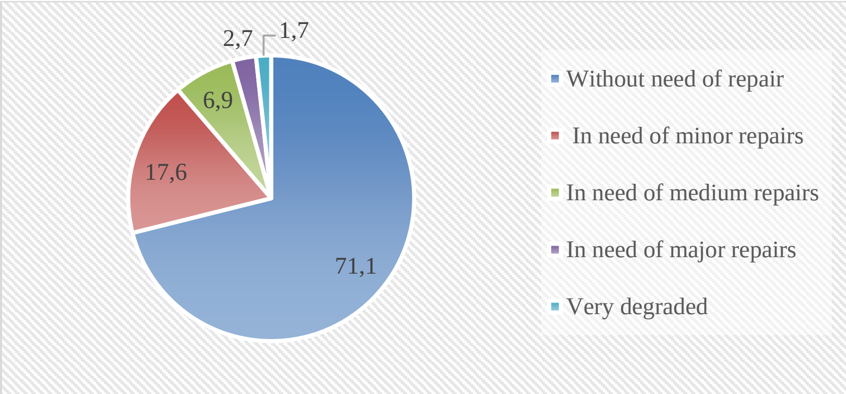


FIG. 2.15 – PERCENTAGE OF REPARATION NEEDS IN PORTUGUESE BUILDING STOCK [18]

The majority of repair works that are needed on buildings should focus on exterior walls and window frames (approximately 1.256.094 buildings with reparation needs). However, there was also a significant number of repair works in coverage and in the structure, with respectively, 1.169.591 and 1.087.849 buildings needing some kind of repair (Fig. 2.16).

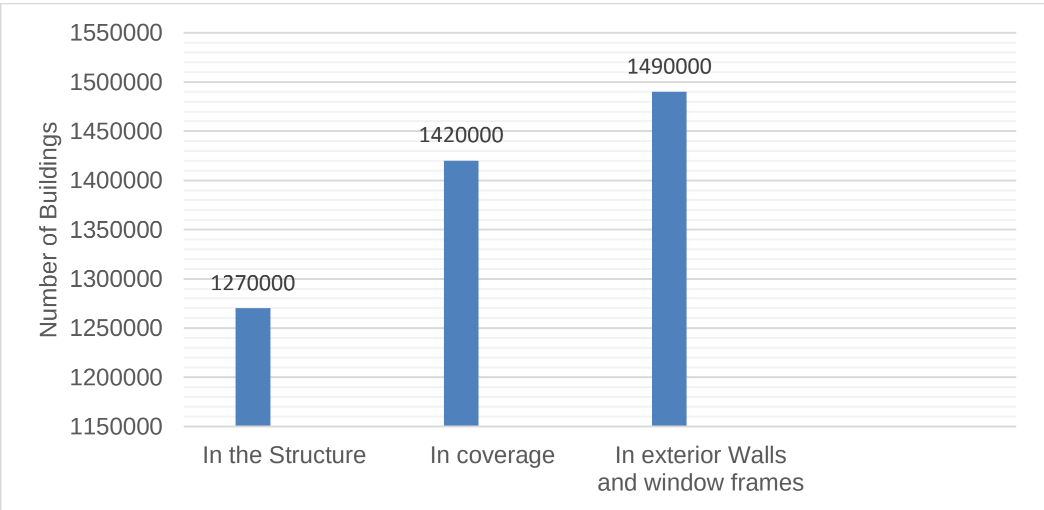


FIG. 2.16 – NEEDS OF REPAIR IN PORTUGUESE BUILDINGS [18]

The chances/possibilities to a building be rehabilitated are directly influenced by the type of owner. In Europe the majority of the residential building stock is private ownership while 20% corresponds to social housing. However countries like Austria, Czech Republic, Ireland and France there is an increasing trend towards private involvement. Rehabilitation should be saw as an opportunity to upgrade the existing building stock, increasing their energy efficiency, comfort conditions and market value. In response to social needs, the investment on rehabilitation would contribute to increase the life quality of the residents and to create new job opportunities.

2.5 Incentives to Rehabilitation in Portugal

2.5.1 Urban Rehabilitation: An investment opportunity

Since 2013, the Portuguese real estate market has shown signs of recovery, with both domestic and foreign investors looking to invest in the renovation of properties, mainly those located in downtown areas of Portugal’s major cities (Lisbon and Oporto). Renovated properties are mainly being used for either investment purposes or short-term leases, tourism purposes and some of them are being converted into small boutique hotels, mainly located in the heart of historic districts.

There are some important factors responsible for this reconstruction revival, such as:

- Law 32/2012, which grants municipalities broad powers to establish urban renovation policies;
- An attractive tax regime;
- Law 30/2012, which grants landlords willing to repair leased properties the right to terminate lease agreements with a mere six months' notice.

Decree-Law 53/2014 was recently approved by the government, as an exceptional and temporary regime that suspends for a seven-year period the application of a range of technical rules and requirements concerning the rehabilitation of buildings that are located in urban rehabilitation areas or are more than 30 years old and earmarked for residential use, either in total or in part. The rehabilitation is also identified as the main mean of development and regeneration of urban centers by law 31/2014, which sets out the general basis of the soil, land use planning and construction public policies.

2.5.2 Tax Benefits

Tax incentives are provided by the law for the rehabilitation of properties where:

- Rehabilitation works commenced on or after January 1 2008 and conclude by December 31 2020;
- The property is located in an urban rehabilitation area.

This regime includes the following tax incentives:

- Exemption from property transfer tax for the first purchase of property used as the purchaser's main residence;
- Exemption from property transfer tax for the purchase of property to be rehabilitated, provided that the purchaser starts rehabilitation work within two years of purchase;
- Exemption from municipal property tax for rehabilitated properties for five years which may be renewed for a subsequent five years;
- A reduced value added tax (VAT) rate of 6% (instead of 23%) on rehabilitation works, which applies to all residential properties, irrespective of their location. However, materials that exceed 20% of the total contract value will not benefit from the reduced VAT rate;

- The possibility to deduct from taxable income 30% of rehabilitation expenses (up to €500);
- Autonomous taxation at a rate of 5% for the rental income and/or capital gains earned from rehabilitated property by taxpayers resident in Portugal. However, the taxpayer may choose to waive this special rate and include the income/gains in its overall taxable income. [17]

2.5.3 Support Programs to Urban Rehabilitation

There are in Portugal several financial support programs to urban rehabilitation, each with similar objectives but different means, sponsored by IHRU (Institute of Housing and Urban Rehabilitation).

2.5.3.1 RECRIA

The Special Regime of Participation in the Recovery of Leased Real Estate (RECRIA), aims at funding for execution of works of conservation and improvement, allowing the recovery of fires and buildings in a state of degradation. In this program is made a lost contribution by the IRHU and the corresponding town hall.

Can benefit from the incentives provided under this scheme works in buildings that have at least one housing fraction whose income has been the subject of extraordinary correction pursuant to law N. 46/85, of 20 September. [22]

The reimbursement granted is as follows:

- 60% by the Government, through the INH;
- 40% by Local Administration, through its municipality;
- or 80% by INH 20% by the municipality in the works of partial recovery, repair or renovation of roofs or terraces of coverage.

The value of reimbursement may increase on 10%, since the works aimed at the adequacy of precautionary measures of buildings security against risks of fire in the ancient urban centers.

2.5.3.2 REHABITA

The program REHABITA, was created in 1996, as a program that stands out from the rest because its application is not restricted to a single building but before encompasses urban scale. In this sense, this program tries to somehow lessen the tendency of rehabilitation options resulting from previous programs that rely on unitary and which refers to the decision of the intervention, for better or for worse, for individuals (landlords and owners). Rehabita is a program to support municipal urban rehabilitation operations which should be articulated with the municipal planning. To this effect works as an extension of ‘Recria’ because when incorporated into Rehabita, the reimbursable works under program Recria, have an additional percentage, fund lost, of 10%; and as an extension of the Special Rehousing Programme (PER). [23]

The program aims to support the implementation of conservation works, improvement or reconstruction of houses and the provisional or permanent relocation actions resulting thereof, within the framework of municipal operations of rehabilitation of historic urban centers which are declared as ACRRU and having PP or urbanistic regulations approved. Once the Rehabita aims to financially support municipalities in the recovery of old urban areas access is granted subject to the conclusion of collaboration agreements between the IHRU, municipalities and other authorized credit institutions. The works included in Rehabita, subsidized by Recria, in addition a reimbursement the bottom 10% lost, supported by IHRU and the municipalities involved, along the same lines of Recria. As in Recria, when the city is replaced the landlords or owners, on completion of the works, can resort to low-interest loans to finance the value of works not subsidized.

2.5.3.3 Recriph

The program Recriph is created in 1996, concurrently with amendments to Recria, and provides financial support to the realization of works on horizontal property buildings, but only on component of common spaces. Support for building units, although planned, assumes the form of a subsidized loan, you can still verify that this small and initial expansion to the property tries to address, albeit very shy, the increasing adoption of horizontal property regime.

The Recriph aims to support financially the implementation of conservation and renovation works that allow the recovery of ancient buildings, incorporated in horizontal property regime.

However, only have access to this scheme the administrations of condominium and the owners of buildings that have been constructed until the date of entry into force of the RGEU or after that date, those who have use license issued until January 1, 1970 and are composed at least for building units and 4 one of them be affects the exercise of a commercial activity or small hotel industry.

The contributions at lost fund are intended for ordinary and extraordinary conservation works in the common parts of the buildings, whose maximum value cannot exceed 20% of the total amount of works, being 60% supported by IHRU and 40% by the municipality. May be granted by the IHRU, or another credit institution authorized for this purpose, a funding subsidized to apartment owners, whose ceiling may go up to the value of sponsored not works. [23]

2.5.3.4 SOLARH

The Program of Solidarity and Support to the Recovery of Housing, allows the granting of interest-free loans by the IHRU for performing interventions in permanent housing or in amounts that are housing owners municipalities, private institutions of social solidarity, collective public utility people pursuing administrative assistance purposes, and housing and construction unions. The loan to be granted by the IHRU can achieve a maximum value of 11971.15€ for housing. [24]

This program is governed by Decree-Law No. 39/2001, of 9 February, subject to amendments established by Decree-Law No. 25/2002, of 11 February.

2.5.3.5 PROHABITA

The financing program for access to Housing enables local authorities to applying for funding for the acquisition of buildings and fires also being degraded and derelict reimbursed the costs of restoration of the building and the surroundings in which it is inserted.

This program was approved by Decree-Law No. 135/2004, of 3 June, and revised by Decree-Law No. 54/2007, of 12 March. [25]

2.6 Rehabilitation and sustainability

During the last decades, the cities decentralization was witnessed, in the seeking of better living conditions. The privileged in society are often able to improve their quality of life, for instance by moving to better neighborhoods or to the countryside in order to escape from unhealthy conditions [26]. This kind of actions has developed disqualifying physical, functional and built environment in the historic centers and their urban degradation.

The question is: What's the importance of urban rehabilitation in the context of sustainability? Rehabilitate the urban environment implies inhabiting existing buildings, so that they can acquire life and thus assigning movement to the public spaces. To inhabit these buildings it is necessary to recover them, providing good living conditions, space functionality and environmental effectiveness, that is, rehabilitate the existing buildings, improving their efficiency. Urban rehabilitation aims to enhance citizen's life quality by improving the built environment.[26] Therefore, the rehabilitation must be conducted with the intention of promoting spaces with effective premises to give responsiveness to current requirements and social, economic and environmental values integration.

The heritage conservation and urban rehabilitation are strategic areas for Europe, due to its rich comprise cities historical culture character, and so is naturally concerned about the urban policies sustainability. The shift to more sustainable lifestyles is therefore not simply a matter of putting the environment first but also about recognizing that the economic viability of cities must built on a sustainable basis of long-term social, environmental and economic stability and equity [26].

It is then need to ensure the evolving mentalities so that can be available to face a new perspective on quality of life, based this time on sustainability, generating a real increase in quality of life equal to all social groups and encouraging developments so that does not prejudice the future generations. Lies with policymakers to clarify these factors in order to use them as a basis for sustainable cities development so that can effectively contribute to an urban sustainability successful strategy.

2.7 Obstacles and difficulties on Rehabilitation

All rehabilitation projects are different and so are never performed twice under the same conditions. Therefore, the main difficulties/obstacles associated to rehabilitation of buildings are essentially:

- Occupation during the rehabilitation;
- Economic viability;
- Insufficient financial and tax incentives;
- Lack of skilled labor;
- Lack of employers specialized in this sector;
- Lack of information relative primordial construction processes and possible interventions done;
- Absence of regulation oriented to rehabilitation.

2.8 The Evolution of the Structural Elements in Portugal

2.8.1 Building Facades Evolution

The construction technology of the structural elements has been changing with time. Since the year 1940, mainly in large urban centers, there was a further development of building technology with the generalization of reinforced concrete structures on the decks, which later were applied on the vertical resistant elements. Nevertheless at that time the thick and heavy masonry stone walls were the prevalent facades of the Portuguese buildings. Only around 1950's the first double walls started to emerge in Portugal, being that the first double walls consisted of a cloth stone masonry and cloth brick masonry interspersed with an air box. At this time it wasn't used any insulation because it was thought that the air box was enough to ensure good insulation and create the needed comfort conditions inside.

After 1960, the exterior walls in Portugal become constituted by two panels of brickwork, with the interposition of an air-box. The generalization of the double wall ceramic materials façades allowed essentially lightening the weight of the walls. The application of this construction technology continued in the 70's and in the 80's. Despite the first thermal behavior characteristics in dwellings came into force in 1991, the façades insulations were introduced in the 70's, after the first major global oil crisis which demonstrated the high energy dependence of developed countries. But it was only after the entry into force the first regulation of thermal behavior characteristics in dwellings, that the use of thermal insulation in Portuguese building's facade became widespread in Portuguese construction.

The first regulation for thermal comfort in buildings was approved in 1990 by the Decree-Law n.º 40/90 of 6th February and it is known as Regulation of the Characteristics of Thermal Performance of Buildings (RCCTE) which came into force in 1991 [27].

Portugal was the last European Country that impose a regulation about this matter. The Portuguese regulation, was however innovate because has in account some aspects like the comfort in summer, the requirements on sunscreen glazing and the reduction for heating and cooling needs in new buildings. The RCCTE included also rules that can be used in all the major renovations in order to improve the interior thermal comfort of the places. These places should not spend an exaggerated consumption of energy but being comfortable. In the end of 80's HVAC (Heating, Ventilation and Air Conditioning) systems were not very used in buildings.

Nowadays it's possible to note a growing increase in the use of air conditioning equipment in housing sector. The growing use of air conditioning systems but also the need to implement the European Directive 2002/91/CE on the energy performance of buildings called for a new regulatory framework in 2006 [28]. The installation of solar panels to produce hot water is forced in the new version of RCCTE, contributing to the reduction of the emission of greenhouse gases and the importation of energy.

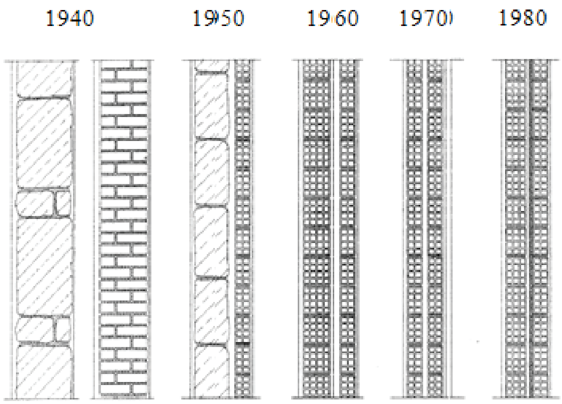


Fig. 2.17 – Evolution of Building Facades in Portugal [18]

2.8.2 Roof Constructive Techniques Evolution

The roofs are a structural element that suffered the evolution of construction techniques. Traditional roofs were done with tiles which were supported with basic and primary structures of wood. Subsequently, the coating of roofing happened to be seated in a wooden lining. Although at that time thermal insulation materials were not applied in roofs and another technique was used in order to attempt to retain the heat from inside. Instead of using wooden lining, needs were interlaced and attached to the beams over which was placed a layer of mortar and then applied the tiles. Coatings stone were also used depending the zone, slate replaced ceramic materials since it had effective protection to temperature oscillations [29].

In the 1940's almost every buildings had inclined coverings, coated with ceramic elements and structurally supported by beams and wood trusses.

In the South of Portugal, particularly, flat roofs started to be used constituted by bricks that formed cap vaults or by application of tiles in two or three layers with mortar seated in wooden beans.

Fig. 2.18 - Covering Structurally Supported by Wood Trusses [18]

Due to the very different climatic characteristics between the North and the South of Portugal, in the first one the pitched roofs continued to be the most prevalent image. However in all country the use of thermal insulation application in the roof was not used. Only in 1990, there was an evolution of initially ventilated spaces of covers for unventilated spaces. The structural elements initially of wood were being replaced by concrete ones, being that one of the great advantages of concrete was the versatility in the manufacturing method. The concrete components used on the roofs could be prefabricated or could be either manufactured in situ by concreting solid slabs.

Fig. 2.19 - Covering Structurally Supported by Pre-Fabricated Beams [18]

In these decades there was a proliferation of flat roofs, nowadays these type of roofs are no longer concentrated in the south, but distributed throughout the country. It was at this time that thermal insulation materials started to be introduced in the roofs components independently if they were inclined or flat.

2.8.3 Pavements Constructive Techniques Evolution

Between the years of 1750 and 1930 the pavements of dwellings with more than one floor were mostly wooden floor with a roof lining, which were supported by wooden beams [30]. Pine and cone were the mainly type of woods employed in the wood floors, which were used on long tables arranged in the same direction that were nailed to wooden beams. Wooden floors were gradually replaced by floors containing ceramic elements. These slabs consist on prefabricated prestressed beams and lightened ceramic elements which is a constructive technique frequently used in the north of the country. With the generalization of building construction in height using reinforced concrete, the use of tunnel formwork became more frequent. The tunnel formwork system consisted of a metal formwork allowing concreting simultaneously exterior walls, interior and slabs [31].

The tunnel formwork walls and reinforced concrete slabs had particular expansion in the early 90's and were mainly applied in social housing construction. However, despite this type of implementation show good characteristics in respect to the functionality and leak requirements in relation to acoustic and thermal insulation behavior they provided a poor quality of life for its inhabitants. As in the other structural elements the application of thermal insulation in slabs in contact with the exterior or non-heated spaces only became a common practice after the implementation of the first RCCTE.

3
Old Buildings

3.1 Masonry Buildings
3.1.1 Historical Framework

The masonry features a high historical importance, once being the main material responsible for habitability of the shelters built by man and also the main structural material.

The first masonry constructions dating from 10000 B.C, having been in the 18^{th} and 19^{th} centuries that large palaces and cathedrals were built and are currently the representation of the season in Portugal.[32]

The masonry structures, scaled according to the intuitive rules at the time, were made up of very thick walls, compared to slender solutions obtained using metal structures and reinforced concrete. The ‘Monadnock Building ‘ (Fig. 3.1) was the latest example of a big masonry building according to tradition, built in Chicago in 1891.

Fig. 3.1 – Monadnock Building in Chicago [33]

Antoni Gaudi stood out in this period by its ' structural rationalism ', employing bows and slanted anchors in masonry. The masonry and simple concrete were solutions little usable by not resisting to traction and the concrete in association with steel developed more quickly unlike armed masonry structures.

Fig. 3.2 – Gaudi's Building Batlo, Barcelona [34]

In the middle of 20^{th} century masonry structures come back to awaken interest in the most developed countries. Associated with new forms of sizing and regarded in a more modern perspective led to the awakening of the economic interest of this solution.

In countries like France, United States, Canada, England and Australia, the use of structural masonry is widely diffused, and there is a set of technical standards and regulations about calculations and construction procedures.

Examples of masonry buildings are:

- Zurique, tower with 18 floors and walls with thickness around 38cm;
- São Paulo, Central Park Lapa, blocks with 12 floors;
- Denver, Buildings 'Park-Mayfair-East' with 17 floors, executed in armed masonry, with walls of 28cm of thickness (2 cloths of brick and one of concrete);
- San Diego, Hotel 'Catamaram' with 13 floors, built with armed masonry in concrete blocks;
- Londons, building in 'King Street' executed in armed masonry.

In Portugal there are also important masonry constructions, as are example:

- Avis, CGD agency built in brick masonry;
- Moita, library Bento de Jesus Caraça built in brick masonry.

Currently, there has been an increase in the evolution of the construction of buildings in structural masonry, which is due essentially to several functions that this technique plays, leaving aside the idea of heavy masonry structures, thick and rigid as in antiquity.

3.1.2 Masonry Elements in Portuguese Old Buildings

- Mansory Walls

In Portugal, the old buildings were mainly using simple masonry walls. The location of the building to be built contract the use of raw material, being noted the predomination of granite, limestone, carved stone and mud brick.

The mortar used in the link between the masonry also varies according to local availabilities.

- Foundations

The foundations were usually made up of isolated shoes or keep, of stone masonry or brick, with minor differences compared to observed for resistant walls.

The sturdy walls of the traditional buildings feature common traits although with some factors of differentiation. Usually these walls feature great thickness being made up of very heterogeneous materials. The great thickness is justified essentially by structural and mechanical reasons, water-tightness and comfort. The availability of materials, the importance of the work and the meanings of the promoter influence many times the differences.

The following elements deserve a special reference in resistance walls:

-Lintel, horizontal element supported in its extremities crossing gaps;
-Arches, which are usually coarse and in more developed constructions in stone or brick massif;

- Subdivision Walls

In Portugal the vaulting walls have constructive solutions which can be national or regional. The solution of national character is the wall, made up of planks placed vertically or inclined floor related receiving small rulers of trapezoidal cross-section, to which the plaster adhere.

In Pombaline reconstruction the space division gives a relevant structural contribute, in particular at horizontal actions, have a skeleton composed of horizontal, vertical parts and crosses of St Andrew and the spaces filled with brick masonry or irregular small stone. Later, it became more popular the use of ceramic brick masonry, for economic reasons and facility of execution. However its contribution to the general structures locking is almost nil, since the links between the walls, the floors and roofs no exist from the structural point of view.

3.1.3 Applications and advantages

In the last years masonry was displaced for many applications by steel and concrete. However it has great importance for load bearing walls in low and medium rise buildings and for internal walls and cladding of buildings which structural function is met by one or other of these materials. The masonry market can be divided into housing and non-housing sectors [35], being the last one to industrial, commercial, administrative and educational buildings. There is also a limited use of masonry construction for infrastructure, for retaining walls [36] In the two sectors there is a significant requirement for masonry in the repair and maintenance of existing buildings [37].

Reinforced masonry can be used to overcome situations where considerable lateral forces have to be resisted in seismic areas and generally where non-load bearing panels are subjected to substantial wind loads. Walls of cellular or T cross-section are particularly suitable for large, single cell buildings where the adoption of such walls is greatly extended by post-tensioning [38].

Masonry wall construction has a number of advantages, being the first one the fact that a single element can fulfil several functions such as, fire protection, sound and thermal insulation, fire and weather protection and sub-division of spaces. [39]

The materials of masonry are normally available with properties capable of meeting the functions before mentioned, requiring sometimes to be supplemented by other materials for thermal insulation, damp-proof courses and the like. The second advantage is related to the durability of the materials that, with a correct selection, must be expected to remain serviceable for many years, or even decades, without a big needed of maintenance.

Masonry offers also advantages from the architectural point of view, in terms of spatial composition, great flexibility of plan form and appearance of external walls for which there are a lot of materials in a wide variety of colors and textures.

Although dependent on skilled labor for a high standard of construction, productivity has been maintained by the use of larger units, improved materials handling and off-site preparation of mortar. The advantages of masonry wall construction are therefore considerable but, as with all materials, appropriateness to the application has to be considered, assuming acceptability from the architectural viewpoint. For example, if the masonry is not to be load bearing it will be necessary to consider the implications of the weight of the masonry as it affects the supporting structure. If the walls are to be load bearing, it will be important to ensure that their layout is consistent with overall stability and with avoidance of failure in the event of accidental damage. This implies that the function of the building is such that there will be a sufficient number of walls to meet this requirement, as for example, is likely to be the case in a hotel. On the other hand, the construction time and its phasing with the overall building schedule will also be relevant factors at preliminary design stage in deciding to use or not masonry walls.

3.1.4 Masonry Units and Mortar

Masonry units has the form of bricks and are produced from clay, concrete, calcium silicate and sometimes natural stone can be used too. The units have all similar uses although they have different properties in important respects depending on the materials used on its producing. Bricks and blocks are produced in many formats, solid, perforated and hollow. Bricks are typically 215x102x65 mm (length X width X height). There are some physical and mechanical properties which are important to the use of blocks in the construction of masonry walls:

-Color;
-Surface Texture;
-Weight;
-Pore Structure;
-Fire resistance;
-Compressive strength;
-Thermal conductivity;
-Tensile strength.

Clay bricks are a different type of bricks that are produced in a variety of colors depending on the mineral content and firing temperature, being the most common colors red and brown. Calcium silicate and concrete bricks are more usually used because they tend to give a more uniform appearance to a wall than clay bricks. Concrete blocks have normally a grey color, however can be achieved a color by painting, plastering or by the use of special textured blocks, in the case its required an enhanced appearance to exposed faces.

The density of clay, concrete and calcium silicate is over 2 t/m^3 , but the weight of units that is more important in construction depends on their size, shape, and type (solid, cellular or perforated). The absorption and pore structure of bricks and blocks varies widely and is important in a number of ways. Thus clay bricks which absorb between 4,5 and 7,0% of their weight can be used as a damp-proof course material and on the other hand, highly absorptive clay bricks, may remove water from the mortar preventing complete hydration of the cement. Thermal conductivity of units is of great importance in satisfying design requirements. Lightweight aggregate and AAC blocks have substantially lower thermal conductivity than the heavier materials. Hollow and perforated clay and concrete units will have intermediate values depending on their initial characteristics.

Thermal and moisture movements in masonry walls require to be tken in account in design of walls and depend on the characteristics of the units [40], thus clay units tend to expand in service whilst concrete and calcium silicate units shrink.

Masonry materials are inherently resistant to fire and the critical factor, in this respect, lies in the detail design of the construction [41] aimed at preventing fire passing through defects in or finding a way around a wall.

The most important mechanical propertie of masonry units is compressive strength which, as well as being of direct relevance to the strength of a wall, serves as general indes to the characteristics of the unit. It’s measured by a standardized test, the result depending to some extent on the conditions prescribed in the particular standard being used. A recent code of practice, EuroCode 6 [42] attempts to standardize unit strength by adjusting the standard test value by a factor depending on the unit proportions.

The tensile strength of masonry units both direct and flexural has an influence on the resistance of masonry under various stress conditions but is not normally specified except in relation to concrete blocks used in partition walls where typically a breaking strength of 0.05 N/mm2 is required.

Although mortar accounts for as little as 7% of the total volume of masonry, it influences performance far more than this proportion indicates. Mortar requires to have certain properties prior to setting, particularly workability. Hardened mortar has to be sufficiently strong and to develop adequate adhesion to the units and also to set without excessive shrinkage which would reduce the resistance of the masonry to rain penetration or even cause cracking of the units. It should also be capable of accommodating some degree of movement in the masonry resulting from creep or thermal effects without cracking. Conventional mortar mixes are based on Portland cement, lime or plasticizer and sand, and are graded according to compressive strength. The stronger the mortar the less able it is to accommodate movement so that it is inadvisable to use a stronger mix than is necessary to meet structural requirements. A workable mortar has a smooth, plastic consistency which is easily spread with a trowel and readily adheres to a vertical surface. In addition to units and mortar, masonry wall construction requires the use of a number of subsidiary components including damp-proof course material, cavity trays, wall ties and fixings. Each of these must be as durable as the masonry itself as well as meeting its particular function

In cavity wall construction, the leaves have to be tied together with suitable wall ties. Several types are used and are made in galvanized or stainless steel. [43]

Special ties are available for repairing walls in which the ties have been incorrectly placed or omitted or have become ineffective as a result of corrosion. Fixings are also required between masonry walls and concrete or steel frames which, as well as being resistant to corrosion, must be capable of permitting differential movement between the wall and the main structure. Other components include light ties for connecting brickwork cladding to timber frames and for supporting timber joist floors from masonry walls. [44]

3.1.5 Structural and Non-Structural Design Factors

Structural design of masonry walls is carried out according to national codes of practice, Eurocode 6. This code is based in limit state principles, safety being assured by the use of characteristic values of loads or actions and material strengths together with partial safety factors, applied as a multiplier to loads and as a divisor to strengths.

The following factors have to be taken into account in the design of masonry walls:

- Movement;
- Moisture exclusion;
- Durability;
- Thermal and acoustic properties;
- Fire resistance.

Movement takes place in all masonry materials as a result of applied stress, moisture and temperature change, chemical reactions. These effects, as well as foundation movements, can lead to cracking of the wall. [45, 46]

Thermal movements depend on the coefficient of expansion of the material and the range of temperature experienced. Dimensional changes take place after manufacture of masonry units: expansion in the case of clay bricks; and shrinkage in the case of concrete and calcium silicate products. Unsatisfactory foundation conditions are a common cause of cracking in masonry walls which have a limited tolerance for uneven settlement. Conditions requiring particular care include shrinkable clay soils, mining subsidence and filled ground.

Salt crystallization is essentially a physical process, somewhat analogous to freezing, whereby salt solution is carried into the masonry from ground water or from pollutants. Salt crystallization is essentially a physical process, somewhat analogous to freezing, whereby salt solution is carried into the masonry from ground water or from pollutants. Many varieties of algae, lichens, mosses and even bacteria as well as higher plants can establish themselves on the surface of a masonry wall and, having penetrated the pores of the masonry can cause damage by generating organic acids with similar effects to atmospheric pollution. Where metal components are used in masonry construction careful selection in relation to exposure conditions is necessary to avoid damage to the wall.

Thermal insulation of buildings is an increasingly important factor in building design. Masonry walls built in conventional units of clay; concrete or calcium silicate will usually require additional insulation although lightweight materials such as AAC may be adequate if sufficiently thick. Condensation in buildings, which may result in damage to decorations and mould growth, can be caused by inadequate insulation and ventilation. [47]

Masonry construction is generally effective in relation to sound insulation between occupancies and in reducing noise nuisance from traffic. This depends essentially on mass but sound transmission is complicated and careful attention to detail is required to avoid the effectiveness of a wall being reduced by flanking transmission. In certain spaces, such as assembly halls, the reflective surface properties of masonry walls may require treatment with absorbing material to provide an acceptable acoustic ambience. Masonry materials are incombustible and therefore inherently effective in providing fire protection for the periods of time specified in building regulations. [48]

3.1.6 Masonry Wall Construction

Conventional methods of masonry wall construction remained virtually unchanged until quite recently, attracting criticism that masonry buildings take too long to construct and that it is difficult to find the necessary skilled labor, partly because of unattractive working conditions on site. [49]

As already noted, many new types of units have been developed in recent years with improved thermal properties, greater uniformity in dimensions and in a greater variety of sizes and types. A further development in the supply of materials offered by block manufacturers in Europe is to deliver units as a package along with subsidiary materials for the construction of particular walls in a building thus reducing site handling and storage. On all but very small sites, mortar is delivered in pre-mixed form, ensuring accuracy of gauging and avoidance of waste. [50]

Attempts in various countries to effect improvement by the use of pre-fabricated wall panels go back at least to the 1960s. The advantages include production under factory conditions with consequent achievement of a high standard of work with available labour and acceleration of site construction. The disadvantages lie in the high cost of plant and factory space leading to the requirement for long, continuous production runs for economic viability. There are also limitations in building design imposed by the size and shape of the panels and the problem of making connections between them. The practical possibility of using pre-fabricated brickwork columns rather than walls has been demonstrated, overcoming the need for expensive, specialized plant and some of the other problems associated with this method of construction.

3.2 Wood Buildings

3.2.1 Historical Framework

From a long time ago, wood has been one of the most important building materials, not only for construction of buildings but also for other manufactures. The practices used nowadays with wood begun many centuries ago and with some refinement are still carried. Early humans used wood more than other construction materials because it was available almost everywhere and didn't need elaborated tools to work on it. In the 10th till 18th century, in Europe, wood was the main building material, being in the 16th century when wood reached a peak and then begun to diminish due to the expansion in agriculture and the limits on its accessibility.

Historically, wood has played a very important paper in what concerns to people transportation. The fuel used on railroads contributed to wood being the primary energy source in South America at the middle of 19th century. [51]

The style and durability of timber structures built at various time and places have depended on many factors, such as, the type and quality of timber available, conditions of use, as well as the culture and way of life of people concerned. More recently construction with concrete and stone became common and wood was used more in the construction of concrete forms and supplementary structural components such as roof supports and trusses.

3.2.2 Wood Properties

- Physical Properties

The main three physical properties of the wood are durability, hygroscopicity and flexibility. Durability is the property that wood has in resist to prejudicial materials without putrefy and because of that it's a material with long durability. Hygroscopicity is the capacity of the wood to absorb moisture from the around atmosphere and also to lose it by evaporation (retraction). The last one and very important too is flexibility, that refers to the capacity of the wood resist and flex, to external forces, that can be applied on it, without break. These three properties make wood a good material to apply in many situations and in specific environments.

- Chemical Properties

Wood is composed mainly by two types of compounds, which can be divided into structural and non-structural. The first one is relative to macro cellules (cellulose, hemicellulose and lignin) responsible by the mechanical properties of this material. Non-structural compounds include different substances, normally designated by extractives and ash, with a normal percentage between 0 and 10 in wood's chemical constitution.

- Mechanical Properties

The mechanical properties of wood are mainly strength but in three different concepts:

- Compressive Strength - resistance of wood to forces that tend to short its length;
- Tensile Strength – resistance of wood to forces that tend to extend its length;
- Flexural Strength – resistance of wood to forces along its length;
- Hardness – resistance of wood to penetration forces.

3.2.3 Wood in Old Buildings

The main structure of an old building consists of: middle walls built in stone masonry (granite) being possible in older buildings be built in mixed partition, floor and cover, composed of beams in form of rolled sticks, typically in Brown or Nordic Wood. The secondary structure can be described by: walls of facades in stone masonry (granite), mostly composed of shaped stonework kerbs, interior walls and stairs in simple partitions or simple reinforced partitions and structure of the skylight and attic structures or other smaller elements.

Fig. 3.3 – Example of Old Wooden Building [52]

3.2.4 Wooden Elements

- Floors

Wooden floors feature all the advantages associated with the material and therefore represent a very interesting solution to rehabilitation. This interest is not from now, since they have numerous special features that make them excellent solutions for execution of horizontal structures and therefore been used on a large scale throughout the centuries. [53]

The wooden floors are usually consisting of the frame, the floor and secondary elements, such as billets and chains that performing specific functions make the set more uniform. It’s possible to include elements such as beams, billets and chains in the ‘gross works’ that are ‘’all woodworks which this was just sawn, without presenting another appliance and designed to be steeped in masonry or, at least, to not be visible’’. The floors can be included in the group of ‘clean’ or ‘carpentry of white work’ that are woodworks that require a more careful finish in order to be visible.

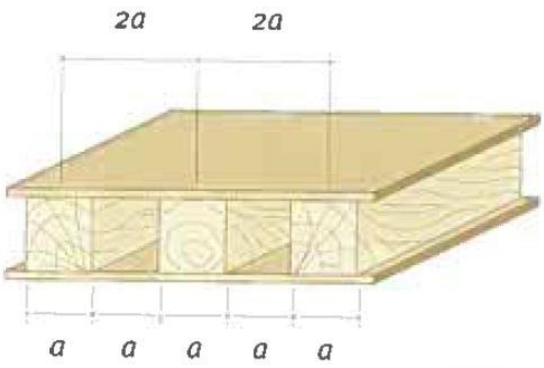


Fig. 3.4 – Structural Design of a wooden floor [54]

- Coverings

The typical Portuguese coverage presents trusses as main structural element with a pending variable between 20º and 30º, being materialized by ceramic tiles supported on poles spaced from 40 to 50cm that lie in the ridge, the wooden purlins and wooden beam.

The geometry of the Portuguese typical coverage is characterized by presenting a horizontal element, tie beam, two principal rafters to form the ends of the roof and attached at its base to the tie beam, a central vertical element between the two rafters, the king post, and two inclined struts supporting the rafters to the king post (Fig. 3.5). The complexity grade of the structure gets higher with the span to cover. The spacing between trusses is about 3 or 4m.

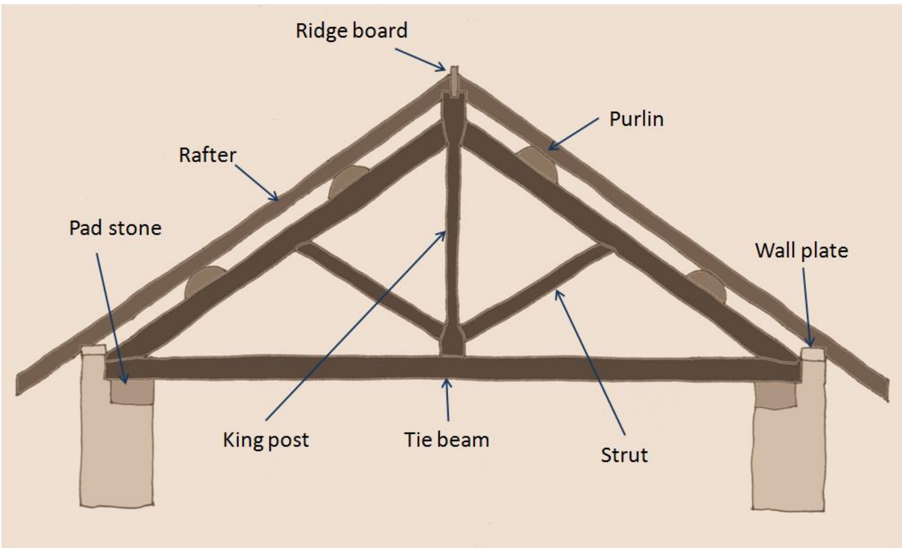


Fig. 3.5 – Traditional King Post Roof Truss [55]

It's possible to adopt configurations even more simple, in the case of trusses with only 4 or 5 meters, presenting a primary structure constituted by tie beams and rafters.

Adaptations to the different geometries observed in previous images, led to the development of simple trusses for composite truss that allows for greater lengths of ties and rafters, through the placement of anchors. However, the addition of anchors requires the addition of risers in order to withstand the traction component that arises due to the anchor-beam connection, forming the truss. [56]

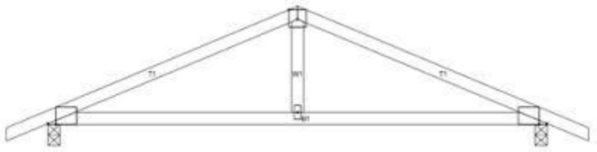


Fig. 3.6 – Example of Sample King Post Truss [57]

- Partition Walls

A constructive element of 'tabique', such as a wall, is constructed through the nailing of, usually, strips of wood placed horizontally on wooden planks placed vertically, being the set coated on both sides, for a land-based material.[58] Wooden boards are nailed at the top and bottom in two fixed rules, one in the floor and other in the ceiling.

The materials usually used in these elements are solid wood, land (simple or with a hydraulic binder) and metallic nails. These elements can emerge as interior walls, with thickness between 0, 10 and 0,15m, assuming sometimes structural functions, when the spans are small, as reflected in many buildings, particularly between 1870 and 1930.

The application in facades is normally associated to humble buildings, especially in the last floor, where the 'tabiques' rising from a wooden beam, which supports at the ends protruding from the floor and therefore have to be light.

Fig. 3.7 – 'Tabique' Wall [59]

3.2.5 Wood as a Rehabilitation Material

Wood is used since antiquity as a rehabilitation material very usually, having been one of the most widely used materials in the world throughout history. With the industrial revolution wood began to be replaced by another type of elements, such as structures in metallic elements. The emergence of new materials and techniques caused the wood to pass to secondary plan, being that the situation worsened during the emergence of reinforced concrete. Despite this, the wood remains a material of preference in some countries, like the Nordic countries.

The fact of the wood be considered, at structural level, as a material of low quality, little durable and sometimes unable to perform its functions, leads to the fear of its use and consequently its devaluation. [60]

In what concerns to sustainability and environmental impacts, the wood presents itself as the only structural material of construction comes from a continue source of regeneration, the forest. In addition, wood allows meet the needs of present without compromising the future needs and may also can be reused. [61]

With regard to ancient buildings, wood is assumed as one of the most important materials, since pavements and coverings are mostly composed by this material. It's possible to find all over the world secular buildings which keep their floor and original covers playing effectively its functions. [60]

3.2.6 Structural Design

Structural design of wooden elements is carried out according to EC5. The current calculation models of 'Materials Resistance' and 'Structural Theory' are applied in the design of this elements. [62] However, difficulties arise related to the material in question, wood. One of the difficulties is the fact of wood have a mechanical anisotropic behavior, being normally considered a transverse isotropic mechanical behavior.

Considering this behavior assumes that, in simple form, in the perpendicular plane to the wire resistance is uniform according to any direction, resulting then only two resistant directions: the direction of the wire and the direction perpendicular to the wire. This behavior has important influence on the way to assemble the pieces. Another difficulty arises in the calculation of the connections and the importance that these have on the efforts that the pieces are subjected and the consequent need to choose correctly the calculation model in accordance with the binding process chosen. It's also obligatory to analyze the vibrations and deformations problem that many times affect the sizing.

3.3 Concrete Buildings

3.3.1 Historical Framework

The appearance of concrete as a construction material dates back thousand years to the days of ancient Egyptians, Greeks and Romans. [63]

The first components of concrete were mainly based on lime, being the Romans known for their development of pozzolanie cement and light weight concrete based on pumice. Although, concrete was used in earlier periods, was after the 18^{th} century when it became a very useful material. A good testimony to the durability of this material is the domed roof of Pantheon. However there are others important buildings that are still in operation, such as, the Thames Tunnel, the Axmouth Bridge and Plymonth Hol.

Fig. 3.8 – Domed roof of Pantheon in Rome

In 1897, Hennebique built the first reinforced concrete frame building in Britain at Weaver's Mill, Swansea, being one of the responsibles for the introduction of steel as reinforcement. Lambot in 1855 with the ferrocement boats and Monier in 1867 were other two responsibles.

Notable steps forward in this century have been the introduction of pre-stressed concrete by Freyssinet in the 1940's, the extensive use of reinforced concrete during World War II including the famous Mulberry Harbours, the rapid post-war concrete-building boom of the 1960s involving concrete pavements and bridges and most recently the contribution of structural concrete to very large offshore structures. [63]

Nowadays attention is focused on environmental attacks to concrete structures that are reducing the life period of these, mainly due to corrosion of reinforcement steel.

3.3.2 Concrete: The Material

The word 'Concrete' comes from the Latin 'Concretus' meaning compounded. [63] Concrete is required to be strong, resistant to penetration by water and chemical attack, possess a low thermal conductivity and free from excessive volume changes.

Concrete can be understood as a graded range of stone aggregate particles band together by a cement paste. The water-cement ratio is responsible for the strength and permeability of the concrete, being a low ratio good for high strength and low permeability.

Normally select a water-cement ratio is the best procedure to provide the required strength. For all structural concrete it's also usual to define a specific context of cement in order to ensure a high level of alkalinity that inhibits any tendency of corrosion in the embedded steel.

Concrete is a material relatively strong in compression but weak in tension and that's the reason why for structural members subject to tensile stress must be reinforced with steel bars, that resist to tensile stress.

The effectiveness of reinforced concrete as a structural material depends on the following:

- The interfacial bonding between steel and concrete which allows it to act as a composite material;
- The passivating effect of the concrete environment to inhibit steel corrosion;
- The similar coefficients of thermal movement of concrete and steel.

The utilization of reinforced concrete became more noticeable in the beginning of the 20th century, with an extraordinary development in the use and comprehension of the functioning and possibilities of reinforced concrete. That development is due to the implementation of numerous patents where are indicated the calculation bases and provisions of armor taken to different structural elements.

Nowadays there is a common regulation to the design of reinforced concrete structures – EUROCODE and REBAP that will be referred more particularly in a next topic (3.3.4).

3.3.3 Advantages and Disadvantages

Concrete can be considered as one of the oldest and widely used construction material all over the world. This material offers hundreds of unique advantages for owners, architects and engineers. Among the most sought after advantages of concrete building are present in the following table.

Table 3.1 – Advantages of Concrete as a construction material

Economic	Social	Environmental
Costs	Inherent fire resistance	Flexibility
Programme	Low vibration characteristics	Thermal mass
Buildability	Good acoustic performance	Locally sourced materials
Mouldability	Reduced skilled labour	Prestressing
Continuity	Inherent robustness	Long clear spans
Speed of construction	High-Quality finishes	Durability
Short lead-in times	Air tight	
Building services	Aesthetics	
Low maintenance		
Whole life value		

However this material has not only benefits and as other materials there are some disadvantages. Compared to other building materials concrete has a relatively low tensile strength as mentioned before (3.3.2) this problem was solved with the appearance of the reinforcement with steel bars. The main disadvantage of this material is the possibility of cracking, mainly when it’s not correctly sized. Despite these limitations and other with little relevance concrete remains the material of choice for many applications.

3.3.4 Structural Design

The series of European Standards commonly known as ‘Eurocodes’, EN 1992 (EC2) deals with the design of reinforced concrete structures – buildings, bridges and other civil engineering works. EC2 allows the calculation of action effects and of resistances of concrete structures submitted to specific actions and contains all the prescriptions and good practices for properly detailing the reinforcement.

EC2 is composed by three parts:

- EN 1992-1 Design of Concrete Structures – Part 1-1 General rules and rules for buildings , Part 1-2 Structural fire design (CEN,2002)
- EN 1992-2 Design of Concrete Structures – Part 2: Concrete Bridges – Design and detailing rules (CEN,2007)
- EN 1992-3 Design of Concrete Structures – Part 3: Liquid retaining and containment structures (CEN, 2006).

3.3.5 Practice of concrete

The obtainment of a new material, homogeneous in appearance, texture, chemical and mechanical characteristics, as cement, allows a control of its manufacture and application mainly based in the technique. The technique was obtained through the evolution of their manufacturing processes and application of new emergent professions in the 19th century. These new professions are new way of work and tend to internationalize the product and regularize it to every international markets.

This regularization ensures quality and control as well as the replacement of artisanal and artistic methods for others internationalized with more technology. Associated to this new reality emerge another one that stigmatize the master craftsman to the new specialist or technical designer of reinforced concrete structures.

4

Rehabilitation and Strengthening of Reinforced Concrete Structures

4.1 Generality

The internal structure of concrete changes over time, mainly due to interactions with the environment which it is inserted. In the way to concrete present a good performance and durability, should have features and properties that fulfill the desired requirements, i.e. should be able to resist the actions of the project (Permanent, Overloads, Accidental) and environmental conditions, without presenting excessive deformations, wear or breakage.

The performance of reinforced concrete structures depends on the mechanisms of transfer of tensions between steel and concrete. The imbrication between the concrete and the armor ensures the necessary transfer of stresses of concrete to armor's surface.

The state of preservation of a structure can be evaluated through structural inspection jobs, thus enabling a constructive and structural characterization, conditions of safety verification, durability of the building, as well as, shape and speed of possible emergence of anomalies.

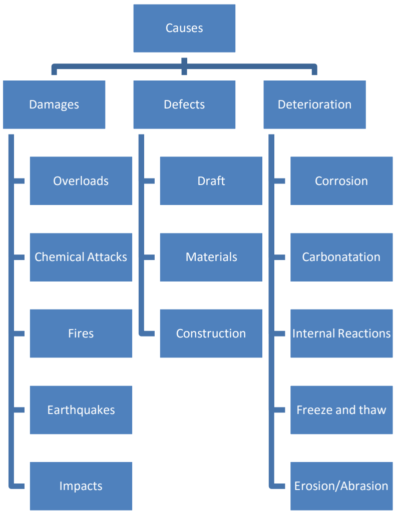


Fig. 4.1 - Responsible Factors Reinforced Concrete Structures Damage and Deterioration

A crack in a floor slab, a spall ate the base of a column, or rust stains that discolor the underside of a beam are conditions present in many structures built with reinforced concrete. [64] It's easy to identify these problems in concrete structures, however determining why these deficiencies are occurring can be the difficult part.

The main deficiencies associated with concrete structures are due to mechanical causes, such as overloads; physical causes, concrete retraction, temperature, leaching, wear; natural and accidental causes, caused by the settlement of foundations, earthquakes, or problems related with humidity due to lack or deficiency of sealing; chemical effects caused by alkalis-silica reactions and reactions with sulfates, which lead to internal expansive reactions, carbonation and chloride contamination. [65]

The useful service life of a concrete structure is typically a function of the corrosion rate of the reinforcement. Before this corrosion can start, aggressive elements such as chlorides or carbon dioxide must penetrate the concrete in sufficiently high concentrations, to the depth of the embedded reinforcing steel. Corrosion of steel is an expansive process. The process fractures the surrounding concrete and weakens the steel as it rusts. Concrete can also deteriorate because of chemical reactions between and within the cement matrix, aggregate and moisture.

4.2 Standard EN1504

The European Standard 1504 defines the principles that shall rule the protection and repair of concrete structures. This standard was elaborated by the Technical Committee CEN/TC 104 and covers the following aspects:

- Assessment of the condition of the structure;
- Identification of the causes of deterioration;
- Determining the objectives of protection and repair;
- Selection of the appropriate principles of protection and repair;
- Methods selection;
- Definition of products, systems and it's properties;
- Specification of maintenance requirements following protection and repair.

This standard includes the classification, in accordance with the damage, of all the causes for reinforced concrete structures deterioration.

4.3 Causes of Concrete Deterioration

4.3.1 Corrosion of Embedded Metals

Corrosion of reinforced concretes can be separated in two processes, anodic and cathodic. The anodic process is the dissolution of iron atoms to ferrous ions when the protective layer at the surface of the reinforcement has been destroyed. The cathodic process involves the reduction of oxygen as it reacts with water to form hydroxyl ions. The anode and cathode are separated by distances that can vary greatly. The anode and cathode areas may alternate along a continuous reinforcing steel bar when areas of the bar become anodic and adjacent areas become cathodic. Oxygen is only required at the cathode to remove electrons from the bar that were liberated from the oxidation of the iron.

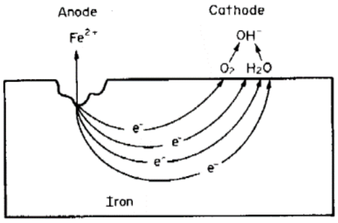


Fig.4.2 – Reactions responsible for the corrosion of concrete [66]

As the iron oxidizes, expansion inducing tensile stresses in the surrounding concrete. When the tensile strength of the concrete is exceeded, the concrete fails with a crack or spall. The alkalinity of the concrete normally protects the steel by significantly reducing the rate of corrosion; however, open cracks, reduction of concrete alkalinity, exposure to corrosive chemicals, and dissimilar metals can all increase the rate of corrosion.

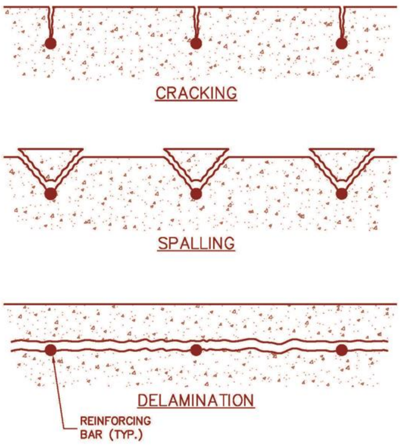


Fig. 4.3 – Corrosion in embedded steel [66]

Fig. 4.4 – Common Failure Mechanisms [66]

- Chlorides

Chlorides may be presented in concrete either because calcium chloride was added at the time of construction as an accelerating admixture or because of ingress of de-icing salts, particularly in highway structures, ingress from seawater or spray in the case of marine structures or impurities in the aggregates and/or mixing water**.** Once the chlorides combine with the oxygen and moisture, occurs the corrosion of steel.

The rate of corrosion will be controlled by the level of moisture and oxygen present.

Fig. 4.5 – Spalling of concrete due to chloride attack of embedded reinforcing steel [66]

- Carbonation

Concrete carbonation is one of the main phenomena to initiate the process of reinforcement corrosion. A series of physical-chemical reactions that occur in the presence of carbon dioxide characterize carbonation. Carbon dioxide penetrates concrete through a diffusion mechanism and associated with the carbonation leads to a carbonated layer that increases in thickness over time.

Carbonation won't occur in the same way in all mixes; different mixes will exhibit distinct carbonation and the same mix exposed to different environments will not show the same carbonation. [67]

- Dissimilar Metal Corrosion

In the case of two different metals be in contact within concrete, such as steel and iron, it's possible to occur corrosion because each different metal has a unique electromechanical potential. In reinforced concretes, dissimilar metal corrosion can occur in balconies where embedded aluminum railings are in contact with the bars of steel. A list of metals in order of electrochemical activity is presented below:

1. Zinc	7. Lead
2. Aluminum	8. Brass
3. Steel	9. Copper
4. Iron	10. Bronze
5. Nickel	11. Stainless Steel
6. Tin	12. Gold

When the metals are in contact, the less active metal (the one with lower number) corrodes.

4.3.2 Freeze-Thaw Deterioration

Freezing conditions are not compatible with wet concrete mainly because water expands when it freezes. The air bubbles caused by air-entraining admixtures provide space to accommodate the expansion of freezing water. The damage caused can occur in two forms, the first is common to open parking decks and other horizontal surfaces that collect standing water.

Freeze/thaw cycles gradually deteriorate the concrete surface, exposing aggregate and leaving the concrete with an enrolled appearance. With the broke of the surface, it becomes more porous, which in promotes even further deterioration.

Fig. 4.6 – Freeze/Thaw Concrete Deterioration [68]

4.3.3 Chemical Attack

Chemical attacks are susceptible to affect every type of concrete structure and are caused by the ingredients used in the mixture or by materials in contact with concrete. The main chemical attacks are: sulfate attacks, acid attacks and bacterial attacks.

- Sulfate Attacks

As announced by its name, this type of degradation is associated with the presence of a chemical called sulfates. Sulfates can be present in seawater or in sulfate contaminated soils. Sulfates can attack concrete by reacting with hydrated compounds in the hardened cement, reactions that can induce sufficient pressure to disrupt the cement paste, resulting in loss of cohesion and strength.

- Acid Attacks

Normally, Portland Cement Concrete does not have resistance to acid attacks. However it's possible to tolerate some weak acids, particularly if the exposure is occasional and the pH>7. In the case of an exposition to an acid (pH<7), the solid minerals become unstable, which leads to the dissolution and the decom position of the material.

- Bacterial Attacks

Bacterial attacks are another potential pathology of concrete structures and are result of certain bacteria, normally present in organic materials, transform or produce corrosive by products. The attack by bacteria can cause structural collapses and damages to the surrounding environment.

4.3.4 Alkali-Silica Reaction

Alkali-silica reaction (ASR) is of more concern because aggregates containing reactive silica materials are more common. Aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it absorbs water from the surrounding cement paste or the environment and consequently it can induce enough expansive pressure to damage concrete.

The typical indicators of ASR are random map cracking and more unusual closed joints and attendant spelled concrete. The most common areas to the appearance of cracking are near the ground behind retaining walls, near joints and free edges in pavements, in piers and in columns subject to wicking action. This reaction can be controlled with the use of certain supplementary cementitious materials, such as, silica fume, fly ash, ground granulated blast-furnace and more recently lithium compounds have been used. Not all ASR gel reactions produce destructive swelling.

Fig. 4.7 – Example of Alkali-Silica Reaction cracking [69]

4.3.5 Abrasion/Erosion

Erosion by abrasion is a phenomena which leads to the concrete surface wear, noting particularly in road pavements and industrial decks subject to actions that mobilize repetitively rubbing the surface of decks and others subject to hydrodynamic action of water draining in great speeds at total or partially submerged structures.

Fig. 4.8 – Example of deterioration by erosion [70]

4.3.6 Fire/Heat

Concrete is a material that has good performances at temperatures encountered in almost all applications but however when exposed to unusually high temperatures can lose strength and stiffness. Various degrees of damage can be sustained on concrete depending on the severity of the fire and the high temperature levels reached.

The most fire damage would involve the total exposure of main bars, significant cracking and Spalling, buckling of steel reinforcement, exposure of prestressing tendons and eventually fracture and deflection of concrete components.

The presence of combustible materials in commercial, domestic or industrial buildings makes these more vulnerable comparing to other structures as bridges.

Fig. 4.9 – Structure damaged by fire [71]

4.3.7 Overload

Overloading of a structural member can cause distress of concrete and it happens when the structure is incapable of supporting the imposed loads. In rare cases the collapse can occur. However normally early warning signs appear in the form of excess deflection or critically configured cracks.

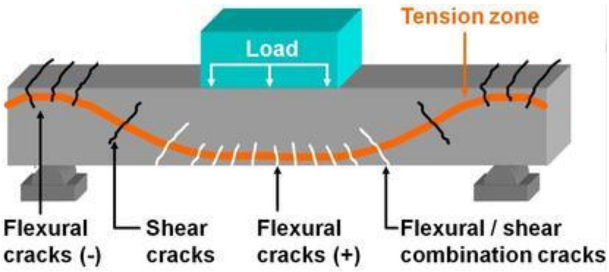


Fig. 4.10 – Overloading Cracks [72]

4.3.8 Thermal Effects

The mass of concrete can expand or contract, as it's heated and cooled. Thermal effects can be found in structures exposed to differential temperatures. For example in a concrete bridge the top surface is heated by the sun, but the lower layer is cool being possible develop cracks due to this differential thermal movement. The upper layer will try to expand but the lower not and this may induce cracking in the lower layer if the tensile stresses in the concrete are excessive.

4.3.9 Shrinkage

Normally shrinkage happens when happen a rapid evaporation of water in concrete. An example are slabs placed in hot weathers, where the curing process has begun and water can readily evaporate from the slab surface. The upper layer shrinks at a faster rate than the lower layer and cracks appear in the first one.

4.3.10 Segregation

Segregation is related with the separation of the concrete components, more properly the process in which the aggregate separates by size and weight. The result of this process is the fact of the largest aggregate collects at the bottom at the section and the cement paste at the surface. This phenomena can be attributed to a high concrete slump, over-vibration of the placed concrete or improper placement procedures.

4.3.11 Construction Tolerances

All constructions requires tolerances to achieve acceptable structures using a reasonable amount of time and effort. A precise planning by the designers and careful and execution of the work by the contractor are the requirements to an extraordinary tolerance. In cases which tolerances are not adhered to, the as built condition affect the strength and durability of the structure. An improper slope in a floor slab may permit the collection of surface runoff that is prevented from reaching an area drain. In this case it's not only the concrete surface exposed to a direct and possibly cyclic moisture source as well as the collection of water may affect the structure and induce flexural cracking.

4.4 Techniques of Repairing Deteriorated Concrete

4.4.1 Treatment of cracks

In general, if the crack present a width greater than 0.3mm, it must be injected with a material, in accordance with the Standard, be either able of transmitting forces, or be flexible enough to keep up with crack movements or, be hidroexpansive, being able to absorb water and filling the crack. The selection of the technique and product depends upon knowing the reason for its existence and if it is expected further movements on it. Material that can be used are for example mineral products, cement grout or polymers, such as, epoxy resins.

4.4.2 Patching Repair of deteriorated surface with mortar or concrete

There is the possibility of existence of superficial zones that, due to spalling or extensive deterioration of the surface, leave the steel unprotected and exposed to environment conditions. These areas must be filled, normally with mortar or concrete, after an adequate concrete removal and surface protection. Sometimes, when steel is much deteriorated is needed to remove it and replace with new bars or even complete sections. The materials used should have special admixtures, to reduce shrinkage and increase workability, being a good option the addition of fly ashes and polymers.

4.4.3 Electromechanical treatment of contaminated concrete

In the case of carbonation depth be significantly depth, there is the possibility of electromechanical realkalisation that provides new alkalis to the area surrounding the steel, increasing pH, creating a new protective layer. In case of chlorides presence inside the concrete, these can be removed. The two techniques use a metal mesh outside concrete, electrically connected to reinforcement, with imposed current. The installation must be kept for a few days, being this process quite effective and durable.

4.4.4 Other techniques

Some other techniques of less importance for intervention are possible and named in Standard: Electromechanical moisture control, replacing old deteriorated elements and limitation of oxygen content at the cathode by saturation or surface coating.

The table shown below shows the different possible techniques that must be applied in different situations, as well as, the materials to use (Table 4.1):

Table 4.1: Different repair techniques in function of different defects

	Defects	Techniques	Materials
Repair	Live cracks	- Strapping; - Overlaying; - Caulking; - Pressure injection; - Strengthening.	- Steel wire or rod; -Membrane or special mortar; -Elastomeric sealer; -Epoxy resin; -Steel plate, post tensioning;
	Dormant cracks	-Caulking; - Coating; - Overlying; - Jacketing; - Patching; - Shotcrete; - Dry-pack;	-Cement grout or mortar; -Bituminous coating; -Asphalt overlay with membrane; -Steel rod -Cement mortar or Polymer concrete; -Mortar or cement; -Dry pack;
	Voids and Hollows	-Dry pack; -Patching; -Shotcrete; -Replacement.	-Dry pack; -Mortar or cement; -Fast-setting mortar;
	Scaling	-Overlaying; -Grinding -Coating -Replacement.	-Portland cement concrete; -Asphalt cement or polymer concrete; -Bituminous or silanes treatment;
	Spalling	-Overlay; -Coating; -Replacement; -Shotcrete; -Patching.	-Asphalt concrete or concrete; -Bituminous or silanes treatment; -Fast setting mortar; -Concrete, Polymer, Asphalt;

4.5 Strengthening Techniques

The application of any strength technique presupposes the need to improve flexural, tensile, cut and compression strength. [73]

Deflection and Over Loading are the most common problems in reinforced concrete structures that can lead to structural failure and serious safety hazards and often requires the strengthening or replacement of structural members. However there are other problems that lead to strengthening of reinforced concrete structures, such as the described below:

- Deterioration due to ageing;
- Poor initial design and/or construction;
- Lack of maintenance;
- Accidental events (Earthquakes);
- Increase in service loads;
- Large cracks or deformations.

In the selection of the strengthening system, should be taken into account the following factors:

- Intervention cost;
- Architectural constraints;
- Useful life of the structure after the reinforcement;
- Environmental exposure conditions;
- Qualified labor availability;
- Intervention nature (tensile, cut or compression strength) and new design actions.

Strengthening techniques and its design leave the scope of this work. The most traditional techniques for strengthening reinforced concrete structures are described below:

- Section Enlargement

Section enlargement is one of the methods used in retrofitting concrete members and consists of the placement of reinforced concrete jacket around the existing structural member to achieve the desired section properties and performance.

The increase in the concrete member size and the need to construct a new formwork are the main disadvantages of this system. With section enlargement members can be enlarged to increase their load-carrying capacity or stiffness.

This method complain some important stages in its application: 1) removal of the deteriorated concrete and the exposed reinforcement, surface cleaning and preparation, replacement or addition of reinforcement and application of the repair material.

The cost of the materials used in this method are relatively low but it needs a specialized labor.

- External Plate Bonding

This method is considered by some publications as a ‘’classic’’ method. [73] It consists in bonding steel plates or flat steel bars to the structural elements and it is widely appear in the strengthening of bridges structures. Epoxy adhesives ensure the bonding of the steel plates or steel flat bars to the concrete members. This method only can be applied to the relatively sound structures. In case of severe concrete deterioration and major cracks of the RC structure this is not the best option and other methods should be considered.

- External Post-Tensioning

This method is used since a long time ago, being very effective in increasing the flexural and shear capacity of concrete members. The main goal of this method is correct excessive deflections and cracking. Prestressing tendons or high-strength steel rods, normally located outside the original section deliver the post tensioning forces. These tendons are connected to the structure at anchor points, normally located at the end of the member.

The strengthening method must only be applied after a correct reparation of existing cracks and repair to the structural members must be performed in order to a uniformly distribution of prestressing forces across the section.

This system provides active forces being more compatible with existing constructions and therefore has been effectively applied in bridge rehabilitation.

- Ferrocement Covers

Ferrocement method is a type of thin composite material made of cement mortar reinforced with wire meshes. Wire meshes must be uniformly distributed across the concrete layer. This technique is normally used to replace damaged concrete layers. This strengthening improves cracking resistance, flexural stiffness and the ultimate loads compared to the original unstrengthen element. [73]

4.5.1 Applications on traditional methods

- Beams

Strengthening is needed in reinforced concrete beams when the existing steel reinforcement or cross section is unsafe, insufficient or when loads applied are higher than that at the moment of its design. There are different solutions to apply on beams, which depend on the aim of it, if it’s needed to enhance flexural or shear capacity. The techniques described above can be applied in this type of RC elements. (Fig.4.11)

Fig.4.11 – Adding new steel bars to the bottom of the beam (left) and using of steel plates (right) [74]

- Columns

The load carried by the column is normally associated due to either increasing in floors number or due to design mistakes and also if percent7type of reinforcement are not according to the Standards requirements. If column inclination or foundation settlement are more than allowable the column needs the application of a strengthening method. The mains techniques for reinforced columns strengthening are described below.

- Steel Jacket

When it’s not permitted to increase the cross sectional area of the column this technique is normally chosen. This technique is effective to enhance the seismic performance of old bridge columns. This method requires difficult welding work and in long time potential problems of corrosion can appear. The steel jacket is manufactures before and then welded around the column. (Fig.4.12)

Fig.4.12 – Column strengthening by installing steel jackets along the length of the column [74]

- Steel Angles and Plates

Tis method differ from the described before by the fixation of horizontal steel angles, which are fixed to slab at the top and bottom of the column and after steel strips are welded to the vertical angles all around the column perimeter with a specified distance. (Fig.4.13)

Fig.4.13- Strengthening of concrete column using steel plates and angles [74]

- External Steel Plate Bonding

This technique must appear is used to make requires confinement to the column and use steel plates added all over the surface of concrete column. (Fig. 4.14)

Fig.4.14- Column Strengthening using steel plate bonding [74]

- Confinement with external pressure

This strengthening reinforced concrete technique is innovative and its specially used in beam columns and beam-column connections. A set of elongated members is fixed along the element length using strips, increasing the strength and ductility of the RC elements without significantly increase the dimensions and weight of the elements. In addition, the lateral strains, internal cracking and volume increases are reduced with the employment of this technique.

The main problem of this technique is the susceptibility to corrosion damage that results in failure of strengthening system. The Fig.4.15 show 3D perspective that illustrate mechanism during and after the process of strengthening.

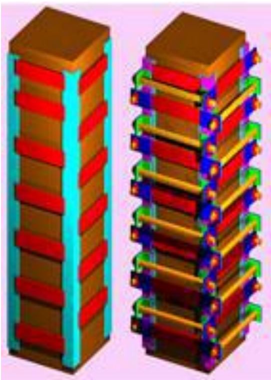


Fig. 4.15 – Strengthening of concrete column using external pressure [74]

The common strengthening techniques can be grouped in a table comparing it’s advantages and disadvantages, as shown below (Table 4.2):

Table 4.2 – Common Strengthening Techniques

	Techniques	Advantages	Disadvantages
Strengthening	Section Enlargement	-Members can increase load-carrying capacity or stiffness; -Cost of the materials relatively low; -Possible implementation in beams and columns;	-Increase in the member size; -Need to construct a new formwork; -Need of specialized labor;
	External Plate Bonding	-Availability; -Cheapness; -Easy to work; -High ductility and high fatigue strength;	-Only possible to apply in sound structures; -Transportation, handing and installation are difficult; -Need of expensive false work; -Corrosion of steel plates;
	External Post-Tensioning	-Very effective in increasing flexural and shear capacity; -	-Only effective when the shear cracks are repaired;
	Ferrocement Cover	-Effective application in tension zone of reinforced concrete slabs; -Improves cracking resistance and flexural stiffness;	-The cost is higher;

4.6 Surface Treatments

To reach a desired durability of new concrete structures as well as existing structures (repair), three main types of surface concrete quality improvement are considered (formalized also in the European Standard EN 1504) [75] :

- Improvement of near-to-surface layer quality by hydrophobic treatment or impregnation;
- Removal of deteriorated concrete and repair with fresh mortar;
- Application of adhesive coating to improve barrier properties.

- Impregnation

The impregnation technique can be used in two different forms, simple impregnation or hydrophobic impregnation. The simple impregnation consists in the superficial concrete penetration of certain products that make it less porous, while hydrophobic impregnation use products that make concrete water-repellent. Both methods aim the obtainment of a concrete more resistant to aggressive agents.

The main materials used in the simple impregnation are synthetic resins, such as acrylic paints or low-viscosity epoxies. In hydrophobic, are used silanes or siloxanes.

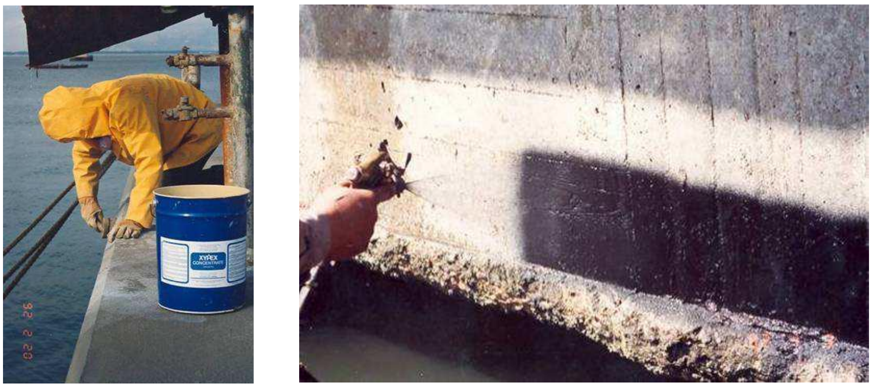


Fig. 4.16 – Impregnation of a surface (left), surface protection with paint (right) [75]

- Surface Coating

The surface coating consists in the application of a coating by painting or with mineral and mixed binders over all concrete surface in order to reduce the concrete porosity and permeability.

- Membranes

Membranes can be described as a type of flexible surface coating of polymeric, bituminous or concrete base which grants total impermeability to water and concrete gases. The use of this technique is only acceptable in special cases, in particular, aggressive chemical environments or cases with high hydrostatic pressure.

- Physical External Protection

It's used a new coating layer to protect the concrete, which thickness can vary between 5 and 60 mm or, also can be used for example a precast concrete panel or composite plates.. For this range of thickness, the coating layer is made with a cement mortar with polymers or Portland cement that can be armed with steel mess or fibers. For thickness greater than 60mm is used shotcrete (small size aggregate mortar), being possible to add silica smoke to improve the properties of this concrete.


Fig. 4.17 – Membrane application (left), physical external protection with fiber glass pates (right) [75]

4.7 Prevention against corrosion

- Steel protection against corrosion

The steel protection against corrosion can involve two different processes: rebar coatings or the use of corrosion inhibitors. The first one contains active pigments with anticorrosive properties or acts as a barrier isolating the steel from water, which is, for instance, the case of resins. Corrosion inhibitors are used in the concrete and they act in the anode, reconstructing the protective layer of steel or they act in the cathode. The last ones are not so common and its effectiveness is still questioned nowadays.

- Cathodic Protection

The cathodic protection is a method that involves the installation of a system that forces the rebars to act as cathodes. It can be passive or active, being the first when is installed sacrificial anodes with lower electric potential than the steel, in electric contact with the rebars. Otherwise, it is active if electric current coming from an external font is imposed to a system that is formed by the rebars and a neutral anode that is collocated on the element’s surface.
This way is very effective to protect the steel against the corrosion due to chloride penetration.


Fig. 4.18 – Steel protection coating (left), cathodic protection of a bridge pier (right) [75]

4.8 Common Repair Materials

The available common repair materials to rehabilitation of concrete structures can be sorted into two different groups: cementitious materials and polymer materials. Table presented below summarizes some of the most common repair materials used in current practice.

Table 4.3 – Comparison between the most common repair materials [76]

	Material	Advantages	Limitations	Applications
Cementitious Materials	Conventional concrete	Easy to handle. Low cost.	Not appropriated to harsh environment. Potential problems due to shrinkage	Thick sections and large volumes of materials.
	Conventional Mortar	Easy to handle. Low Cost.	Not adequate in harsh environment. Greater drying shrinkage.	Same as conventional concrete but for smaller repairs.
	Dry Pack	Durable.	Not adequate for shallow depressions. Performance is dependent of curing process.	Large or small cavities if compaction allows. Vertical and overhead surfaces.
	FRC	Addition of fibers provides reinforcing. High resistance to plastic shrinkage.	Low workability. Potential corrosion.	Overlay of pavements, repair of structures subjected to vibration loading. Slope stabilization.
	Chemical grouts	Short setting time . Moist environments.	Expensive. Skilled labor.	Fill fine cracks.
	Cement grouts	Easy to handle. Low cost.	Minimum crack width shoul be about 1/8 in.	Fill large dormant cracks.
	Low Slump Dense Concrete	Rapid gain strength. Reduced permeability.	Consolidation Problems. 7 days moist curing. Drying shrinkage cracks.	Overlay due to its high abrasion.
	Magnesium phosphate concrete and mortars	Rapid strength gain. Short setting times.	Potential carbonation problems.	Cold weather.
	Preplaced aggregate concrete	Low shrinkage. No segregation. Underwater repairs.	Skilled labor.	Extensive repairs.
	Rapid-Setting Cements	Short setting times	Not adequate in harsh environment.	Time is essential.
	Shotcrete	Areas with restricted access.	High skilled labor High sensitive preparation of the substrate.	Thin section with large surface area and irregular shapes.
	Siliac-Fume Concrete	High strength. High abrasion-erosion resistance. High durability. Similar handing to NC.	Potential shrinkage problems. Wet curing for 7 days with minimum of 40ºF.	Hydraulic Structures. Overlays and parking.

Table 4.3 – Comparison between the most common repair materials [76]

Polymer materials	Polymer-impregnated concrete	Improvement of durability.	Durability issues if all cracks are not sealed.	Long term performance.
	Polymer-modified concrete	Excellent long-time performance. Minimum bond failure.	Susceptible to shrinkage cracking. Placing and curing at 45 to 85ºF-	Overlays for bridge decks, parkings and floors.
	Polymer Concrete	Rapid curing. High strength. Similar handing to NSC.	High thermal expansion coefficient. Poor performance at high temperatures.	Repairs where only is possible to apply thin sections. High protection against chemical attack.

5
MODERN MATERIALS

5.1 Ultra High Performance Concrete

Ultra-High Performance Concrete is one of the breakthroughs in the 21st century in the field of concrete technology where this composite material providing an important improvement in strength, workability, ductility and durability when compared with normal concrete. UHPC can also be defined as a new type of concrete which is also characterized by its constituent material make-up: typically fine-grained sand, silica fume, small steel fibers or basalt aggregates and Portland cement, with a low water/cement ratio, high cement content and mineral admixtures that are selected to increase the bond between the aggregates and the cement paste.

There are different concrete classes considering the compressive strength, although these strength don't describe the complete characteristics of HPC and UHPC.

Table 5.1 – Concrete classes according to compressive strength [76]

Concrete class	**F_{ck} (MPa)**
Conventional Concrete	20-50
High Performance Concrete (UHP)	50-100
Ultra High Performance Concrete (UHPC)	100-150
Exceptional Concrete	>150

In 2010, Harris, made reference, not only to compressive strength but also to tensile strength and elasticity module. [77]

Table 5.2 – Concrete classes differentiation [78]

Property	**Conventional Concrete (MPa)**	**HPC (MPa)**	**UHPC (MPa)**
Compressive Strength	25-55	76-124	138-228
Tensile Strength	2-5	5-6	12
Elasticity Module	25-34	33-44	55

5.1.1 Typical mix of UHPC

UHPC mix designs differ significantly from those of conventional concrete or even high-performance concrete. The basic composition of a typical UHPC mix, by descending percentage of the mix by weight, includes fine sand, cement, pozzolanic supplementary cementitious materials, ground quartz, fibers, water, plasticizing or water reducing admixtures and accelerator.

The introduction of pozzolanic SCMs, such as silica fume, into the concrete mix allows the byproduct CH to react with the SCMs. The result is the production of more CSH and a reduction in the amount of CH. This reduces the volume of the interfacial transition zone between the matrix and aggregates, strengthening and improving the concrete.

Silica fume is normally used in quantities between 5% and 10% of the cementitious materials by mass but can be used in amounts approaching 30%. With an increase in the silica fume content of a mix, the concrete becomes increasingly sticky and less workable, and slump flow values steadily decrease.

SCMs like silica fume can have average particle diameters really small (about one hundredth of cement), which allows the SCM particles to fill the interstitial voids between cement grains and ground quartz particles and consequently improve the bond between the aggregate and hydrated cement. This improved particle packing contributes to the higher density oh UHPC microstructures, and the resulting disconnection of pore spaces decreases penetrability.

5.1.2 Inclusion of fibers in UHPC

UHPC members exhibit ductile behavior due to the use of reinforced fibers and elimination of passive reinforcing bars. Usually fibers are the last component to be added during the mixing, and when used properly, are uniformly distributed throughout the batch. Architectural applications require organic plastic fibers instead of steel fibers in structural elements.

Fibers has an important role in inhibition of both plastic shrinkage cracks and service cracks. As excessive forces are applied to a member and cracks begin to develop, the even distribution of fibers throughout ensures they will be present at the side of fatigue. At the moment that cracks start forming, the tensile forces applied transfer to the fibers, which can have tensile strengths in excess of 245,000 psi. The fibers bridging the cracks lend their strength to the member, allowing it to remain ductile, with stand increasing stresses, and impede crack propagation. Conventional concrete does not possess the same degree of ductile behavior before cracking and are not apt to support increasing loads after reaching their yield strength, what not happen with UHPC.

5.1.3 Ultra High Performance Fiber Concrete

According to *Uchida 2006* [79], UHPFC can be defines as follow:

"The UFC is a type of cementitious composites reinforced by fiber with characteristic values in excess of 150 N/mm^2 in compressive strength, 5 N/mm^2 in tensile strength and 4 N/mm^2 in first cracking strength. The matrix of the UFC is as follows: it should be composed of aggregates, whose maximum particle sizes are less than 2.5 mm, cement, and pozzolans and the water-cement ratio is less than 0.24. It contains reinforcing fibers of more than 2% by volume, whose tensile strength exceeds 2000 N/mm^2, ranging 10 to 20 mm in length and 0.1 to 0.25 mm in diameter. "

5.1.3.1 Properties of UHPFC

- Tensile behavior

UHPFC offers additional advantage of a very dense low-permeable matrix comparing with the group of high performance fiber reinforced cementitious composites (HPFRCC). The UHPFRC exhibits a significantly increased tensile strength and strain-hardening behavior as compared to other cementitious materials. [4]

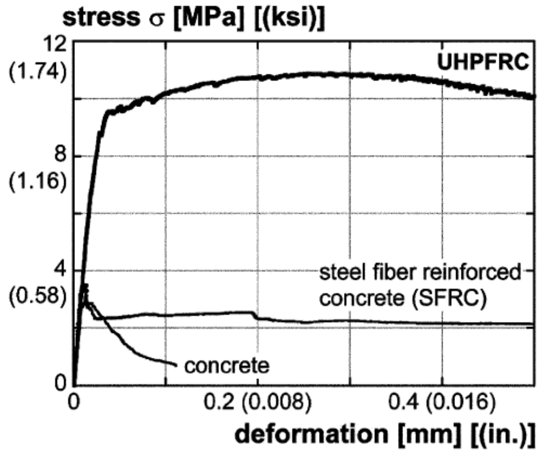


Fig. 5.1 – Comparing UHPFRC, conventional concrete and steel fiber reinforced concrete in uniaxial tensile behavior [80]

- Flexural Strength

The ductility of UHPFC is 250 times greater than that of conventional concrete. [81] It's possible to characterize the behavior of UHPFC under flexure loading by three phases, that are 1) the linear elastic behavior up to the first cracking strength of the material, 2) a displacement-hardening phase up to the maximum load and 3) a deflection-softening phase after the maximum load is reached. A typical load-deflection diagram for UHPFC in bending is shown below.

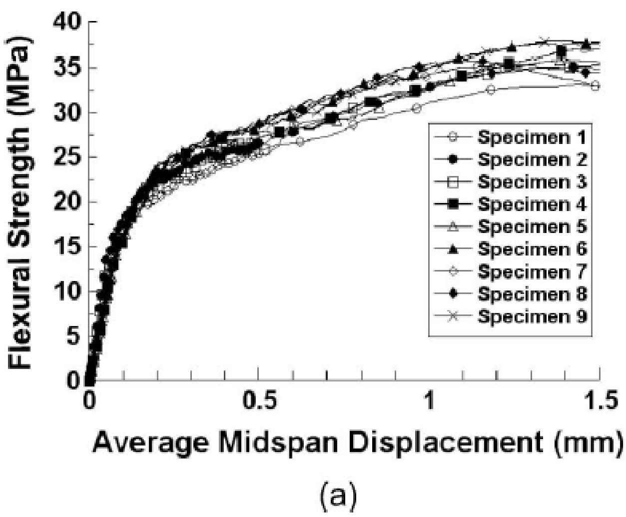


Fig. 5.2 – Flexural Strength versus midspan displacement [82]

- Durability

The microstructure of UHPFC leads to greater durability properties that makes this material not only a high strength but also a high performance material. The very low porosity of UHPFC, particularly capillary porosity, leads to improvements in the durability and this consequently may lead to reduce maintenance costs for the material and a possible reduction in the layer to cover concrete against the weathering effects.

In Fig. 3 is shown a research that compares the durability properties for UHPC to HPC and normal concrete (lowest values identify the most favorable material).

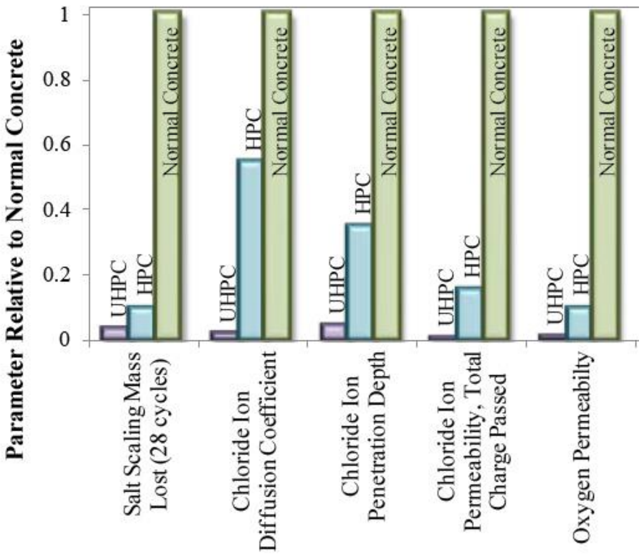


Fig. 5.3 – Durability properties of UHPC and HPC with respect to normal concrete [83]

5.1.4 Application of UHPC in building construction

The most significant feature of UHPC is high compressive strength which allows the design of more slender structural elements. This material offers new solutions, mainly in what concerns to innovative construction in more exposed situations, such as aggressive environments (proximity to sea, industrial and polluted environments) or exceptional loads (earthquakes, floods, strong winds, blasts etc.).

Even UHPC is currently more used in infrastructures like bridges and roads, there is a big potential to the use of this material in building construction. The main advantages of the application of this material are as follows:

- Higher compressive strength enables construction of slender and lighter structural members with reduced use of primary material;
- UHPC can be used for larger spans and heavier loads;
- UHPC can be used in aggressive environment (high resistance to carbonation and abrasion, freeze-thaw cycles, chloride attack);
- Lower load from lighter structural members on supporting members;
- Structural members from UHPC are more strong and can be more ductile;
- High durability and operating life;
- High resistance in starting age;
- Low fluency and retraction;
- Lower environmental impacts.

The first known use of UHPC (with more than 150 MPa) in building construction dates to 2001, in Joppa, where a clinker silo was built with the roof from Ductal® concrete with compressive strength up to 220 MPa and flexural strength 50MPa. The panels were designed without any conventional reinforcement by steel bars.

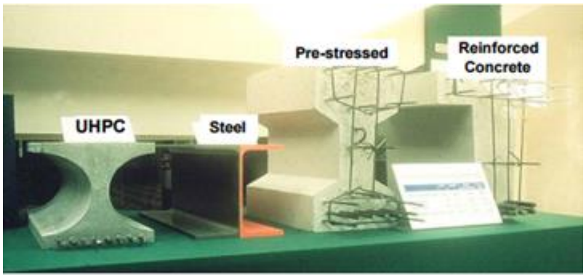


Fig. 5.4 – Comparison between different types of beams [80]

Table 5.3 – Mass ratio to steel for equivalent capacity members [80]

Ductal	Steel	Pre-Stressed	Reinforced
1.3	1.0	4.2	4.7

5.1.5 Potential for reduction of environmental impact by the use of UHPC

The use of UHPC allows the design of slender shell structures with reduced use of materials that leads to reduction of environmental impacts due to the use of primary natural sources and reduction of waste from demolished structures. Potential reductions of environmental loads are mainly the savings in natural resources, savings in transport environmental loads (less material and lighter structural elements), savings in maintenance (high durability) and reduction of the volume of the waste material in the end of structure life cycle.

5.1.6 UHPFC in Rehabilitations

5.1.6.1 UHPFC as a repair material

Reinforced concrete structures prevailing in the building area around the world a long time ago. The utilization of reinforced concrete as a building material become more common around 60 years ago (1950) as was referred in 3.3.1 of the present study. From this moment till nowadays, RCS represent around 50% of total classic buildings in Portugal and similar numbers in other countries. This fact took the industrialized countries to invest substantially in their RCS, that were primarily designed to withstand the mechanical loadings, but it has also learned that these structures were also constantly subjected to physic-chemical phenomena that result in early deterioration and subsequently reducing its reliability to perform adequately.

Rehabilitation of deteriorated concrete structures is a heavy burden from the socio-economic viewpoint since it leads to significant user costs. As a consequence, new concepts for the rehabilitation of RCS must be developed and the concrete constructions of the future will be those which require just minimum interventions of only preventive maintenance with little service disruptions.

The selection of repair materials for concrete structures requires an understanding of material behavior in the anticipated service and exposure conditions. The dimensional behavior of a repair material relative to the substrate is one of the greatest challenges to a successful performance. If the repair material is not properly selected can appear tension cracks, due to high internal stresses, loss of load carrying capability, delimitation or deterioration.

Over the last years, considerable efforts to improve the behavior of cementitious materials by the incorporation of fibers lead to the appearance of UHPFRC. These new materials provide the structural engineer a combination of 1) extremely low permeability which prevents the ingress of detrimental substances and 2) very high mechanical strength, i.e., compressive strength higher than 150MPa, tensile strength higher than 10 MPa and considerable tensile strain hardening and softening behavior.

The utilization of UHPFRC allows a good permeability to external agents, guarantee more durability compared to normal concrete and allows a speed construction due to the rapid strength. Normally it’s possible to UHPFC materials gain compressive strength of 80MPa and 100MPa after 1 day and 2 days respectively, of ambient air curing. [85] Reactive Powder Concrete (RPC) displays excellent repair and retrofit potentials on both compressive and flexure strengthening due to its possesses high dynamic modulus value, high bond strength capacity and outstanding bond durability as compared with other types of concrete. [86] Other fact is the adhesion between the steel bars and RPC that is much higher compared to other concretes.

5.1.6.2 Repair and rehabilitation interventions with UHPFC

Ultra High Performance Fiber Concrete must be used only in those zones of the structure where the outstanding UHPFC properties in terms of durability and strength are fully exploited; i.e. UHPFC is used to ‘harden’ the zones where the structure is exposed to severe environmental conditions and high mechanical loading. The other parts of the structure don’t need, necessarily, to be repaired with this concrete, being possible the use of conventional structural concrete.

The properties of this new material allows its application in the rehabilitation of buildings, mainly in cases where is needed the rehabilitation of concrete elements or its strength. It’s more usually in monumental buildings, where the needs of rehabilitation are normally realated with the increase of load capacity or superficial reparation.

UHPFC’s have an excellent rheological properties in the fresh state allowing for easy casting of the self-compacting fresh material with conventional concreting equipment on the construction site and in the prefabrication plant. The typical configuration of a composite structural element combining UHPFRC and a layer with conventional concrete is presented below (Fig.5).

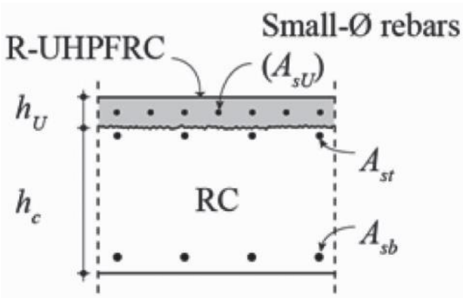


Fig. 5.5 – Basic configuration of structural element combining UHPFC and conventional RC [87]

The potential compatibility of UHPC with the normal concrete substrate is presented below.

- Bond Strength with the substrate

The bond performance influence the success of any rehabilitation. Several researches shown the following conclusions [88] :

- Bond strength is greatly dependent on the test method used and the bond tests must be selected such that they represent the state of stress the structure is subjected to in the field;
- The measure bond strength decreases with the test method in the following order: slant shear, Bi-Surface shear, splitting and pull-off;
- Bond Strength increases with silica fume content for all test methods, being negligible beyond a silica fume content of 7%;
- Rough surface preparation leads to higher bond strength. These influence is more pronounced when the repair materials have low adhesion, e.g., cementitious materials;

Other studies were done with the aim to investigate the impact of concrete substrate surface treatment on bond quality in repair systems, being possible to draw the following conclusions [89]:

- The selection of surface treatment technique should be preceded by the analysis of its aggressiveness in relation to the concrete substrate strength, taking into account both the development of the roughness profile and the decrease of surface tensile strength due to micro cracks in the near to surface layer: for concrete substrates with compressive strength lower than C30/37, less aggressive treatment is recommended, because it does not generate cracks in the near-to-surface layer. In case of higher quality concrete substrates, it is better to use more aggressive treatments which significantly increase surface profile and improve the mechanical interlocking;
- Surface tensile strength is a very accurate parameter for characterizing the quality of substrate prior to repair and is easier to evaluate than density of micro cracks;
- Surface roughness is an important parameter influencing the adhesion of repair layer to concrete substrate;
- Compressive strength of concrete substrate is not a very important parameter in the evaluation of adhesion in repair systems if surface treatment was properly selected;
- It is possible to quantify the effect of surface treatment on the bond strength evaluation based on the multiple regression approach using surface tensile strength and surface roughness index as explanatory variables. This allows the estimation of the bond strength with an accuracy of about 0.5 MPa.

- Curing requirement/setting properties

The compressive strength of UHPC in ambient curing is almost non-existing at one day after casting. It’s possible to use the infrastructure in a short time after repairing, due to the gain of strength of UHPC to 9.4 ksi at 48 hours after the initial set takes place. [90]

- Dimensional Stability

Shrinkage tests on UHPC at early ages resulted in the development of stresses of approximately the 45% of the first crack tensile strength. [91] UHPC can absorb most part of the loads without suffer any problem of failure due to its mechanical properties. The higher modulus of elasticity of UHPC to the one of NSC is compensated by its higher bending, tensile and compressive strengths.

- Constructability

UHPC has similar placing and treatment practices than normal concrete due to its cementitious characteristics. Some several difficult steps, such as compaction by vibrating and installation of waterproofing membranes can be skipped by using UHPC.

- Durability

As previously stated, UHPC shows excellent performance under different environments what become this material an excellent choice in what concerns to durability and maintenance works.

- Cost

The initial cost of HPC's will be higher than conventional concretes, therefore in its production, where will be needed a special effort in the preparation, because production errors can compromise the durability of the structure. In big constructions, where is expected a long life time (around 120 years) without major repairs, a failure in the production of HPC which put in question this durability could have damaged consequences.

The initial costs of HPC and UHPC are higher due to the non-optimization of companies in the production of these materials and the high cost of the constituency materials, being at the date the cost estimated in 10 times higher than conventional concrete. It's expected that with the most abundant use of this type of concrete in constructions, the costs of its production might reduce and these materials may till the end of its lifetime justify the investment financially in the employment. Below is shown a figure that illustrate this reality (Fig.6) .

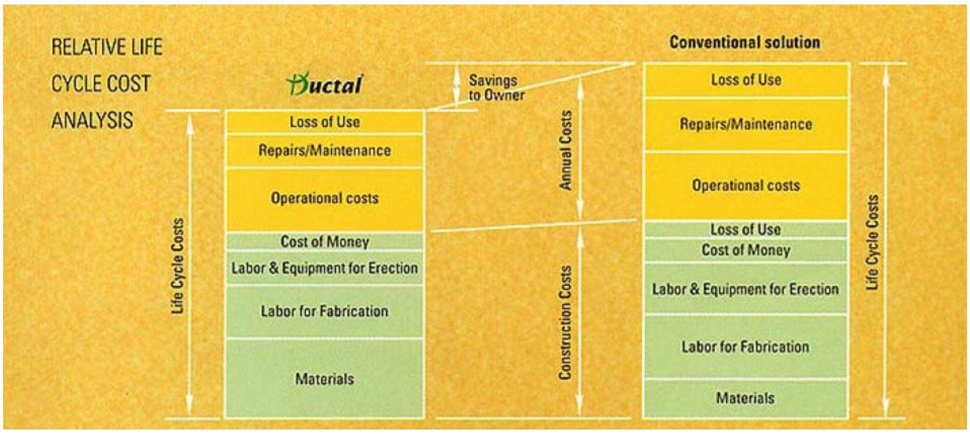


Fig. 5.6 – Relative life cost analysis between Ductal® (UHPC) and conventional concrete [92]

In an economic analysis of the rehabilitation of bridge over La Morge River in which the cost of the rehabilitation by using UHPC was compared to that which would have cost by a traditional solution composed of mortar and waterproofing membrane was stated that UHPC solution is 12% more expensive than the conventional alternative. If it's taken in consideration factors as the long service life and short down time are into consideration, it would be expected that the use of UHPC is cheaper from a life cycle perspective.

5.2 Fiber Reinforced Polymers

A considerably amount of research, development and innovations are carried out in the construction sector in the last years. Fiber Reinforced Polymers materials have been one of the materials most used in the construction of new structures and mainly in rehabilitation and strengthening of existing structures and is one of today's state-of-the-art techniques. These composites are currently viewed by structural engineers as 'new' and highly promising materials in the construction industry. [93]

These materials hold great for the future of construction industry. The use of FRP reinforcement in repair is a highly practical strengthening system, having some advantages compared to steel as referred below:

- Low weight;
- Easier application;
- High flexibility during installation;
- High tensile strength;
- High elastic modulus;
- Good fatigue resistance;
- Immunity to corrosion;
- Life cycle cost can be competitive to steel;
- Minimal modification to the geometry, aesthetics and utility of the structure;

Although the material cost of carbon FRPs was several times more than that of steel plates, the fact that 6,2Kg of carbon FRPs could be used in place of 175Kg of steel is enough to explain the advantages of FRPs over steel plates. [94]

5.2.1 Fiber Composites

There are a multitude of materials that FRP composites can be created from, being three of them more common that will be focused on this topic. These three materials are carbon, glass and aramid fibers, having each one a different set of qualities making it suitable for certain applications and also the ability to be used in various different FRP systems that may contain FRP strips, sheets, fabrics or bars. Carbon fibers have the highest strength and stiffness followed by aramid and glass fibers. The composite's properties can be enhanced with the addition of additives, e.g. improve the bond between the composite and the strengthened material by a sizing compound. [94]

Depending on the type of fiber used, the FRP material can be referred to as CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer) and AFRP (Aramid Fiber Reinforced Polymer). The combination of these materials is also possible into a composite and then tailor-make the mechanical properties to correspond to the preferred characteristics

Glass Fiber Reinforced Polymers sheets are being increasingly used in rehabilitation and retrofitting of concrete structures, since low cost comparison with other types of FRP fibers are generally high strength-to-weight ratio, corrosion resistance and fatigue resistance. Glass fibers are classified as chopped strand mat, woven roving, continuous rovings, E-glass, S-glass, satin weave cloth and laminate. The low cost is the main factor that turn GFRP the most fashionable and used FRP reinforcement in civil engineering applications.

Aramid Fibers are prepared from liquid crystal polymers, which in the liquid state retain some measure of crystalline molecular orientation and order. The main advantage of this FRP reinforcement is the very low density, giving high values of tensile specific strength and stiffness, which combined with good toughness, allows frequently use in applications where impact resistance is important. However, the fibers have low shear modulus, poor transverse properties and low axial compression strength. Taking this, aramid fibers are frequently used in combination with other fibers, such as carbon and aramid, providing toughness characteristics to the composite.

Carbon fibers today in Structural Engineering are used in FRP strengthening sheets, fabrics, strips and tendons. These fibers have diameters ranging from 5 to 10 micrometers and have teo dimensional atomic structure. Along the longitudinal axis of the fiber the modulus and strength are high as opposed to the transverse axis which provides little of either strength or modulus. When in the presence of metals, care must be taken due to the fact of carbon fiber be an electrically conductive.

5.2.2 Epoxy Resins

The resin of a FRP material acts as a matrix and is a substrate which bonds the fibers of an FRP together and also in many cases, bonds the FRP to the structure. The adhesive properties and strength of epoxy resins turn that these become the choice in many FRP strengthening applications, being possible to apply directly to dry fibers in strips form, fabrics, or sheets and the concrete substrate to act as both the adhesive and matrix for the FRP fibers.

The epoxy resins used in these FRP's are similar to the ones used in other structural applications, such as crack injections, bonding of concrete elements, etc. These resins have excellent corrosion resistance and less shrinkage than other resins when cured. The price of these resins is a little high but the time saved in installation and downtime make these systems competitive.

5.2.3 Common FRP Strengthening methods

- Strengthening Using Sprayed Fiber Reinforced Polymers

Strengthening using sprayed fiber reinforced polymers (or Sprayed FRP) is a new strengthening method by sprayed carbon or glass fiber with vinyl ester resin upon concrete structures. In this method carbon or glass fiber chopped is sprayed with vinyl ester resin using the air compressive machine on the surface of concrete structures directly. The benefits of this method is that it takes shorter time to harden the resin compared to epoxy resin, being the mechanical properties the same as epoxy resin.

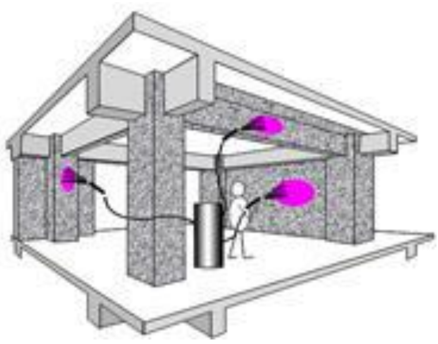


Fig. 5.7 – Sketch illustrates sprayed FRP strengthening technique for different elements [80]

- Externally Bonded FRP Composites Based Solutions

Strengthening causes of old or/and reinforced concrete elements and elements using FRP composites can be described as the following [80]:

- Inadequacy in longitudinal reinforcement in elements like beams and columns lead to flexural failure. In these cases the bending capacity of concrete elements can be increased through the use of externally bonded FRP strips, plates or fabrics. NSM strips or rods can be also utilized (Technique described below).
- Inadequacy in transverse reinforcement can lead to shear failure in structural members like columns, beams, walls and beam-column joints. The application of externally bonded FRP with fibers oriented in the transverse direction of the elements or in the direction of these is a good way to enhance the shear capacity of concrete members.
- In regions of flexural plastic hinges, where the concrete crack may be followed by cover concrete Spalling, failure of steel reinforcement, or compressive crushing of concrete. The add of confinement in form of FRP jackets with fibers placed along the element perimeter prevent the spalling of cover concrete and restrain the buckling of the longitudinal steel bars. The implementation of this method allows ductile responses and larger inelastic deformations can be sustained.
- Poor detailing in lap splice can cause debonding, which can occur once vertical cracks develop in the cover of concrete and progresses with cover spalling. With the installation of fibers, the lap confinement is increased and flexural strength degradation can be prevented or limited.
- The stiffness characteristics of existing RC elements cannot be modify by the use of FRP reinforcement. The FRP technique is not applicable if the structural intervention is aiming at increasing stiffness rather than strength or ductility.

- Flexural Strengthening of Beams

The need to reparation and strengthening of RC members has been due to corrosion of steel reinforcement, cracking caused by excessive carbonation, freeze-thaw action, chemical reactions and spalling of concrete cover. In buildings is mainly the deterioration and changing needs that lead to strengthening and reparation of existing beams.

The addition of adhesive-bonded steel plates on the tension side of the reinforced concrete beams is one of the most common methods for external strengthening. Epoxy-bonded steel plates are very used but they show some disadvantages, such as high weight, transport, handle and installation difficulties. Even with the restriction of the length to 8-10m it may be difficult to erect them due to pre-existing service facilities; contaminants on prior to bonding; steel plate thickness at least 5mm , complex profiles are difficult to be shaped; durability and corrosion elects remain uncertain and it’s needed an expensive false work to maintain these elements in position during bonding.

The fibers are oriented along the longitudinal axis of the beam and it’s efficacy depends mainly on the appropriate selection of the composite material and on the efficiency of the bond between the fiber and concrete surface. The addition of anchor bolts in FRP ends is sometimes done to prevent end peeling. Two different possible types of application of FRP reinforcement are shown below (Fig.5.8).

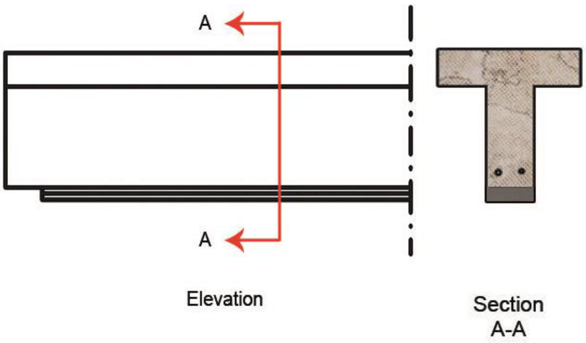


Fig. 5.8 – Flexural Strengthening of a RC T-beam and a building using externally bonded FRP reinforcement (left) and CFRP strips (right) [80]

- Shear Strengthening of beams

The shear strengthening must be considered when a concrete beam is deficient in this effort or when shear capacity is less than flexural after flexural strengthening. Various bonding schemes of FRP strips have been utilized to improve the shear capacity of RC beams. The fiber direction must coincide to that of maximum principal tensile stress to maximize the shear effect of FRP external reinforcement. Normally structural members subjected to transverse loads form an angle between the shear critical zones and the member axis of about 45º. However its more usual to attach the reinforcement with the main fibers direction.

Shear strengthening must be satisfied in both directions being necessary to arrange fibers at two directions. These procedures are shown in the following images (Fig.5.9,5.10,5.11).

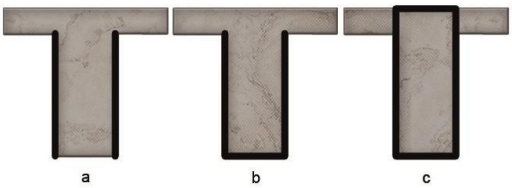


Fig. 5.9 – Shear Strengthening illustration – a) FRP bonded only to the sides b) U – Jacketing c) Complete Wrapping [80]

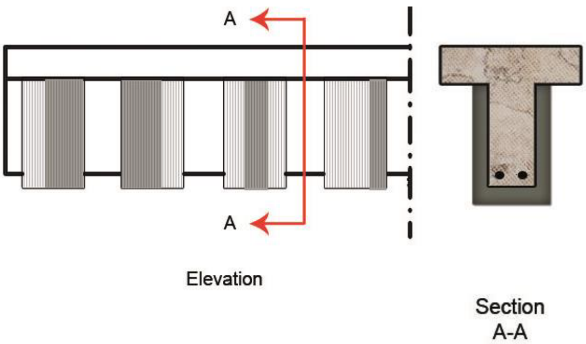


Fig. 5.10 - Shear Strengthening of a RC T-beam using externally FRP reinforcement [80]

Fig. 5.11 - CFRP L-shaped installation over CFRP strips for flexural strengthening [80]

- Strengthening of RC slabs

The strength of slabs is normally done when its required more load capacity or changing needs. There are two different methods to apply FRP strips depending on the way how its supported. If the slab is simply supported the strength must be done with the application of FRP strips to the soffit along the required direction and when is a two-way slab, the strength must be applied for both directions, by bonding FRP strips. The FRP strips can be terminated far away from the edges. [95] That's because the possible collapse mechanism of a two-way slab suggests the application of FRP strips in the center of it. The figures below show different configurations of FRP applications (Fig. 5.12,5.13).

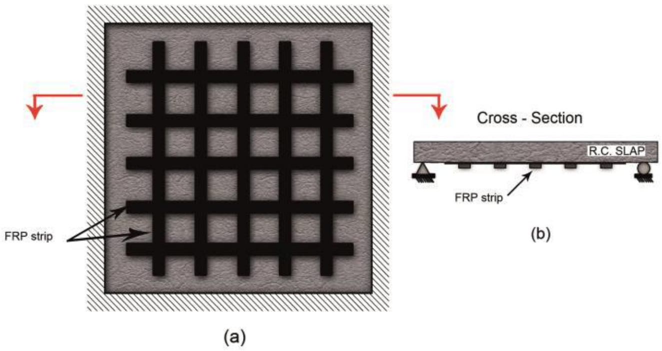


Fig. 5.12 – Strengthening of two-way slab (a – slab soffit, b – cross section) [80]

Fig. 5.13 – Strengthening of concrete slab of a building using CFRP strips on the top (left) and underside of the slab (right) [80]

- Strengthening of RC columns

The conventional methods to columns strengthening are effective but they have some disadvantages, such as, requiring intensive labor, consume many time, can intercept the correct functioning of the structure, the quality is often questionable and they are susceptible to degradation by corrosion that can influence the seismic force levels.

The strengthening of these elements using FRP jacketing is based on a well-established fact that lateral confinement of concrete can substantially enhance its axial compressive strength and ductility, being the most common form of strengthening, the external wrapping of FRP straps. The use of FRP composites provides means for confinement without increase stiffness, rapid fabrication and durable jackets. Concrete and FRP jackets are used to their best advantages due to the fact of FRP jackets being loaded mainly in hoop tension and concrete is subjected to tri axial compresson.

FRP confined concrete possesses an enhanced ductility instead of the brittle behavior exhibited by concrete. In the case of FRP wrapped, the design philosophy relies on the wrap to carry tensile forces around the perimeter of the column as a result of lateral expansion when loaded axially in compression. The column and consequently lateral expansion constraining confines the concrete , increasing its axial compressive capacity. It is important to refer that passive confinement of this type requires significant lateral expansion of the concrete before the wrapping and the initiation of confinement.

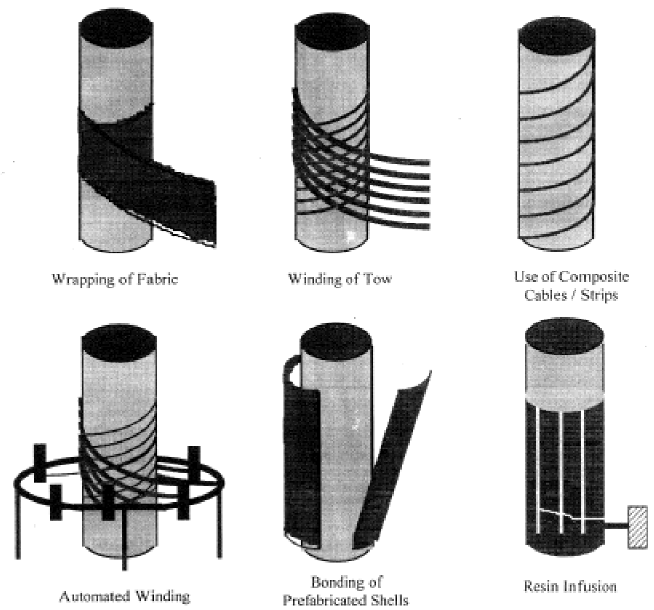


Fig. 5.14 - Methods of FRP strengthening to RC columns [96]

In case of rectangular or square columns its different and rectangular columns corner radius must be applied to corners of column or transform column section to elliptical shape to be possible utilize the effect of confinement.

Fig. 5.15 – Installation of FRP wrap [80]

- Pre-stressed composite systems

Prestressed composite systems are an economical alternative to conventional prestressing methods used in new construction. Nowadays the prestressed FRP methods are not well established. The installation techniques, both manual and automatic, have to be perfected and development work has to be done before they are suitable for practical applications.

The installation of prestressed strips prior to bonding has some advantages, such as, delay crack formation in the shear, closes cracks in structures with pre-existing cracks, improves serviceability and durability and improves the shear and flexural resistance of section. However this technique has also some disadvantages, as, it's more expensive than normal strip bonding and the installation operation is longer. [93] In the figures below is presented the concept for applying a prestressed FRP and an application in a bridge (Fig. 5.16,5.17).

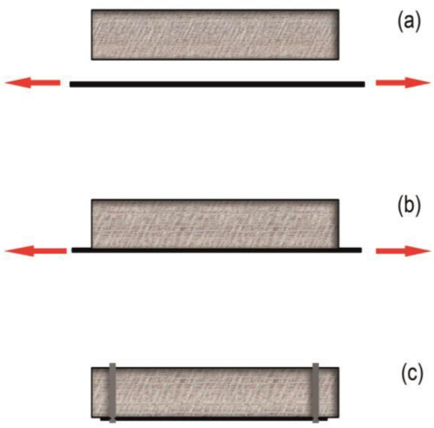


Fig . 5.16 – Strengthening with prestressed FRP strips – a) prestressing b) bonding c) end anchorage [80]

Fig. 5.17 – Strengthening of bridge using CFRP strips with steel end anchorage. [80]

It’s also possible to prestress column jackets by pretensioning the fiber bundles during winding or with unstressed jackets by making use of expansive mortar or injection of epoxy under pressure.

- Near Surface Mounted Technique

When EBR may be difficult or impossible to setup it’s possible to use the technique of Near-Surface Mounted reinforcement, where a composite rod is bonded in a pre-sawn groove in the concrete cover, can be used. [98] This method is normally used to increase the load carrying capacity of existing RC elements, that is possible by addition of tension reinforcement in surface grooves made along the cover on the tension side (in case of flexural strengthening) or in the web (in case of shear strengthening) (Fig. 5.18, 5.19). [98]

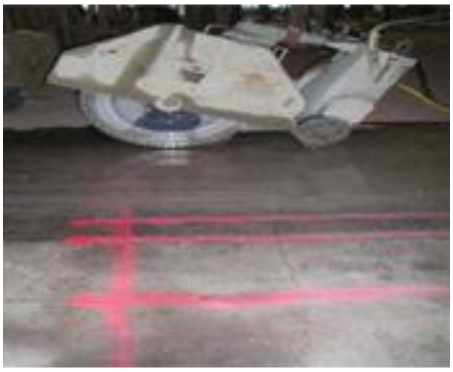


Fig.5.18 – Electrical cutting of slots in NSM technique. [80]

Fig.5.19 – Vertical grooves for shear strengthening with NSM FRP. [80]

This technique is particularly attractive for flexural strengthening in negative moment regions of slabs and decks and where concrete shows damaged sections requiring protective cover. It becomes particularly interesting to be used in old buildings concrete elements rehabilitation what makes that this technique has attracted an increasing amount of research and has been frequently applied.

The use of FRP rods for this application is very recent, NSM steel rods have been used in Europe for strengthening of reinforced concrete structures since the early 1950s. [99] Nowadays FRP rods are used in place of steel and the epoxy paste can replace cement mortar. The rods are very close to the surface, which exposes them to the environmental attacks being the resistance of FRP to corrosion particularly important in this case. The figures below shows different NSM strengthening methods (Fig.5.20, 5.21).

NSM technique can be used in addition to other advanced techniques like externally bonded FRP.

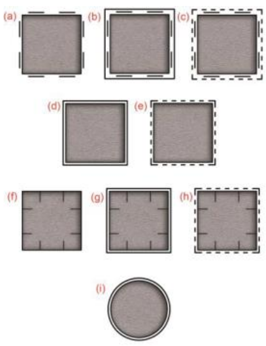


Fig. 5.20 – Different NSM systems [80]

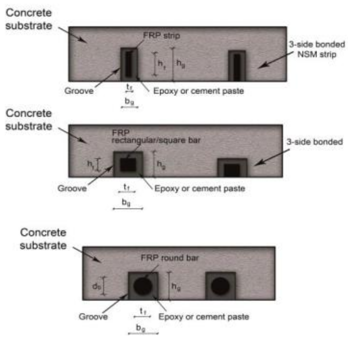


Fig. 5.21 – Strengthening solutions for structural elements in compression [80]

5.3 Textile Reinforced Concrete

Textile Reinforced Concrete (TRC) is an alternative strengthening material that has become of interest as of late. This technique is comprised of a cementitious matrix as the bonding agent and textile fabric as reinforcement. The TRC system is mounted with a fine-grained, high strength concrete as bonding agent, having this high strength concrete a maximum aggregate size of 1mm. The reinforcing fibers present are predominately made of AR-Glass or also its possible a combination between carbon fibers and AR-Glass fibers. Due to its high strength, TRC can be effectively used in strengthening elements in bending such as slabs or beams [100]. This technique can also be applicable to strengthening of columns.

The application of one or several layers of TRC at the bottom or top of the element which is strengthened, the resistance in flexural loading is increases by wrapping the core of the beams with layers of TRC and the shear performance of the entire structure is enhanced.

The strengthening of slabs is used a very simple method that consists on: 1) bottom face of the slab is pre-wetted and roughened by sand-blasting and then the first layer of fine-grained concrete is applied, being possible the application by spraying or just by simple hand lay-up. The textile mesh is applied by hand on the fresh-grained concrete and the process of alternating these two materials can be repeated until the desired amount of reinforcement is applied under surface of the slab. A small amount of concrete is used to strength the slab, which gives a small self-weight.

The main advantages of this strength technique are the high modulus of the cement-base matrix which may open the way for the use of lower modulus fabrics, which are less expensive than using EBR method and the cement binders are less expensive and less sensitive than epoxy matrixes to deterioration causes as fire hazards, freeze thaw effects and high temperature environments.

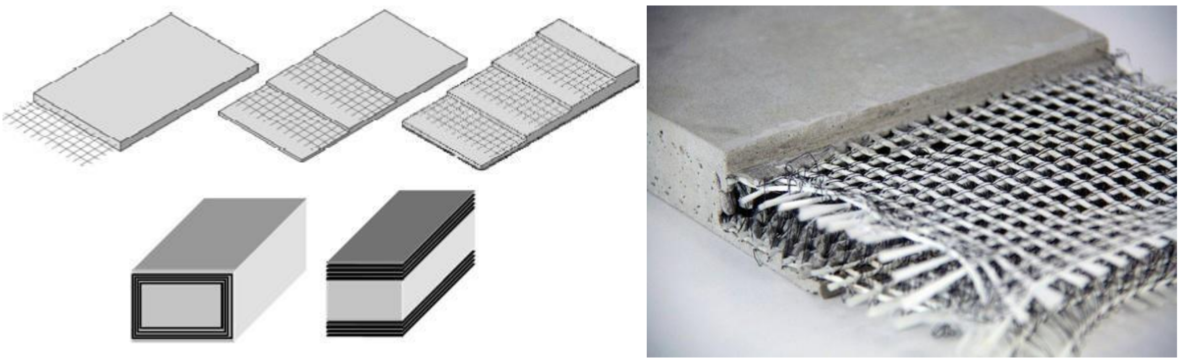


Fig. 5.22 - Schematic sketches for TRC layers and application techniques (left) and illustration of TRC (right) [80]

6

BOND STRENGTH IN CONCRETE REPAIR

A good quality bond between an overlay and concrete substrate is an important requirement for assuring efficiency of repair. [101] The bond strength between two different concrete materials is influenced by many factors, such as substrate surface (wetting conditions, roughness, presence of micro cracks, cleanliness), compaction method, curing process, concrete substrate, use of bonding agents, age of the bond, and overlay material (strength and thickness). These factors can be grouped in three main groups where each factor have different degree of influence.

Factors	Importance		
	1	2	3
Substrate characteristics			
Substrate properties	X		
Microcracking			X
Laitance			X
Roughness	X		
Cleanliness			X
Overlay characteristics & application technique			
Pre-wetting		X	
Bonding agents	X		
Overlay properties		X	
Placement	X		
Compaction			X
Curing			X
Environmental conditions			
Time		X	
Early traffic	X		
Fatigue	X		
Environment	X		

Fig. 6.1 – Factors affecting bond between concrete substrate and repair material [102]

Usually the quality of the bond between the concrete layers is linked to the roughness degree of the interface between the two parts. The process of preparation the substrate surface of a RC member must be studied and normally the main question in this process is to know if it is rough enough or not.

The correct roughness preparation and characterization of a concrete surface must meet three essentials steps: 1) an adequate preparation method, to remove the superficial layer of concrete and/or increase the surface roughness; 2) a method capable of obtaining a 2D profile or 3D sample of the surface and 3) a method to calculate numerical parameters from these 2D profiles or 3D samples and to assess the effectiveness of the preparation method.

6.1 Methods of Surface Preparation

There are different types of methods to remove the superficial layer of concrete, either for the removal of damaged concrete or only to increase the surface roughness. According to ACI 555R (2001) the methods can be classified in: a) mechanical removal; b) particle impact removal; c) hydro demolition; and d) chemical removal.

The use of an abrasive preparation method, such as sand-blasting, after the use of a mechanical removal technique can help in the reduction of micro-cracking.

- Mechanical Removal

Mechanical removal involves the use of manual or mechanized systems to remove the superficial layer of concrete. This category includes techniques like scarification, chipping and wire brushing.

The first is also known as milling and is a technique that removes concrete by applying a rotating cutting wheel to the surface. This technique is mainly used in horizontal concrete surfaces as bridge decks or pavements.

Chipping is a term used when the technique includes the use of hand, electric or pneumatic hammers with a chisel or a bushing tool. The equipment must be adequate to be used in horizontal and vertical areas.

Wire-brushing makes use of a brush attached to an electrical rotary hammer to remove the concrete layer. It’s appropriated to small areas and early age concrete due to be a light removal technique. The increase of the application time, the rotation speed and the pressure applied to the surface can easily increase the surface roughness.

Fig. 6.2 – Scarification [103]

One of possible problems of this techniques is the presence of reinforcement bars in some zones where the concrete cover is reduced and the bars can be damaged. The selection of an appropriate cutting head, with the ideal spacing and shape of the teeth.

- Particle Impact Removal

Particle impact removal is related with the process of roughening a surface by forcing solid particles across it at high speeds, being possible to use these methods in concrete removal. The most used techniques of this process are shot-blasting (metal particles) and sand-blasting (sand particles)

These techniques can be used in small or large and vertical or horizontal surfaces in a fast and effective way.

Fig. 6.3 – Sand – Blasting [104]

- Hydrodemoliton

The term hydrodemoliton can also be named as water-jetting or water-jet basting and defines the technique that uses high pressure water jets to remove the superficial layer of concrete. This technique must be used in situations where is allowed the use of water and the reinforcement bars will be reused. The final surface of concrete members is influenced by several parameters, such as: 1) nozzle type; b) distance to surface; c) water pressure and d) operating time.

Fig. 6.4 – Hydrodemolition [105]

- Chemical Removal

Chemical removal is a technique that uses the application of an acid solution to a concrete surface, allowing the acid to react with it and etch the concrete. Acid etching is the most common designation of this type of technique, being this technique less popular and not so much used comparing with other mentioned before.

The products used in this technique are highly dangerous acid solutions and the application must be made according to specific regulations for chemical residuals.

The techniques mentioned before can be grouped in a table referring it’s advantages and disadvantages (table 1).

Table 6.1 – Different techniques of Surface Preparation

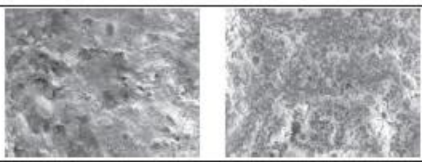
Technique	Advantages	Disadvantages	Possible applications
Chipping	-Can be used in vertical and horizontal surfaces; -Possible to define the type of face and roughness;	-Reduced speed; - Noise;	-Slabs and pavements;
Wire Brushing	-Can be applied to almost all surfaces; -Possibility to increase the surface roughness;	-Very wok intensive; -Light removal technique; -More appropriate to early age concrete; -Reduced speed; -Noise;	-Slabs and pavements;
Scarification	-Good to be applied in large areas and pavements;	-Cost higher than the others; -Reduced speed; -Noise;	-Slabs and pavements;
Shot-Blasting Sand-Blasting	-Capability to be used in horizontal and vertical surfaces; -Fast and effective way; -Low risk of producing microcracks; -Possible use to clean steel bars;	-Requirement careful application;	Walls, Beams and Columns;
Water Jetting Water-Jet Blasting	-Reuse of steel bars; -Higher bond strengths obtained;	-Incorrect distance to surface, water pressure or operating time can compromise the effectiveness;	Walls, Pavements, Beams and Columns.
Acid etching	-Fast application and results; -Easy application (without many means of application);	-Products highly dangerous;	Walls, Pavements, Beams and Columns.

6.2 Microcracking and adhesion

In the case of concrete of relatively low quality, beside the surface roughness, the presence of cracks in the near-to-surface layer is a very important factor that may affect the adhesion of repair systems. The influence of the various surface preparation techniques can be evaluated by microscopic observation of the prepared surface (Table 6.2).

According to some investigations, low pressure water jetting does not generate microcracks and scabbling may induce a big amount of micro cracking in very near to surface-area. The preparation with jack hammer and it weight increasing results in higher number of cracks and total crack length. [6]

Table 6.2 – SEM observations [106]

Example of surface view SEM: magnification 25x (left) and 500x (right)	Description
Grinding	
	surface without sharp edges with rarely and non-uniformly located valleys at the surface; at higher magnifications, the narrow cracks were observed
Sandblasting	
	surface similar to that after grinding; shallow irregularities of surface - peak-to-valley height did not exceed 1 mm; at higher magnifications, sharp edges of aggregate grains and microcracks, very often forming non-uniform network, were observed
Shotblasting	
	highest surface roughness increasing with the treatment time; high irregularities of surface - the peak-to-valley height increased locally to 7 mm after 45 s treatment; the increase of treatment time caused the forming of a dense network of microcracks and cracks, often along aggregate grains as well as presence of deteriorated or debonded particles
Milling	
	surfaces after milling similar and close to the concrete surface after shotblasting; very high irregularity of the surface, but less than that after shotblasting; at higher magnifications, deep and wide cracks, detached particles and loose concrete fragments were observed

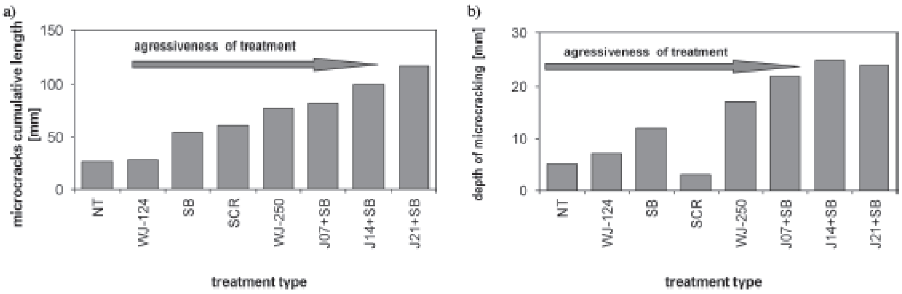


Fig. 6.5 – Length of the cracks (left) and depth of microcracking (right) vs type of surface treatment: NT – No Treatment, WJ – Water jetting – pressure 124 psi/250Mpa; SB – Sand Blasting; SCR – Scabbling; J+SB – Jack Hammering of Weight 7,14,21 Kg + Sand Blasting [6]

The results shown above are a result of an investigation made with the aim of analyze the effect of substrate roughness and superficial microcracking upon adhesion of repair systems using concrete surface engineering approach. The analysis of Fig.5 allows the written of some conclusions about the aggressiveness of treatment and its influence in the length and depth of microcracks. The length has a linear behavior with the aggressiveness of the treatment, being the Jack Hammering of weight 21Kg + sandblasting the treatment that causes microcracks more lengthy. In the case of microcracking depth it’s different and it’s not influenced by the treatment type in a linear way. In this case the treatment that causes lowest depth is Scabbling.

6.3 Test Methods to evaluate bond strength

Nowadays the tests most used for assessing the bond strength between concrete substrate and overlay material are classified into three categories according to stress measure.

The first category of tests measures the bond under tension stress. Pull-off (a), direct tension (l) and splitting (m,n) are the main tests under this category.

The second category of tests measures the bond under shear stresses, and are called shear methods. Several tests fall under this category, including L-shaped, mono-surface shear (K), etc.

The third category measures the bond strength under a state of stress that combines shear and compression. All slant shear tests mentioned previously fall under this category. The shear-compression test (d) and the slant shear test (k) belong to this category.

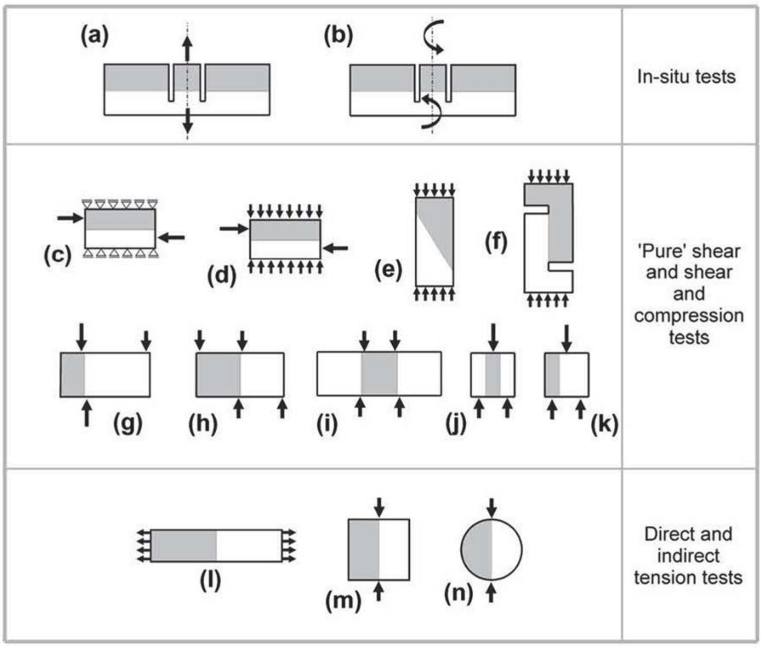


Fig. 6.6 – Most common bond strength tests [107]

7
CONCLUSIONS AND FUTURE WORKS

The first point of this thesis was the study of the Portuguese construction and rehabilitation sector, as well as the classification of the Portuguese building stock. This study allowed us to obtain some important conclusion in this field as are described below.

The construction sector in Portugal has been oriented mainly to the new construction. However it’s possible to verify that the sector of rehabilitation has assumed a great importance in the construction sector, without an increase of real activity in that segment. It’s possible to notice a reduction on the new building construction pace, but the rehabilitation sector shows a limited dynamism. Several factors can be collapsing the activity segment of rehabilitation, in particular, the lack of financial liquidity of companies and real estate promotors, the difficulty of disposing new housing or the existence of a legal framework of construction that is not suitable for the rehabilitation interventions. Companies should be more specialized in rehabilitation of buildings including more qualified labor. The introduction of some improvements in legislation that regulates the entrance and permanence in construction activity would be also desirable.

The development of rehabilitation sector is justified by the number of buildings that need intervention, the permanence of a number no despicient of accommodations with qualitative needs and allow to compensate the reduction in new housing construction activity.

The reorientation of construction sector to rehabilitation of buildings may contribute to the improvement of functionality and security conditions of the building stock, the maintenance or increase of productivity and employability in construction industry and finally the social and economic revitalization of the urban zones, currently abandoned and degraded.

The Portuguese old buildings has mainly three materials in their structure, which are wood, concrete and masonry. Each material has different origins and applications, being the buildings made with each of these materials different and more or less usual.

Most of the Portuguese buildings have in their structure concrete, being this material one of the most used over the years. Due to this and the need of rehabilitate old buildings was presented in this thesis some modern materials useful in rehabilitation of buildings, particularly in the interventions that can be done in concrete.

The main problems in concrete structures were described, being possible to conclude that the environment is one of the responsible to deterioration of concrete structures. Physical, chemical, natural and accidental are the main causes associated to concrete structures deficiencies. There are some common techniques and materials useful to repair these kind of structures, most of them normalized and usually applied. It was possible to notice that a rehabilitation intervention can be not only rehabilitate the structure or a set of elements, but also strength it.

Strengthening concrete elements has a great importance in this topic and the techniques associated were also referred in this thesis, being importante to make reference to the technique of steel jacket and external steel plate bonding.

Associated to common repair and strengthening techniques are associated common materials that were used over the years. However, nowadays has been done many researches and studies about other new materials that can replace the common ones. In this field was study in this thesis the possible application and use of Ultra High Performance Concrete and Fiber Reinforced Polymers in the process of rehabilitation, particularly in the repair and strengthening of concrete elements and structures.

The potential use of UHPC as a repair material was showed throughout this thesis. UHPC exhibits several properties that make it appropriate for this purpose. The extremely low permeability, very high strength and outstanding mechanical properties of this material appear to make it suitable for use as a standard overlay material that is capable of resisting mechanical loadings and severe environments. The improved durability characteristics and high compressive strength suggests that UHPC could be used as an attractive choice to conventional overlay materials and solutions. The use if this material in rehabilitation interventions guarantee a long-term durability which helps to avoid multiple rehabilitation intervention on concrete structures during their service life. It's possible to recognize that UHPC will not replace the general use of the traditional materials and associates techniques, because for some applications these meet all the requirements, but the use of UHPC may offer a competitive alternative, mainly in the repair of concrete slabs.

However, for a better acceptance, it has to be demonstrated that the bond between UHPC and NSC will offer a good performance without help of a bonding agent. The success of the rehabilitation depends on whether the bond interface can stand the different combination of stresses that it will be subjected throughout its service life, such as overlays shrinkage and carrying loads. These facts took to the study of mechanical preparation and profiling of the concrete surface to be repaired. It's possible to conclude that the condition of the substrate surface of reinforced concrete composite members plays an importante role on the development of the bond strength at the concrete to concrete interface. A certain degree of roughness is normally required for the substrate interface in order to achieve an adequate bond between concrete layers.

The preparation of the substrate surface can use different methods. Factors such as the available conditions on site, the existence of steel reinforcement near to surface, the associated cost or the possibility of using water normally are the responsible to the selection of the preparation method, being the most common, chipping, wire brushing, scarification, sand blasting, shot blasting and hydro demolition. After the preparation of the substrate surface it's essential to control the quality of the finishing surface and should be not only adopted as a first approach.

After the study of UHPC as a repair material it was also referred other important material that is Fiber Reinforced Polymers. FRP composites have been available to the civil/structural engineering for rehabilitation, retrofitting and strengthening of RC structural members for more than two decades. FRP systems have the ability to be customized through the use of different FRP configurations, installations and different material properties. Whether reinforced concrete structures are comprised of beams, columns or slabs, FRP's can be used to improve strength and ductility while benefiting form a large service life extension. The materials included in these FRP systems, are not only driven by the local costs of these systems. It's necessary that the engineer evaluate all aspects of the project, including the location of the structure. The environment where the structure is insert has the ability to degrade these FRP materials depending on the exposure of different elements and also the duration of time exposed to these elements over the life of the system. The material must be chosen and designed taking account these considerations in mind to maximize the benefits of this rehabilitation technique.The methods of rehabilitating and retrofitting FRP composites to various structural components have been given in this thesis, being their design outside the scope of this chapter.

FRP composites can be used in many applications, such as flexural strengthening of slabs (Strips and Sheets), flexural strengthening of beam (Strips, Sheets and Fabrics), shear strengthening of beams (Angles, Sheets and Fabrics), shear strength and confinement of column (sheets, fabrics and shells) and shear strengthening of beam-column joint.

The conclusions described above are result of the written of this thesis and research associated. It’s important to notice that in this thesis the main objective was to refer some modern materials and specify their possible application in rehabilitation works, as well as, their characteristics, advantages and disadvantages. On a future work would be interesting to study more depth the use of these materials in rehabilitation of buildings, namely monitoring the application of these materials in a real case of building rehabilitation. This process should start with the study of different options to use in the interventions to be done and later apply these materials with proper design. It would be good to understand the behavior of the materials in a real case, subject to the normal actions that every structures are subjected. After these study and application would be interesting to encourage to the use of these modern materials in future rehabilitation works.

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