IMPACT OF ELEVATED TEMPERATURE, CHEMICAL AND WORKMANSHIP ON PERFORMANCE OF BEAMS WITH NEAR SURFACE MOUNTED FRP BARS

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Dedication

I would like to dedicate this thesis to my dearest family. Without their consistent motivation and infinite support, I wouldn’t have been able to accomplish and complete it. Actually, without their contribution in my life, I wouldn’t be who I am today; the least I owe to them is the utmost gratitude and respect. To my father, Metwally Metwally, thank you for giving me a firm foundation, guidance and love. You will always be my role model; I will always look up to you no matter what. To my mother, Samar El Sheribini, you have always believed in me and raised me with unconditional love and care. I hope that one day I will be able to payback and make you proud. To my brother and sister, Moataz and Mai, you have always had my back especially you my young sister, and I can blindly rely on both of you. A special gratitude goes to my wife, Amina Mokhtar, who believed in me and gave me all the support and time I needed, no words can describe how grateful and lucky I am to have you by my side.
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Of course, I can’t disregard Mr. Fares and all AUC laboratory personnel effort. They were really helpful throughout the thesis.

It is of course indispensable to express my absolute appreciation and gratitude to my dearest family. Unfortunately, any amount of appreciativeness and thankfulness won’t be enough. You worked so hard to construct the perfect atmosphere and ambiance in order for me to succeed.
Abstract

Near surface mounted (NSM) is growing exponentially into the strengthening and repair of concrete structures over the past decades worldwide. CFRP NSM offers a superior strength over conventional steel reinforcement as well as a good durability in various environmental service conditions. However, the effect of elevated temperature, adhesiveness and chemicals has not been sufficiently studied.

This study aims at assessing the impact of elevated temperatures, adhesives, and chemicals on beams exposed to flexural loading. To meet this objective, a set of 60 beams were prepared with locally available NSM and exposed to temperatures of 70, 120 and 180 °C for 1, 2, 4 and 8 hours. Beams were also evaluated with three levels of adhesiveness placement and were also exposed to five weeks of wetting and drying in fresh water, brine water and magnesium Sulphate.

The results of this work reveal that CFRP bars NSM mounted at a depth of 25 mm introduces more than double flexural strength of conventional steel reinforced beams. Exposure to different degree temperature at various duration, placement of adhesive and exposure to chemicals all lead to substantial drop in the flexural strength and thus affect the potential gain of NSM. This study should be resumed by future research work to validate the findings on one hand and to examine the effect of numerous other parameters. Construction industry needs to be aware of the findings of this work to make better use of its implementation in future repair and retrofitting.

Keywords: (Near Surface Mounted, Fibre Reinforced Polymer, Repair and Retrofitting, elevated temperature, adhesive, chemicals)
## Notations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSM</td>
<td>Near Surface Mounted</td>
</tr>
<tr>
<td>EB</td>
<td>Externally Bonded</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fibre Reinforce Polymer</td>
</tr>
<tr>
<td>AFRP</td>
<td>Aramid Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>MMFX</td>
<td>Martensitic Microcomposite Formable Steel</td>
</tr>
<tr>
<td>RC</td>
<td>Reinforced Concrete</td>
</tr>
<tr>
<td>PC</td>
<td>Plain Concrete</td>
</tr>
<tr>
<td>Tg</td>
<td>Glass Transition Temperature</td>
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</tbody>
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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Fibre reinforced polymer (FRP) rods are commonly comprised of carbon fibre reinforced polymers (CFRP), glass fibre reinforced polymers (GFRP) or aramid fibre reinforced polymers (AFRP). Those rods are composed of extended fibre strands, bonded longitudinally in a resin hardener matrix. This resin system embraces everything together, and it transfers mechanical loads to the rest of the structure through the fibres. Along with, binding the composite structure together, and it protects from abrasion, impact, corrosion, and rough handling. Resin systems come in a various chemical families, each designated and designed to serve the industries in providing some advantages like structural performance, economic, and resistance to numerous factors. Only the resins most commonly used in composite construction are described, those are polyester, vinyl ester, phenolic and epoxy. The resin matrix allocates the load acting on these fibres, strengthening and stiffening the rod. FRP rods are categorized by expressively higher strength-to-weight ratio than steel rods, which may surpass one thousand MPa in short-term tensile strength. CFRP has less density than conventional steel which makes them a better option regarding the weight, with non-metallic properties enhancing the durability and the resistance to corrosion. They show diminutive to no electromagnetic or to thermal conductivity, but having lower fire resistance than that of steel due to the composite nature of fibres in polymers. Moreover, FRP rods are considerably more costly than conventional steel and lacks ductile failures behaviour, revealing purely a linear elastic brittle failure. These factors limit directly the widespread usage of FRP rods as another alternative to conventional steel in reinforced concrete (RC) structure (Helbling et al. 2006).
Strengthening of existing reinforced concrete (RC) structures is a necessity due to the destructive environmental conditions, increased service Fibre reinforced polymer (FRP) are used in numerous reinforced concrete strengthening techniques, which have been employed and tested over the last two decades. These techniques are being used for both repair and strengthening, improving the flexural capacity and stiffness of structural members. This technology provided shear and flexural enhancements in built structural beam members, as well as flexural enhancements in constructed beam members (Mauselli 2013). Furthermore, its usage extended to concrete masonry unit (CMU) construction and steel as well (Myers 2007). Initially, this type of technology was embraced in the form of FRP rods, strips or plates, bonded externally to concrete element using a cementitious adhesive or epoxy. This presented clear shortcomings, explicitly exposure of these unprotected reinforcement to the external environment factors that risk the integrity of adhesiveness, through chemical or thermal exposure, also as the direct exposure of an entire system impacting foreign objects. However, the system main strength is laying in favour of material qualities of FRP reinforcement by itself, which are resistive to corrosion and to aggressiveness of chemical attacks, unlike conventional steel. (Hassan 2014)

More recently, efforts have been made in order to mitigate the above mentioned limitations of externally bonding repair system, by the development of the near surface mounted system as shown in Figure 1.1. This technique use existing concrete covers in different structural members, through making grooves within these covers that allows the installation of FRP reinforcing rods or plates. These rods afterwards are adhered to this groove by using cement grout adhesive or epoxy, before the rest of the groove is levelled and filled, leaving the reinforcement embedded in the structural member itself and not
bonded externally. Using this unconventional system added value to its practicality of use, which even allows for both bottom and top reinforcement without being threat of any environmental damage or exposure. The Separation of reinforcement due to delamination shows to be the issue owing the embedment of reinforcement, also as the advantage of not needing strict surface preparations for the members to bond the FRP rods or strips. Experimental findings indicates that, this technique tends to improve ductility as if compared to externally bonded technique (Wan et al. 2006). Conversely, this technique poses additional challenges, specifically its requisite for having enough concrete cover, also a sandblasting treatment for the rods in order to improve its unite with the adhesive (Zsombor 2013).

![Figure 1.1: Groove Cutting and Doweling of FRP into a Wall (Zsombor, 2013)](image)

Strengthening of already existing reinforced concrete structures is always a necessity because of the harsh environmental conditions, service loads which increased,
the errors in many designs and also during construction phase. Near surface mounted (NSM) reinforcement is a leading strengthening techniques which is used for strengthening RC structures being designed and already existing RC structures. Furthermore, fibre reinforced polymer (FRP) are more resistive to thermal, mechanical and environmental damage. NSM strengthening uses the concrete surrounding to protect the NSM strips or rods from thermal, mechanical and environmental damage. Improving durability, fatigue performance, and stress sharing mechanism are another advantages of NSM reinforcement to be mounted inside the structural member. (Al-Mahmoud 2013)

A core feature within this research domain is studying the bond behaviour of added FRP reinforcement to an already existing reinforced concrete structural member. While, FRP strips mainly fail because of tensile rupture, on the other hand, FRP rods fail mainly due to failure in the FRP adhesive interface, or due to debonding. One more mode of failure observed in the system, is split failure in the concrete adhesive surface (Choi et al. 2012). Consequently, the effect of having an increased FRP reinforcement to the vital capacity of this member is basically limited to the bond strength which is developed by both the FRP adhesive and FRP concrete surface. Many parameters are being studied in order to increase the optimization on the bond strength, by an increase in the groove adhesive layer depth and size, along with the effect caused by the rod bonding length over improving the capacity of the structural member (Zsombor, 2013).

Moreover, the rods shape prompts circumferential tensile stresses on the adhesive, which provokes the necessitate optimizing of tensile strength of the adhesive grout material. Also, a possible cohesive shear failure in the grout material, which likewise requires high shear strength. While most of the research made use of the epoxy filler, the cement based
adhesives are also used and cheaper, less hazardous for workers, more environmental, can bond on wet surface and they provide better compatibility and homogeneity with concrete members. However, owing much higher and stronger bond strength of that of epoxy over that of cement based adhesives, epoxy still remains the more preferred type of an adhesive in NSM applications as shown in Figure 1.2 below (De Lorenzis et al. 2006).

For the purpose of this research, CFRP was selected as the type of FRP material and epoxy for testing in the NSM system,

![Figure 1.2: FRP Strengthening NSM FRP Rod (Azadeh, 2016)](image)

### 1.2 FRP Applications and Durability

Strengthening of already existing reinforced concrete (RC) members is becoming a necessity because of the destructive harsh environmental conditions, the increased service loads, the errors in design which is caused also during construction. NSM system depends on composite action between bonded CFRP rod and steel reinforced concrete member. So, this composite action is reached by installing CFRP rods in the groove, and bonding it with the epoxy. As such, this system functionality is limited on how well is the CFRP rod bonded
with the epoxy, indicating in turn the bond to the concrete member (Hong et al. 2007). At a specific strain, enough differential elongation happens between the RC and the CFRP section, letting the section lose the composite action, CFRP to debond, and considering the CFRP reinforcement failed. The strain is debonding strain and it is the leading factor in the designing of the NSM reinforced members.

At elevated temperature, the organic polymer matrix mechanical properties decrease which accordingly reduces the ability of transmitting forces between fibres and the concrete surface. Consequently, this structural system is considered as ineffective. Furthermore, when temperature increases, deterioration of adhesive bond and slipping of the boundary appears and it is commonly known that FRP materials are exposed to mechanical properties degradation when at elevated temperature. Mechanical properties of FRP materials at high temperature are scarce. Also, there is lack of information concerning the mechanical properties and bond properties of FRP materials when exposed to elevated temperature (Bishy 2011).

1.3 Applications in Egypt

Geographically Egypt is one of the countries that encompasses various combination of different environmental factors such as the ultraviolet radiation caused by sunlight, periodic temperature changes and humidity especially on the northern coast. The fast deterioration in concrete structures observed in Egypt are constant and ongoing challenges facing the construction industry. Also, areas like Mediterranean and Red Sea, in particular, suffer from accelerated deterioration process from the harsh environment (Mohamedin et al. 2013). In the past couple decades in Egypt, implementing FRP strengthening structural system has grew a distinctive consideration followed by establishing the first Egyptian FRP
code in 2005 (Housing and Building National Research Centre 2005). In 1998, was the first strengthened structural concrete project carried out using FRP materials completed in Egypt (Abdelraham et al. 2003). Afterwards, a lot of historical buildings were enhanced using FRP materials some examples of these are the Kiatbay Fence and the Egyptian Museum (Abdelraham et al. 2003).

1.4 Statement of the Problem

The concept of NSM reinforcement on the tension side to a beam is claimed to increase the beam flexural load capacity, and it was introduced by Meier (Meier 1987). It was then found by Dong et al. based on the experimental results, that flexural strength of CFRP strengthened beam changes between 41 to 125%. Hence, further research and study are needed in order to better understand the limitations of CFRP materials strengthening capacity (Dong et. Al. 2012).

In addition, under some conditions exposure to an elevated temperature or fire hazards is for sure a primary concern that could discourages FRP usage. Wu and Li stated that CFRP strengthened concrete can exhibit a 65% strength reduction when reaching high temperatures as of 300 °C in return this will affect the serviceability of this strengthened concrete structure (Wu and Li 2016). Reviewing the available information and recent findings, the definite behaviour of NSM CFRP materials after the exposure to elevated temperature remains fundamentally unknown (Foster and Lisby 2006).

Lately, the urge of supplementary data and information in regard to the effect of elevated temperature, adhesiveness and chemicals, on CFRP strengthened beams has not been sufficiently studied, which prevail on the need to further studies and investigation of
their long term performance. This is accompanied by the critical classification of some available researches to the little information for the future widespread and implementation of FRP systems in concrete systems (Harries et al. 2003; Karbhari et al. 2003; Al-Tamimi et al. 2014).

1.5 Objectives and Scope

The objectives of this research, is to assess the impact of elevated temperatures, adhesives, and chemicals on beams exposed to flexural loading. In order to meet this objective a set of sixty beams were prepared with locally available NSM and exposed to temperatures of 70, 120 and 180 °C for 1, 2, 4 and 8 hours. Beams were also evaluated with three levels of adhesiveness placement and were also exposed to five weeks of wetting and drying in fresh water, brine water and magnesium Sulphate. NSM CFRP rods were installed as shown below in Figure 1.3.

![Figure 1.3 FRP Rod Installation in Beams (Azadeh, 2016)](image-url)
1.6 Methodology

The methodology of this work is based on that beams are nearly the closest structural members to be idealized, pure flexural member, and rectangular without needing to account on shear within the analysis of the scope. Simultaneously, beams steel reinforcement, have a small concrete clear cover, makes it prone to deterioration and hence need the usage of NSM reinforcement more than most other structural member. Finally, it appears that there is deficiency in reviewed literature at the degree which beams have previously been investigated, leading it to be one of the least member types investigated. So the work conducted is summarized as follows:

1. Add NSM reinforcement to beams (specimens)
2. Determine flexural load failure of beams under different environmental factors
3. Determine the NSM CFRP durability.
4. Perform three-point flexural test on NSM reinforced concrete beams as shown in

Figure 1.4

![Three Point Testing Apparatus](image-url)
1.7 Organization of Chapters

Beside this chapter, the thesis include four more chapters which are outlined hereunder:

- Chapter 2: presents literature review in regard to Near Surface Mounted Fibre reinforced polymers bars development and history, proportioning, theory, mechanical properties, applications and production aspects. Reviewing recent studies and papers performed in achieving comprehensive perspective of the technology.

- Chapter 3: illustrates the experimental work carried out in this study. The materials being used along with a detailed procedure of the experimental work conducted.

- Chapter 4: presents the results of the durability, flexural strength testing of reinforced concrete specimens. Results are compared and listed to other specimens, for a better understanding of properties to this technology. Interpreting and explaining results in order to identify the behaviour and the reasons of their occurrence.

- Chapter 5: presents conclusions of the study. Conclusions are drawn from experimental results obtained from precious Chapters 3 and 4. A set of recommendations to the industry applicators were highlighted to smoothen the implementation of this technology. Finally, the recommendations for future work and the construction industry.
CHAPTER 2: Literature Review

2.1 Fibre Reinforced Polymers (FRP)

Several investigations were made by researchers all over the world in retrofitting of RC beams area. Many parameters were considered starting from strengthening material type, number of layers, wrapping scheme, and concrete grade for both analytical models and experimental. Using composite materials gives several advantages, as being easier and faster in installation, has a smaller weight and much higher durability than traditional steel reinforcements. The FRP is the composite material which is most widely used. FRP consist in different types of fibres (glass, aramid and carbon) embedded in polymer matrix, were is mostly epoxy resin. (Larzon, 2014)

FRP resembles a composite material made from a fibre reinforcement matrix of polymer. Fibres regularly are in the form of aramid, glass, and carbon. Other forms of fibres which sometimes are used are as paper, asbestos and wood. Regarding the polymer itself, it comes in the different forms as thermostatic plastic, epoxy, polyester and vinyl ester. FRP applications are not only limited to construction industry; it was initially used in aerospace, automotive industries and marines. Implementation of FRP materials continues to grow to almost all advanced fields of engineering. The key of this widespread of FRP materials is its new advanced systems development. These new developments of FRP materials include innovative reinforcement’s types as the carbon nanotubes and nanoparticles in addition to high performance adhesive systems (Hong, 2015).

The idea behind composite materials is to develop a product formed by combining between two or more materials with a significant chemical and physical properties, having
each of them remaining different and independent within its composite material. This mostly occurs due to a process called polymerization which changes the polymers properties when combined with the different additives in order to improve its mechanical properties (Mauselli, 2013). The components forming the composite materials can be occurring naturally or engineered together. Composite materials primarily consists of two substances, firstly the matrix which contains the polymer and the structural element carrying the load element. Usually structural elements come in form of fillers, sheets, fibres, and flakes. Not only binding the fibres and protecting them from external environment, the matrix also allocates and distorts load to fibres. FRP composite materials includes mainly three elements, which are fibres, polymers, and additives. Additives mostly appear in form of plasticizer. Moreover, synthetic polymer composites examples are CFRP and GFRP and the most commonly used matrix with carbon and glass fibres is the thermosetting polymer which is made of either epoxy or polyester (Mauselli, 2013).

The main function of composite materials are enhancing primarily the structures strength and stiffness. This is accomplished by having stronger material with lower density in weak matrix polymer. The composite materials mechanical properties depend on the components properties specifically the matrix and fibres accompanied by their manufacturing process (Setunge, 2015). As a result, it is particularly important to understand the components properties in order to be able to understand the composite materials properties.
2.2 FRP Material Properties

Unlike conventional steel rods, tensile strength of the FRP rods is not usually constant and depends on the cross sectional area. When FRP rod through the surface is pulled in tension, a differential movement between surface fibres and core may occur, resulting in an ununiformed distribution of the normal stresses throughout the cross section area of the rod. Moreover, FRP rods are manufactured in several different surface treatments that greatly affects its bonding behaviour when being used as NSM reinforcement as shown in the below Figure 2.1. (Lee and Estrada, 2009)

![Surface Treatment of Some Available FRP Rods](image)

Figure 2.1: Surface Treatment of Some Available FRP Rods (Lee and Estrada, 2009)

Generally, young’s modulus of the FRP rods are lower than of steel and it remains practically more constant up until the failure point which is the elastic brittle behaviour. On the other hand, steel rods were ductile behaviour is more expected and therefore reflected in the design codes. Because of the lower values of the modulus of elasticity, FRP
reinforced concrete deformations are expected to be larger than steel reinforced concrete. Having these two differences in the mechanical properties will affect the bond behaviour and thus it is essential to take them into consideration when design codes are being developed. Glass fibre reinforced polymer (GFRP) have the least value of the modulus of elasticity and are the cheapest when compared to other types of FRP. The GFRP rods tensile strength can be as more as twice the tensile strength of conventional steel rods, while aramid fibre reinforced polymer (AFRP) and carbon fibre reinforced polymer (CFRP) rods can develop much more reaching more than threefold, but depending on the fibres and matrix nature (Setunge, 2015). Comparison between tensile properties of steel rods and FRP rods is shown in Table 2.1 and Figure 2.2 below.

Table 2.1: Mechanical Properties of FRP and Steel Materials (Azadeh, 2014)

<table>
<thead>
<tr>
<th>FRP Types</th>
<th>Unit</th>
<th>GFRP</th>
<th>CFRP</th>
<th>AFRP</th>
<th>Steel</th>
</tr>
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<tr>
<td>Fibre Content</td>
<td>wt%</td>
<td>50-80</td>
<td>65-75</td>
<td>60-70</td>
<td>-</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>1600-2000</td>
<td>1600-1900</td>
<td>1050-1250</td>
<td>7850</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>GPa</td>
<td>25-55</td>
<td>120-250</td>
<td>40-125</td>
<td>200</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>400-1800</td>
<td>1200-2250</td>
<td>1000-1800</td>
<td>400</td>
</tr>
</tbody>
</table>
FRP have been widely used in numerous fields such as electrical, automotive, aerospace, marine, sporting industries, and military. Nevertheless, it differs when we come to environmental factors and loading conditions, especially affecting the long term performance and durability of the applications of the construction industry. Reasoning all of this back to durability challenge which is offered by construction industry nature. The durability mainly is about whether if environmental factors is a singular or an assembly of exposures which will be involved (Karbhari et al. 2009). Each FRP system, has a distinctive $T_g$ which is the glass transition temperature of the polymer matrix or adhesive is lower than that of the surrounding temperature; its range is usually from 60 to 82 °C depending on the available FRP systems (ACI 440.2R-02, 2002). As established in many preceding studies, the adhesive bond softens usually when temperature gets close to $T_g$ which leads

Figure 2.2: A Comparison of the Tensile Properties of FRP and Steel Rods. (Azadeh, 2014)
to substantial reduction in elastic modulus and strength as illustrated in Figure 2.3 (Ahmed and Kodur, 2010). The FRP strengthening systems ability to define temperature limits is still questionable and neither fully specified nor denied. There are no enough experimental verifications that supports the limitation of the glass transition temperature (Burke et al. 2012). Accordingly, the interface between NSM FRP composite materials and concrete will always represent a weak point in the strength of the system as a whole (Ahmed and Kodur, 2010).

Figure 2.3: Schematic Graph for the Tg effect on the Tensile Strength and Elastic Modulus of the Adhesive Bond (Ahmed and Kodour, 2010)
2.3 FRP Applications

The two mainly strengthening techniques of RC structures which uses FRP materials are NSM reinforcement and EB reinforcement as shown in Figure 2.4.

![Figure 2.4: Different FRP Applications (Azadeh, 2014)](image)

The bonding of FRP sheets on the tension side surface of the concrete to reinforce the existing RC structures is the method called EB technique. Earlier, externally bonded technique showed their effectiveness in the strengthening of RC structures. Using bonded steel rods and plates for the rehabilitation and strengthening reinforced concrete has been popular for many years. Lately, many new techniques used the corrosion resistant, high strength, and light weight FRP laminates for retrofitting and repairing applications. The usage of EB FRP laminates is one of the attractive methods strengthening RC structures and a numerous number of practical projects and works have been carried out. Bonding adhesively FRP CFRP plates to RC structures surface is an established form of retrofitting
mathematical models and advanced design guidelines that quantify debonding mechanisms. Yet, externally bonded plates lean towards debonding at low strains which limits this retrofitting technique effectiveness (Estrada 2012).

Performance of FRP to the concrete interface to provide an effective stress transfer is an extremely important issue. Certainly, an amount of failure modes in the FRP strengthened RC structural members are directly produced by the interfacial debonding between concrete and FRP. One of these failure modes, referenced to as the intermediate crack induced debonding (IC debonding) which involves debonding which initiated a major propagation and crack along the FRP concrete surface. The investigation conducted on IC debonding of the EB FRP plates reached the stage of where the fundamental governing mathematical models is established and have both quantified and identified the major most contributing parameters that governs IC debonding. Similarly, to increase shear capacity of the reinforced concrete (RC) beams by bonding adhesively FRP to the beam sides, where fibres are in vertical or transverse direction is now an inexpensive, convenient, and a certainly well-known procedure (Toutanji et al. 2008).

FRP materials over the past decade have been used for increasing the flexural strength of bridges members leaning on the serviceability of harsh environments and the high strength ratio. Externally bonded FRP sheets were used to strengthen the bridge members. Construction industry mainly uses externally bonded FRP materials in various applications. Firstly, it provide shear and flexural strength to the different concrete structures; mainly columns, slabs, and beams. Secondly, using these materials as liner for structures. Thirdly, it slows the inception of steel corrosion thru preventing chloride from migrating and acting as a rowdier. Some cases the fatigue performance is improved,
becasue FRP composite materials when externally bonded to the steel members, it act as a cracks connector (Lee and Estrada, 2009).

Alternatively, NSM FRP has become one of the attractive methods for RC members increasing their shear and flexural strength, this technique, uses the FRP reinforcement which is bonded into the grooves that is cut in concrete cover. NSM FRP technique is used in numerous applications and it provides several more advantages over EB FRP technique in the strengthening of reinforced concrete structures. The most remarkable advantages of NSM reinforcement applications are that it does not need any preparation work for the surface except grooving, and once NSM reinforcement is covered by concrete, it is suitable in strengthening the slabs and beams negative moment regions; a noteworthy decrease of mechanical damages, detriment resulting from fire, and other different effects, the NSM reinforcement is less susceptible to debonding from concrete substrate, and besides, aesthetics of the strengthened structures with NSM reinforcement are practically unchanged. Even though, bond performance is significantly improved when compared with the EB system, the key factor is still the design of the NSM FRP strengthened element. There are two different interfaces about this technique, the concrete epoxy and rod epoxy, where the bond is affected by some factors which includes rod size, FRP properties, groove surface, FRP surface treatment, adhesive, groove geometry, concrete properties and test setup (Wu and Li, 2016).
2.4 FRP Durability

Many test methods are proposed in studying the bond of the NSM FRP reinforcement. To be able to evaluate and assess the work conducted earlier on beams externally and internally reinforced and in order to identify the effective method of external strengthening, the bonding adhesive and the structure reinforcing material, a detailed literature review was undertaken. The literature review focuses on beams internally reinforced with FRP rods and its flexural strength.

A material long term performance is define as material durability. Also, durability was referred by Karbahri et al. as the concrete resistance ability to chemical degradation, cracking, or any damage in a certain time period when kept for suitable load and environment conditions. Nevertheless, to have effective CFRP composite materials, material durability should be well reviewed and taken into consideration. As stated by Deng et al., CFRP short term performance is well investigated. At the same time, we are still lagging in long term performance field because of long term test data absence, unified testing method shortage, plenty of contradicting evidence which leads to studying difficulty in various bonding behaviour and properties of FRP system (Deng et. al. 2015). A durability analysis gap was performed for FRP in construction industry which highlighted the utmost eight environmental parameters impacting FRP materials durability. These eight factors mentioned are moisture, thermal conditions, ultraviolet, fire, fatigue, creep, fire and chemical solutions (alkali) (Karbhari et al. 2012).

De Lorenzis et al (2000) studied the shear and flexural performance of the beams upgraded with NSM CFRP and GFRP rods in different sizes. Also, the rod spacing, amount of the internal steel shear reinforcement, the rods end anchorage, and strengthening scheme
were all the parameters are taken into consideration for the experiment. Two failure modes were observed, FRP deboning and concrete cover splitting of the main reinforcement. It was also found that in order to prevent debonding, an anchoring of the FRP in a flange or the usage of a 45 degree rod much closer to each other. It was concluded that an increase in the load capacity ranges from 25.7% to 44.3% for the beams strengthened for bending and for the shear 105.7% with that of control beam.

Toutanji and Gomez (2000) verified that adhesives are affected by chemical rather than fibres. Since chemical solutions act like water and affects the adhesive similarly, the chemicals, aid in accelerating the adhesive damage of the strengthened system. Sen et al. examined CFRP strengthened beams against torsion and tension, afterwards exposing it for seventeen months to seawater, subsequently six months of outdoor environmental exposure. It was then reported that 0.55 % of the bond strength was lost after exposure to seawater and a loss of 0.45% of the bond strength after environmental exposure. This was coupled by the findings of the study carried out by Sen et al. 1999. Where tests of CFRP strengthened concrete beams, in a four point flexure, were exposed to soaking in saltwater for continuous four hours and after that with two hours exposure to 35 °C and a 90% relative humidity for seventy five days. This dropped the flexural strength within a range of 5 to 30%. Thus, CFRP strengthened structure flexural strength decrease when increasing chemical solutions exposure.

Nanni (2000) where the application of FRP were studied in real projects as the strengthening of a damaged beam bridge deck by externally bonded sheets and NSM technique, and the replacement of the deteriorated steel pipe culvert bridge with a new internally reinforced concrete GFRP box culvert bridge. This damaged bridge deck was
then strengthened and then tested before demolishing it to gain the needed knowledge about the strengthening techniques efficiency.

El-Hacha et al (2005) performed various tests on NSM GFRP and CFRP strengthened beams in order to examine the ultimate limit states, serviceability, and effect of the tension stiffening as a result of strengthening. A comparison between the NSM and the EB sheets and strips with the same axial and material stiffness. The results of the experimental work were validated by the developing of an analytical model. It concluded that NSM FRP rods resulted in a higher ultimate load than that of EB FRP this is because of the maximum utilization reached of the tensile strength of NSM FRP.

Jung et al (2005) conducted experiments on EB and NSM beams. Using the mechanical interlocking grooves prevented CFRP debonding failure. It was reported that the NSM is more efficient in flexure than EB. It was also observed having ultimate load of NSM mechanically grooved higher by 15% than common NSM.

When exposing FRP to elevated temperature, a rapid viscoelastic reaction is observed. This happens because of the adhesive softening which is accompanied with an increase in moisture diffusion and a decrease in mechanical properties. Like so, the polymer deterioration is enhanced (Karbhari et al. 2003). It was also mentioned, that FRP materials when exposed to elevated temperature above 100 °C, failure and distortion of the carrying capacity load takes place because of the matrix softening. However, when exposed to higher temperature ranging between 250 and 400°C, blasting of the FRP composite is expected because it reaches the range of the matrix pyrolysis temperature (Mouritz, 2007).
Kang et al (2005) evaluated NSM CFRP sheets efficiency based on the depth of the groove and the sheets spacing by conducting experiments and performing a finite nonlinear element analysis. Based on the mentioned analytical study it concluded that increasing the groove depth up to a certain limit affected the strengthening efficiency and having a maximum groove depth of 35mm, NSM reached 1.6 times the increased load capacity when compared to the control specimen. The CFRP sheets spacing, which is another parameter being considered in the analytical study, showed a smooth relationship between the ultimate loading and the spacing variation. The best spacing possible range was found to end with a higher strengthening efficiency.

Wu et al (2005) studied the shear span ratio effect on debonding the NSM FRP and its influencing factors on an effective bonding length using the element finite analysis and another nonlinear fracture mechanics. It was determined that increasing the shear span ratio increases the bonding length effective but not the macro debonding. It also exposed adhesives that have low interfacial stiffness helped to reduce concentration of stresses in FRP which lead to a delayed debonding of FRP.

Balendran et al (2006) performed an experiment where ten beams were strengthened by NSM GFRP rods. The experimental variables were the concrete type such as normal concrete, and lightweight polystyrene aggregate concrete, type of the reinforcing rods conventional steel and GFRP, and also type of the adhesives. It discussed ultimate moment, moment deflection, and the modes of failure and it reported that bending capacity and flexural stiffness of beams with NSM GFRP rods improved and its ultimate moment increased with the range of 23% to 53% when compared to conventional beam.
Castro et al (2007) tested the NSM effectiveness as an external reinforcement for beams. GFRP and CFRP rods, also CFRP strips and sheets were used for the experiment and it determined that the ultimate load of all strengthened beams are higher than its estimated load flexural failure.

Yost et al (2007) performed experiment on twelve full scale concrete beams which were externally reinforced with NSM CFRP strips. Using three different steel reinforcement ratios and other two different CFRP ratios, the ultimate strength and yield, ductility and failure modes were discussed as from strain and deflection data. Results revealed that CFRP strengthened beams raised the yield strength to range from 9 to 30%, and the ultimate strength from 10 to 78% when compared to the control specimen.

Michael et al (2008) carried out experiments on seven different bridge deck specimens that were strengthened with CFRP, GFRP and MMFX NSM rods. The rods were then embedded in cement grout and epoxy. Where the results indicated the flexural capacity of the NSM epoxy bonded decks increased from 1.4 to 1.8 times and that for the NSM cement grouted decks from 1.3 to 1.4 times of the control specimen. Also, grout splitting or rod slippage failure was observed in the NSM cement grouted specimen.

Al-Mahmoud et al (2009) studied experimentally strengthening flexural strength of the RC structural members with NSM technique using CFRP rods. This experimental study consists of seven strengthened specimen as well as one unstrengthen specimen in order to investigate the effect of the NSM rod strengthening lengths, NSM rod diameter, concrete compressive strength, , and the bonding filler materials weather mortar or epoxy resin on the performance of RC beams strengthened. It was concluded that using NSM
reinforcement significantly improved flexural performance of RC beams through increasing the ultimate moment capacities and by limiting midspan deflection at failure.

Bournas and Triantafillou (2009) examined RC columns strengthened behaviour with NSM reinforcements which was subjected to lateral cyclic loading. Variables included were using different type of NSM reinforcing technique such as GFRP rods, CFRP strips, and stainless steel rods, also, the amount and arrangements of NSM, adhesive type used, and with and without jacketing the NSM reinforcement. By observing the responses such as drift ratios, peak force, energy dissipation, and stiffness under loading. It was concluded that the NSM CFRP strips are effective even with low concrete cover situations and both CFRP and GFRP strips that are of equal axial strength, they provided equal strength, and that the CFRP deformation capacity was slightly greater than that of GFRP. It was also found that local jacketing prevented buckling of NSM reinforcement and thus, it permitted it at failure to reach higher strains.

Gamage (2010) carried out tests on FRP strengthened concrete, where the specimens were exposed to moisture and different sets of temperature for 1800 hours. The concrete specimens were exposed to accelerated environmental factors of repeated moisture and temperature accompanied with loading exposure of 15 and 35% of its maximum loading. The tests were conducted in a single lap shear test, where the failure occurred through the bond line. It was concluded that serviceability of the NSM FRP system depends on the whole system degree of chemical and physical ageing.

Ceroni (2010) recently examined flexural performance of the beams strengthened by externally bonded CFRP sheets and NSM CFRP rods. The results compared the
strengthening methods which consists of equivalent percentages of reinforcement, and it was concluded that beams which were strengthened by NSM showed enhancement in the failure load and the ductility when compared to EBR reinforcement. Moreover, it was reported that NSM beam failure mode was due to the concrete crushing in compression and accompanied with separation in the concrete cover. The ductility was observed that it could have been improved if providing anchorage which could delay or even avoid the EBR system debonding.

Recently, a study work made on EBR versus NSM GFRP strengthened beam was conducted by Rankovic et al (2010). Both EBR and NSM GFRP strengthened beams were exposed to two-point loading in order to observe the crack and deflection width. The results revealed NSM beams perform well when compared to the EBR beams.

Vasudevan et al (2010) considered externally reinforced rods influence on flexural retrofitting on the tension side of the RC beams by two different methods. The first method, where a straight rods was fixed at the beam bottom which led to the initial slackness and in order to avoid this, the second method, used welded lapped rods. As of the experimental results the retrofitted beams which was observed in the first method with a 0.90% embedded and a 0.60% external reinforcement exhibited a moment failure, which was 80% more than the reference beams. While, when using the second method the external reinforcement was enhanced not only by the moment carrying capacity of the beams but in addition it controlled the crack and deflections width with more ductility.

Also, worth mentioning that some factors limits CFRP applications. These factors are cost, electrical conductivity, and brittleness. In prior researches, it was observed that
the performance of concrete strengthening was improvement by NSM FRP materials specifically for CFRP by enhancing the carrying load capacity. Yet, its serviceability is still limited as FRP tensile modulus is relatively less than its strength. However, it is concluded that CFRP rods possess enhanced quality and better performance than GFRP rods at elevated temperature (Peng et al. 2016).

Mikami et al. stated that for efficient bond, a proper binding is ensured between FRP material and concrete substrate, well preparation of the surface by filling all voids, and the uneven areas before the applying of epoxy adhesive. Also, it was recommended to use an adaptable layer of an adhesive for high bond strength insurance (Mikami et al. 2015). El Maghraby et al. verified that in order for CFRP strengthening system efficiency to be ensured, concrete surface roughening is fundamental and the results of roughened surfaces are more superior when compared to results of smooth surfaces (El Maghraby et al. 2010).

A recent work on the bonding between FRP as EBR and concrete and NSM strips was conducted by Kotynia (2012). The variables considered to investigate the bond were beam depth and span, type of CFRP strips/sheets, longitudinal steel reinforcement, CFRP bond length, and concrete compressive strength. All beams were casted into two different concrete blocks with a continuous longitudinal steel reinforcement at the tension zone, and also with steel hinge positioned at mid-span of the compression zone and subjecting beams to a four point loading. It was then concluded that the EBR beams having wet layup sheets showed a higher bond strain than the prefabricated strips. Also, it was reported that debonding delay was due to greater bond strain, when locating the bond length in the flexure zone than when in the flexure shear zone.
NSM FRP rods can be an extremely effective method in improving RC beam flexural capacity. The different positions of NSM FRP in both shear and flexural strengthening applications is shown in Table 2.2 providing a summary of some existing main experimental data in regard of the flexural strengthening applications that were discussed earlier.
Table 2.2: Summary of Experimental Work on the Flexural Strengthening Applications of NSM FRP (Azadeh, 2014)

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Flexure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen</td>
<td>Simply supported RC T-beams</td>
</tr>
<tr>
<td>Cross-section dimensions, 1 x w x d (mm)</td>
<td>Span = 4,572, Flange = 381 x 102, Web = 152 x 305</td>
</tr>
<tr>
<td>Fc (MPa)</td>
<td>36.17</td>
</tr>
<tr>
<td>Test method</td>
<td>4 point bending</td>
</tr>
<tr>
<td>FRP material type and configuration</td>
<td>GFRP (deformed), and CFRP (sand blasted) rods</td>
</tr>
<tr>
<td>FRP diameter df or FRP sheet width wf (mm)a</td>
<td>9.5 and 12.7</td>
</tr>
<tr>
<td>FRP cross-section hf x tf (mm)a</td>
<td>-</td>
</tr>
<tr>
<td>Groove dimensions hg x tg (mm)a</td>
<td>16 x 16, 19 x 19, and 25.4 x 25.4</td>
</tr>
<tr>
<td>Test variables</td>
<td>Bonded length, FRP rod diameter, material, and groove</td>
</tr>
<tr>
<td>Observed failure mode</td>
<td>Concrete crushing, FRP debonding</td>
</tr>
<tr>
<td>Increase in ultimate load</td>
<td>25.7% - 44.3%</td>
</tr>
</tbody>
</table>
2.5 Literature Gap

Despite FRP composite materials significant benefits and their several strengthening systems applications in construction industry, their deployment is still delayed. This is because of the lack of durability evidence in the literature reviews conducted. An approach was carried out to identify the gaps in the durability literature of NSM FRP materials performance when exposure to harsh environmental factors. It is whichever the lack of proper documentation, data are disseminated or not easily accessible. Additionally, the available data is confusingly inconsistent to the people working in the construction industry. Seven different environmental factors were identified of having the most importance on the FRP composite material durability. These seven factors are ultraviolet, thermal conditions, fire, moisture, fatigue, creep, and alkali conditions. The needs to further research and develop FRP durability are highlighted by recognizing the suitable environments for durability findings and testing of NSM FRP strengthening materials, and predicting the serviceability of using FRP (Lee et al. 2012).

After the literature overview, there is a noticeable gap in the CFRP strengthened concrete structures durability field. Further investigation is required to try to resolve the deficiencies in all various aspects. The bond performance of NSM CFRP rods is a multifaceted one because of the many interactions between load, temperature, time and stress. FRP strengthened systems is claimed that it can be effective during the fire scenarios. Conversely, additional studies and investigations are needed in order to fully understand its impact when subjected to different environmental parameters and its performance on the bond. As from the above we can get that different elevated temperatures not only decreases strength and stiffness, but it also affects the adhesive deformability in the bond.
It is agreed previously that the adhesive bond is essential to having an integrity of performance of adhesive bond. Many factors affect the bond performance among them are the fire, elevated temperature, moisture, ultraviolet, fatigue and creep. Those factors impact are only studied in their short-term performance while because regarding the long-term performance there are only limited literature. Several studies were conducted on forecasting the failure of adhesive bond between FRP and concrete. Until now, the studies are still limited about bond time dependent performance (Smith and Teng, 2006). Therefore, an extensive investigation is needed in evaluating CFRP strengthened beams performance when subjected to different elevated temperature over several durations, chemicals and workmanship.
CHAPTER 3: Experimental Work

3.1 Outline

This chapter illustrates the experimental work performed in this study. In addition, to the materials used along with the different factors from elevated temperatures, adhesiveness and chemicals, that the specimens were tested against with a thorough detailed procedure. The preparation and design of beam specimens for this experimental work was performed with accordance to the ACI 318-14 code and ACI 440.2R-08 guidelines. The CFRP rod diameter is 12 mm and the following dimensioning were considered:

1. Minimum depth of the groove (D) = 1.5\phi = 1.5 \times 12 \text{ mm} = 18 \text{ mm}
2. Clear groove spacing = 2D = 36 \text{ mm}
3. Clear edge distance = 4D = 72 \text{ mm}

The short term tensile strength, as opposed to long term, was used for this calculation, since the beams are expected to go under short term loading conditions in a three point flexural test. Based on these calculations, the beam specimens dimensioning was carried out.

Afterwards, 60 beams were casted for testing, with the purpose of scaling them to work within the available manpower, constraints of cost and handling of the beam specimens in the lab. The 12 mm CFRP rods are only available along the beam lengths, meaning that the maximum bonded length which is investigated in this experimental work is 0.75 m. The three point test setup is shown in Figure 3.1.
In order to meet the condition of clear edge distance of 72 mm, a minimum of 72 mm of concrete will be added to both sides of the CFRP rod through the longitudinal direction of the beam, amounting to beam minimum required length of 0.75 m. For the practicality of construction and to be able to give a reasonable supporting length of concrete for the pedestals, a beam length of 0.75 m was selected, 0.15 m was selected as the width of the beam and the thickness of the beam was selected to be 0.15 m.

Owing to beam size, minimum conventional steel reinforcement of 2ϕ8/m and 2ϕ10/m top and bottom reinforcement respectively, with yield strength of 240 MPa, was
selected. This was conducted in order for ensuring the beam tension failure under three point loading. The target is 28 day concrete compressive strength with range of 30-35 MPa, which is a conventional concrete representative range. Some obstacles encountered while going through the study which are mainly related to lab work which was performed. This is related to the fact of dealing with considerably heavy weight specimens which need careful handling, in addition to special labour and equipment type. The beam pouring was executed over six days, ten sample each day, with a three day gap in between to allow for the curing of the samples that were poured. Also, vibrator handling, where the vibrator temperature increase significantly, and it might cause burns if it is held at a different point other than the one instructed. In addition to its heavy weight which was a physical challenge. Moreover, the groove surface preparation, which was performed by putting a wooden strip along the length of all beams to help with FRP installing. This wooden strip was removed after the concrete cured and the challenging part was to keep it in its place during pouring the concrete.

3.2 Materials Selection

This section mentions the materials selection and its use in this study and the reason behind it. Referring to CFRP material and its ability to endure elevated temperature and providing flexural strength to concrete structures, CFRP rods are used in the current investigation. CFRP and epoxy adhesive materials supplier is Sika Corporation Egypt. The materials selected from Sika in this study are Sika Carbodur rods 12 mm diameter and Sikadur 30LP-adhesive.
3.2.1 Sika Carbodur Rods

The Sika Carbodur rods are known as carbon fibre rods designed for structural strengthening and it comes as part of the Sika Carbodur system which is composed of the rod and the adhesive. The CFRP rods may be used as NSM strengthen reinforced concrete beams and slabs. Epoxy adhesive is used for the rods bonding. There were two epoxy adhesive types, firstly the Sikadur 30 which is for normal temperature and secondly the Sikadur 30LP for high temperature, where Sikadur 30LP is the one used in this work and has Tg of 52°C as per Sika’s specifications. The Sika Carbodur rods are used for enhancing the flexural capacity of structures. Along with, enhancing serviceability and durability by decreasing crack width, deflection and fatigue. The CFRP rods are shown below in Figure 3.2.

![Figure 3.2 Sika Carbodur Rods](image-url)
3.2.2 Steel Reinforcement

A steel mesh was prepared using 2Ø8/m and 2Ø10/m top and bottom reinforcement respectively, as well as stirrup Ø8/m every 100 mm for the long direction of the beam. The steel used is mild steel, which is generally known to have a yielding strength of 240 MPa. U-shaped hinges at the corners where used to avoid debonding failure. Shown below in Figure 3.3.

![Steel Reinforcement Mesh](image)

Figure 3.3: Steel Reinforcement Mesh

3.2.3 Cement

Ordinary Portland cement was used type I (ASTM C150) with a specific gravity of 3.3. It is being produced by the Suez Cement Company which complies with the international standards (EN 197/1-2011) and the Egyptian standards (ES 5756/1-2013).
3.2.4 Coarse Aggregates

Surface dry crushed dolomite stones were used as coarse aggregates in this work from the local quarry near Suez with a maximum nominal size of (MNS) < 40 mm and a specific gravity of 2.55 (based on ASTM C 127-88).

3.2.5 Fine Aggregates

The sand used in this study is attained from a local quarry near Suez and a specific gravity of 2.51 (based on ASTM C 128).

3.2.6 Water

A clean potable water was used for the process of mixing and for any purposes of cleaning during the pouring procedure.

3.2.7 Retarding Admixture

Type D admixture was used found in ASTM C 494, targeting for a higher compressive strength through lowering the water cement ratio. Plastizier type D is obtained from Sika, with commercial name Sika Plastiment, in order to enhance the concrete workability.

3.2.8 Epoxy Adhesive

The bonding epoxy adhesive used is Sikadur 30 LP. It is thixotropic which consists of two components; component A and component B in a pallets of 6 kg as shown below in Figure 3.4. Component A is the main part of the epoxy adhesive and it comes in a form of a white paste. Component B a dark grey paste which is the second part. This material
complies with the international standards (EN 1504-4). It is recommended to be used at elevated temperatures laying in the range from +25 to +55°C. This material has a no-sagging behaviour with a high abrasion and a mechanical resistance. Over and above, it is liquids and water vapour impermeable. It provides an extremely strong adhesion to the CFRP rods and concrete.

![Figure 3.4: Sikadur 30LP Components](image)

### 3.3 Sequence of Work

Knowing the quantities of water, coarse aggregate and fine aggregate, and taking into consideration, the following assumed parameters for the purpose of the mix design:
• No correction for saturation potential/surface moisture of aggregates.
• M.N.A is 19 mm (based on ASTM C136)
• Fineness Modulus is 2.25 (based on ASTM C136)
• Slump of 30-50 mm

These parameters had to be assumed as limitations in the resources required to determine the specific gravity of cement according to ASTM C188-95.

No adjustments were made by assuming that the aggregates are in saturated surface dry (SSD) condition. The concrete mix design is summarised in the table 3.1 below:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Quantity (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>185</td>
</tr>
<tr>
<td>Cement</td>
<td>400</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>1150</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>600</td>
</tr>
<tr>
<td>Plasticizer Type D</td>
<td>2 litres</td>
</tr>
</tbody>
</table>

The above mix gives a normal strength concrete mix with compressive strength of 30-32 MPa after 28 days. It was decided that the sixty beams would be poured continuously for consecutive 6 days. The required volume of concrete in each beam (0.75 m × 0.15 m × 0.15 m) was calculated to be 0.0169 m³. An additional 20% of the beam volume was added to each beam as contingency, accounting for possible losses during pouring. Consequently, each beam would require 0.02 m³. Since the available concrete mixer has a
capacity of 0.11 m³, 5 beams would be poured in one batch. Each day of pouring would therefore require two concrete mixer batches (2 × 0.11 m³), in order to pour ten beams.

Ten reusable beam forms were prepared for the purpose of pouring. In order to be able to reuse the forms for subsequent beams, at least three days were needed to elapse in order for the poured concrete to be sufficiently cured and self-supporting. This means that a minimum of three days is required between each of the six pouring days. Accordingly, the below sequence of work was carried out:

3.3.1 Concrete Casting

1. Prepare a steel mesh using 2Ø8/m and 2Ø10/m top and bottom reinforcement respectively, as well as stirrup Ø8/m every 100 mm for the long direction of the beam as shown in Figures 3.5 and 3.6. Mild steel is used, which generally is known of having a yielding strength of 240 MPa. U-shaped hinges where used at the corners of the mesh to avoid debonding failure.

2. The steel mesh is ready, and it is placed afterwards inside a wooden form (inner dimensions of (0.75 × 0.15 × 0.15 m) on 25 mm spacers at the corners to ensure presence of a sufficient cover. Concrete was subsequently poured, the process of concrete pouring was traditional and nothing special was conducted.

3. Normal concrete vibrator is used in order to ensure that the concrete filled all the gaps and the corners of the formwork. In addition, the concrete manual displacement helped distributing concrete and the concrete levelling. Finally, using the straight edge and the hand float helped to produce a plainer and a smoother surface of concrete.
4. Each beam is removed after 3 days from the form in order to ensure that it gained the enough strength for supporting its own weight.

Figure 3.5: Schematic Diagram of the RC and NSM CFRP Beam Specimen

Figure 3.6: Schematic Cross Section Diagram of the RC Beam
3.3.2 Groove Execution

A groove of $25 \times 20$ mm was prepared for each beam during pouring using a wooden strip which was removed after concrete hardens to help later while installing the CFRP, and neutralize the groove effect on the flexural load of the specimen, see Figure 3.7.

![Figure 3.7: Groove Preparation on Beams](image)

3.3.3 CFRP Rod Installation

Prior to installing the CFRP rods, selecting and procuring of a suitable epoxy is required. Thus, a two part epoxy adhesive, Sikadur-30 LP, was selected, based on both availability and suitability. Installation required a professional applicator to do the work, starting with the surface preparations for the groove. Next, loosened particles and debris had to be cleared from the groove with the use of an air blower, before a cloth and organic solvent were used for final cleaning of the groove as shown in Figure 3.8 below.
Figure 3.8: Cleaned Groove Prior to Bar Installation
The harder and resin parts of epoxy were added and then mixed thoroughly as shown below at Figure 3.9, before applying the first layer to the groove using a trowel to approximately half of the groove depth. Preparations are done as shown in Figure 3.10.

Figure 3.9: Mixing Epoxy Components

Figure 3.10: Beams Preparation for CFRP Installation
The CFRP rod is afterwards lightly pressed through the first epoxy layer, displacing epoxy across the rod sides to ensure that it was completely covered with epoxy from all the sides. Finally, the second and final layer of the epoxy is added on top of the rod and the epoxy is then levelled at the beam surface with a trowel. The epoxy is after that left in order for it to harden for 2 days before subsequently proceeding with testing as advised by SIKA representative and specifications as shown in Figure 3.11.

Figure 3.11: Beams Ready for Testing After CFRP Installed
3.4 Experimental Variables

This section provides the different variables investigated in this study shown in Table 3.2 and Figure 3.12. These variables are which the NSM RC beam specimens with the same reinforcement ratios, were tested against and its effect on the specimen flexural strength.

<table>
<thead>
<tr>
<th>Set Number</th>
<th>Number of Beams</th>
<th>Set Materials</th>
<th>Adhesive Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1 (control)</td>
<td>3</td>
<td>Plain Concrete</td>
<td>None</td>
</tr>
<tr>
<td>Set 2 (control)</td>
<td>3</td>
<td>RC</td>
<td>None</td>
</tr>
<tr>
<td>Set 3 (control)</td>
<td>3</td>
<td>RC + CFRP Rods (12 mm Diameter)</td>
<td>Epoxy Adhesive (Sikadur 30LP)</td>
</tr>
<tr>
<td>Set 4</td>
<td>51</td>
<td>RC + CFRP Rods (12 mm Diameter)</td>
<td>Epoxy Adhesive (Sikadur 30LP)</td>
</tr>
</tbody>
</table>
3.4.1 Temperature

36 beams were tested against three various temperature values 70, 120 and 180 °C. Three beams will be subjected to a certain temperature for various intervals of time and there are four intervals of time; one hour, two hours, four hours and eight hours.
3.4.2 Workmanship

The workmanship varied for nine beams, three beams were coated fully in epoxy ensuring good workmanship, three other beams were partially coated with 66% epoxy coverage and the last three was performed with the least epoxy coverage of 50% leaving the midspan area uncovered with epoxy.

3.4.3 Chemicals

Different types of chemicals were used on nine different beams, three beams were immersed in 10% concentration of magnesium sulphate, three other beams were immersed in a fully saturated brine water, and the last three beams were immersed in fresh water. These beams were left soaked for five weeks of wetting and drying for 8 hours on weekly bases, in the above mentioned chemicals to accelerate the chemical effects.

3.5 Experimental Testing

The experimental work was carried in the American university in Cairo laboratories. The study mainly consists of flexural testing using a three point flexure loading test in accordance with ASTM C293 which was shown previously in Figure 3.1, after the specimen exposure to different factors as mentioned in the above section. Where a furnace with heating capacity up to 1000 °C was used for heating the specimens. The system used for testing is a three point testing system with the beam span supported on the 2 pedestals onto a cylindrical steel support to attain contact with the support onto a single line. The load cell applies the load on a main distributor which in turn distributes the load on 1 cylindrical steel support to attain with the support in a single line load. Loading was conducted gradually by the loading cell until complete failure of the beam. The flexural
strength of the concrete specimens was tested according to ASTM C 293/C78 using “ELE” machine, and all the beam specimens failed in flexural mode as shown in Figure 3.13.

Figure 3.13: Specimens Undergoing Flexural Failure
Chapter 4: Results and Discussion

In this chapter, key findings and results of the flexural tests carried out for the sixty beams are presented. The key findings of the effect of adhesiveness, elevated temperature over different durations and chemicals attack on the response of the NSM RC beams are adhered. It is worth mentioning that it is also depended on workmanship, so having a perfect specimens is theoretical. In addition, the number of beams tested for each variable are three beam specimens so it can be within the resources of this study.

4.1 Flexural Strength Results

Comparing between the flexural strength increases of beams from conventional concrete without reinforcement, to reinforced concrete, to reinforced concrete with NSM CFRP to see the increase of flexural strength. The results below show that in conventional environmental conditions the flexural strength of NSM CFRP can increase to reach 212% the flexural strength of the nominal flexural strength of RC as shown in Figure 4.1 and Table 4.1. This percentage is confined to the amount of steel reinforcement used and thus is expected to change when steel reinforcement ratio is altered.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results (kN)</th>
<th>Average ± Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSM</td>
<td>121 130 125</td>
<td>125 ± 4.4</td>
</tr>
<tr>
<td>Steel</td>
<td>60 60 57</td>
<td>59 ± 1.8</td>
</tr>
<tr>
<td>Plain</td>
<td>10 11 12</td>
<td>11 ± 1.1</td>
</tr>
</tbody>
</table>
4.2 Temperature

In this section a detailed analysis on different temperatures effects at different time intervals, to see how this affects the specimens. First, the effect of a 70 °C temperature along different durations on the flexural strength of NSM CFRP beams as shown in Figure 4.2 below:
Table 4.2: Specimens Subjected to 70 °C Temperature for various durations and Flexural Failure Load Results (kN)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results (kN)</th>
<th>Average ± Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hr</td>
<td>68 55 57</td>
<td>60 ± 6.7</td>
</tr>
<tr>
<td>2 hrs</td>
<td>85 72 76</td>
<td>78 ± 6.4</td>
</tr>
<tr>
<td>4 hrs</td>
<td>83 79 80</td>
<td>81 ± 2.1</td>
</tr>
<tr>
<td>8 hrs</td>
<td>77 82 83</td>
<td>81 ± 3.2</td>
</tr>
</tbody>
</table>

Figure 4.2: Failure Load for Specimens Exposed to 70°C for Various Durations.
From the above Figure 4.2 and table 4.2 it shows that at 70 °C and as time increases more than 1 hour, the flexural strength of the specimen increases, which indicates an experimental error that could have occurred during testing of the 1 hour, which led to this high drop of flexural load which should not be the case.

Moving to the 120 °C temperature which shows somehow a steady flexural failure, but with a slight decrease as time increases this shows that the specimen reached its highest strength in the first hr and continued to deteriorate until reaching the least flexural strength at 8 hours. This is shown below in Figure 4.3 and table 4.3.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Parameter</th>
<th>Results (kN)</th>
<th>Average ± Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 °C</td>
<td>1 hr</td>
<td>77 55 67</td>
<td>77 ± 11.2</td>
</tr>
<tr>
<td></td>
<td>2 hrs</td>
<td>71 57 62</td>
<td>71 ± 7.5</td>
</tr>
<tr>
<td></td>
<td>4 hrs</td>
<td>60 57 58</td>
<td>60 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>8 hrs</td>
<td>56 63 59</td>
<td>56 ± 3.5</td>
</tr>
</tbody>
</table>
Going to the highest temperature attempted in this work which is 180 °C, at this temperature the specimen reached the highest flexural strength at the first hour. Then, leaving the specimen for longer time more than 1 hour until reaching 8 hours, the flexural strength started to decrease drastically indicating and showing how destructively high temperature can affect NSM CFRP flexural strength. This is indicated as below in Figure 4.4 and table 4.4.

Figure 4.3: Failure Load for Specimens Exposed to 120°C for Various Durations.
Table 4.4: Specimens Subjected to 180 °C Temperature for various durations and Flexural Failure Load Results (kN)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results (kN)</th>
<th>Average ± Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hr</td>
<td>83 90 85</td>
<td>86 ± 3.9</td>
</tr>
<tr>
<td>2 hrs</td>
<td>46 59 50</td>
<td>52 ± 6.8</td>
</tr>
<tr>
<td>4 hrs</td>
<td>48 43 45</td>
<td>45 ± 2.0</td>
</tr>
<tr>
<td>8 hrs</td>
<td>47 40 42</td>
<td>43 ± 3.6</td>
</tr>
</tbody>
</table>

Figure 4.4: Failure Load for Specimens Exposed to 180°C for Various Durations.

After looking at each temperature by itself and its effect on the specimen now a comparisons between different times and temperatures is conducted to have a better
understanding on temperature effects on NSM CFRP. First, the 1 hour at different temperatures, it shows that as temperature increases for a short period of time as 1 hour, the flexural strength of the specimen increase slightly as in Figure 4.5, which should not be the case, since as temperature increases the CFRP NSM flexural strength should drop as that of the 2, 4, and 8 hours.

![Figure 4.5: Flexural Load after One Hour](image)

Moving to 2 hours and its effect on the flexural strength which is shown below in Figure 4.6 concludes that as temperature and time increases relative to the 1 hour results the flexural strength decreases, and that CFRP flexural strength decreases when put at higher temperatures for a longer period of time.
Further putting the specimen for longer period of time over different temperatures reaching lower flexural strength as shown in Figure 4.7. So, when temperature increases with the duration reaching four hours a more drastic deterioration in the flexural strength increases, this shows how NSM flexural strength decrease while being exposed to elevated temperatures over longer durations.

Figure 4.6: Flexural Load after Two Hours
Going to the longest time period which is 8 hours in this work, where the result are shown in the below Figure 4.8. It is noticed that as the temperature increases for a longer period time the specimens are affected more drastically and fail to a much lower flexural strength.
So to conclude the temperature and time effects on CFRP a percentage deterioration ratio graph of all the above data are presented in Figure 4.9. We can conclude from this graph that as temperature and duration increase the flexural load of the specimens drop. However, at 70 °C the flexural load increased as time passed, and at 180°C for 1 hour yielded higher flexural load than that of 70°C at 1 hour, which should not be the case with FRP, this may indicate an experimental error which led to the increase in flexural load as exposure duration and temperature increased or that at time of flexural testing the specimens returned to the Tg of the material which eliminated the temperature effect. So if averaging all data for each temperature, it concludes that as temperature increases the flexural load of NSM CFRP decreases which gives us an inversely proportion relation.
between the temperature and time and that CFRP is not prompt to high temperature for long time periods. Comparing the data with that of (Abou Ali 2016), it can be concluded that CFRP NSM provided 19% more flexural strength over unprotected CFRP EB beams and 12% over protected CFRP EB beams when exposed to elevated temperatures. This shows the advantage of NSM over EB technique at elevated temperatures.

![Figure 4.9: Specimens Flexural Load Deterioration Ratio between Different Temperatures and Various Durations](image-url)
4.3 Workmanship

In addition, to temperature effects, workmanship also affects the flexural strength of the beam specimen. So applying different partial epoxy to the beams as shown in Figure 4.10 below, the results are shown in Table 4.5.

Figure 4.10: Different Workmanship Epoxy Application Effects
Table 4.5: Specimens Subjected to different Percentages of Epoxy Coverage its Flexural Failure Load (kN)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results (kN)</th>
<th>Average ± Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Epoxy</td>
<td>121 130 125</td>
<td>125 ± 4.4</td>
</tr>
<tr>
<td>Epoxy Partial</td>
<td>100 100 90</td>
<td>97 ± 5.8</td>
</tr>
<tr>
<td>(66% coverage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy only at ends</td>
<td>63 61 67</td>
<td>64 ± 2.6</td>
</tr>
<tr>
<td>(50% coverage)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Testing these beams it concludes the results shown below in Figure 4.11 and that is, if the epoxy is not applied in a good way and that if the workmanship slacked during applying the epoxy, or thought that they could be cost reducing and saving epoxy, and that it would not affect the end result of the flexural strength required, they are defiantly mistaken. CFRP can go to nearly the same flexural strength of not having any CFRP in the first place. The epoxy application affects the flexural strength intensely so it is of high importance to ensure that the epoxy is well applied.
Figure 4.11: Workmanship and Epoxy Coverage Percentages affecting the Flexural Load of the Specimens
4.4 Chemicals

Chemicals affect concrete flexural strength and is one of the main reasons for flexural strength deterioration, in this study three types of chemicals were used to compare between there different effects on specimen flexural strength, these chemicals are fresh water, saturated brine water, and 10% concentration magnesium sulphate, Figure 4.12 below shows the effect of each chemical on the beams.

Figure 4.12: Showing the Effect of the Chemicals on the Specimens, Fresh Water effect (Top Beam), Magnesium Sulphate (Middle Beam) and Brine Water Effect (Bottom Beam)
Three specimens were used for testing for each type of chemical, the beams were left for five weeks and were exposed to drying and wetting to expedite the effect of the chemicals on weekly bases. The three beams for each chemical type were left in three different containers which were designed for the purpose of this study along the five weeks, they were designed to allow the beams to be manoeuvred while drying and wetting and have a total surface contact with the chemicals as shown in Figure 4.13.

Figure 4.13: Container Used for the Chemicals Testing.

After five weeks the beams were tested for flexural strength, to get the different chemical effects and its reaction with the beams and how each chemical can affect the beam differently as shown in table 4.6 and Figure 4.14.
Table 4.6: Chemicals flexural Load (kN)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results (kN)</th>
<th>Average ± Standard Deviation (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Water</td>
<td>115 116 111</td>
<td>114 ± 2.6</td>
</tr>
<tr>
<td>Saturated Brine Water</td>
<td>95 100 92</td>
<td>96 ± 4.0</td>
</tr>
<tr>
<td>Magnesium Sulphate (10% Concentration)</td>
<td>76 81 85</td>
<td>81 ± 4.5</td>
</tr>
</tbody>
</table>

From the figure above it is conclude that leaving the specimens soaked in water does not affect the flexural strength of the concrete, however being exposed to brine water decreased
it by around 30% due to the sodium chloride attacking the specimen, but moving to magnesium sulphate which had the strongest deterioration of them decreased the specimens strength by 40% which shows how aggressive chemicals can get in attacking and reducing the flexural strength of the beams.

Complying all data together which were carried out for different temperatures along various time variations, chemicals and workmanship, Figure 4.15 can be used to summarize all of it together.
Figure 4.15: All Data Compiled
4.5 Deflection

The impact of CFRP on the load deformation performance after the exposure to different chemicals, starting with beams left in water as shown in the below Figure 4.16.

Plotting the specimens immersed in fresh water versus the control specimen, it shows that after being exposed in fresh water for five weeks, they have nearly the same deflection. Going to the specimens soaked in brine water showing in Figure 4.17, shows nearly the same deflection of the specimen of water. Also, in Figure 4.18 were the specimen was left for magnesium sulphate attack the deflection decreased as shown below.
Figure 4.17: Deflection Curve for Beams Soaked in Brine Water

Figure 4.18: Deflection Curve for Beams Soaked in Magnesium Sulphate
So plotting all deflection curves all together for a better observation of the deflection data as shown in Figure 4.19 below. Concluding that if the stiffness of the specimens increase, it yields less deflection.

![Figure 4.19: Deflection Data Compiled Results](image-url)
Chapter 5: Conclusions and Recommendations

5.1 Key Conclusions

Based on the methodology of applications, procedures, materials incorporated, and other parameters associated with this work, and taking into consideration the work limitations as well as statistical and experimental variations, the following conclusions can be drawn:

1. Designing NSM beams has led to substantial increase in flexural strength compared to conventional reinforced steel beams. This increase surpassed 200% of the flexural load of the steel reinforced control beams in respect to the ratio of CFRP to reinforced steel used.

2. There is a substantial drop in the flexural load in the NSM beams upon the exposure to 1 hour and temperature of 70 °C such decrease continues as duration increases to 8 hours. However, one can argue that exposure to 70 °C in the range of 2 to 8 hours results are similar in results.

3. Exposing NSM beams to 180 °C for extended hours yielded the smallest flexural load that was as high as 66 % from the control room temperature beam with the exception of 180 °C the drop of flexural strength is somewhat proportional to the increase of exposure duration.

4. Care should be taken that thorough application of epoxy with good workmanship is indispensable for benefiting from NSM strengthening effect. For instance, less thorough application epoxy can lead to almost zero gain of NSM.
5. While, test duration for beams exposed to fresh water, brine water, and magnesium sulphate was relatively small, a drop in flexural strength has taken place for up to 35%.

5.2 Recommendations for Further Investigation

As the study is by no means comprehensive, the below further work and studies are highly recommended.

1. This work should be further validated through larger set of concrete mix design, steel, types of adhesive and NSM reinforcement with different diameters and with NSM place at various depth from concrete surface.

2. This study should be extended to include larger set of exposure temperatures, larger durations and possibly with exposure to fire not just elevated temperature.

3. Exposure to chemicals has to be conducted for extended duration of several month in a cycling manner to depict more real life conditions of chemical attack.

4. Study the bond behaviour of the NSM FRP strengthening systems needed including additional possible influencing parameters and combinations of them.

5. Durability aspects as well as long term effects such as creep and fatigue are truly needed to be included in future work.

6. Executing NSM using CFRP on Full Scale beams. This would allow us to find the mode of failure of the NSM system using CFRP, where concrete crushing would be less likely.
5.3 Recommendations for the Construction Industry

Based on this study findings and relying on the previous credible work carried out worldwide, the following recommendations provided are for the construction industry:

1. Near surface mounted appears to be a promising technique for strengthening and retrofitting exiting structures. The industry should tap into such high potential in future concrete structures repair works.

2. Egyptian code of practice should be updated to cope with the international advances in the use of NSM.

3. Applicators should be vigilant on the negative effect of temperature, exposure to chemicals, and applications of adhesives. This should cope with considering additional protective layers on top of the concrete to minimize such effects.

4. The Egyptian industry should initiate a wide scale effort to manufacture FRP rods such as the ones used in this study to narrow the gap of initial cost of such materials.

5. A CFRP system remains a composite that renders remarkable increase in flexural strength for concrete beams. Hence, their rational application in repair and retrofitting need to be encouraged.
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