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**REHABILITATION OF HEATED AND DAMAGED  
MEDIUM STRENGTH SELF COMPACTING STEEL FIBER  
REINFORCED CONCRETE CORBELS**

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**BY  
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Compacting Steel Fiber Reinforced Concrete Corbels**

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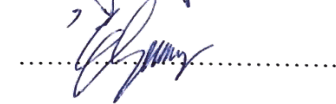
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**Twana Ahmed HUSSEIN**

## **ABSTRACT**

### **REHABILITATION OF HEATED AND DAMAGED MEDIUM STRENGTH SELF COMPACTING STEEL FIBER REINFORCED CONCRETE CORBEL**

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**M.Sc. Thesis in Civil Engineering**

**Supervisor: Assist. Prof. Dr. Mehmet Eren GÜLŞAN**

**Co-Supervisor: Prof. Dr. Abdulkadir ÇEVİK**

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**82 Pages**

This thesis presents an experimental study that investigates the mechanical performance of heated and damaged self-compacting steel fiber reinforced concrete corbels, after rehabilitation of them by epoxy injection and Basalt Fiber Reinforced Polymer (BFRP) fabric. This study is the first experimental investigation that describes the rehabilitation and strengthening of heated and damaged concrete corbels. In this study, a total of 18 normal strength double sided corbels which had been failed and damaged due to high temperature and overloading were repaired. Nine of the damaged corbels were repaired with crack repairing epoxy injection only and the remained corbels beside injection were strengthened with BFRP externally. All the corbels have had same size and reinforced with the same main reinforcement. The experimental results show that proposed techniques can be preferred in order to restore and improve the ultimate load carrying capacity of the damaged corbels. Moreover, strengthening with BFRP fabric increased ductility of the corbels besides enhancement in load capacity. In addition, the results indicate that the failure modes for some of corbels which were repaired with only repairing epoxy have been changed as compared to the first failure while all of the BFRP strengthened corbels have failed because of de-bonding of the fabric from the corbel surface.

**Keywords:** Heat and damaged corbels, Medium strength concrete, Self-compacted concrete, Rehabilitation, Basalt fiber fabric, Epoxy injection.

## ÖZET

### ISITILMIŞ VE HASAR GÖRMÜŞ NORMAL MUKAVEMETLİ ÇELİK LİF KATKILI KENDİLİĞİNDEN YERLEŞEN BETONARME KISA KONSOLLARIN REHABILITASYONU

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82 Sayfa

Bu tez ısıtılmış ve hasar görmüş, kendiğinden yerleşen betonla üretilmiş çelik lif katkılı betonarme kısa konsolların, epoksi enjeksiyonu ve basalt lif takviyeli polimer kumaş ile rehabilitasyonundan sonraki mekanik performansını araştıran deneysel bir çalışmayı sunmaktadır. Bu çalışma ısıtılmış ve hasar görmüş kısa konsolların tamiri ve güçlendirilmesiyle ilgili ilk deneysel araştırmadır. Bu çalışmada yüksek sıcaklıktan ve aşırı yüklemekten ötürü göçmüş ve hasar görmüş 18 adet normal mukavemetli çift kollu kısa konsol tamir edilmiştir. Hasarlı konsolların 9 tanesi sadece çatlak tamir epoksi enjeksiyonu ile tamir edilmiş ve geriye kalan kısa konsollar epoksi enjeksiyonunun yanında bazalt lif takviyeli polimer kumaş ile dışarıdan güçlendirilmiştir. Bütün kısa konsollar aynı boyutlara sahiptir ve asal donatıları aynı miktardadır. Deneysel sonuçlar, önerilen güçlendirme tekniklerinin kısa konsolların yük taşıma kapasitelerini geri kazanmak ve daha da geliştirmek için tercih edilebileceklerini göstermiştir. Ayrıca, basalt lif takviyeli polimer kumaşla güçlendirme yük taşıma kapasitesinin yanında kısa konsolların sünekliğini de arttırmıştır. Ayrıca, sadece tamir epoksisi ile tamir edilen bazı kısa konsolların göçme modu ilk göçmeye kıyasla değişirken, bazalt kumaşla güçlendirilmiş kısa konsollar kumaşın konsol yüzeyinden ayrışmasından ötürü göçmüştür.

**Anahtar Kelimeler:** Isıtılmış ve hasar görmüş kısa konsollar, Normal mukavemetli beton, Kendiliğinden yerleşen beton, Rehabilitasyon, Basalt lif takviyeli kumaş, Çatlak tamir epoksisi.



To My Family

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## TABLE OF CONTENTS

	<b>Page</b>
ABSTRACT.....	v
ÖZET.....	vi
ACKNOWLEDGEMENT .....	viii
TABLE OF CONTENTS.....	x
LIST OF TABLES .....	xii
LIST OF FIGURES .....	xiii
CHAPTER 1 .....	1
INTRODUCTION .....	1
1.1 General .....	1
1.2 Repair and Strengthening of Concrete Structures with Epoxy Resin Injection and Fiber Reinforced Polymers.....	2
1.2.1 Epoxy resin injection.....	2
1.2.2 Fiber-reinforced polymer (FRP) .....	2
1.3 Research Significance .....	4
1.4 Research Objectives .....	4
1.5 Thesis Layout .....	5
CHAPTER 2 .....	6
LITERATURE REVIEW.....	6
2.1 Introduction .....	6
2.2 Fiber Reinforced Polymer FRP Materials for Strengthening.....	7
2.2.1 Carbon Fiber Reinforced Polymer (CFRP).....	8
2.2.2 Aramid Fiber Reinforced Polymer (AFRP).....	9

2.2.3 Glass Fiber Reinforced Polymer (GFRP) .....	9
2.2.4 Basalt Fiber Reinforced Polymer (BFRP).....	10
2.3 Adhesives .....	11
2.4 Factors Effecting Durability of Strengthening System .....	12
2.4.1 Surface preparation .....	12
2.4.2 Temperature .....	12
2.5 Studies on Strengthening of Heat Damaged Reinforced Concrete Structures.....	13
2.6 Researches on Repaired and Strengthened Reinforced Concrete Corbels .....	14
2.7 Conclusion.....	18
CHAPTER 3 .....	19
EXPERIMENTAL PROGRAM .....	19
3.1 Introduction .....	19
3.2 Description of Test Specimen .....	19
3.3 Materials Properties of Corbels.....	20
3.4 Properties of Repairing Materials.....	21
3.5 Preparation of Specimen Surface Before Repairing.....	25
3.6 Rehabilitations Methods.....	27
3.6.1 Injection with only crack repairing epoxy .....	27
3.6.2 Injection of crack repair epoxy and wrapping with basalt fiber fabric .....	29
3.7 Test Setup.....	32
CHAPTER 4 .....	34
RESULTS AND DISCUSSION .....	34
4.1 Introduction .....	34
4.2 Corbels Repaired with Epoxy Injection only .....	34
4.3 Corbels Repaired with Epoxy Injection and Strengthened with Basalt Fiber Fabric (BFF).....	55

.

CHAPTER 5 .....	76
CONCLUSION.....	76
5.1 Conclusion.....	76
5.2 Recommendations for Future Research .....	78
REFERENCES.....	79



## LIST OF TABLES

	<b>Page</b>
<b>Table 3.1</b> Properties of fibers used in the study .....	21
<b>Table 3.2</b> Mechanical properties of steel bars .....	21
<b>Table 3.3</b> The properties of TEKNOBOND 200 epoxy.....	22
<b>Table 3.4</b> The properties of TEKNOBOND 300 epoxy.....	23
<b>Table 3.5</b> The properties of Sikadur-52 epoxy.....	24
<b>Table 3.6</b> The properties of basalt fiber fabric .....	24
<b>Table 4.1</b> Experimental test results for corbels repaired with epoxy injection .....	36
<b>Table 4.2</b> Experimental test results for BFRP-strengthened corbels.....	56

## LIST OF FIGURES

	<b>page</b>
<b>Figure 2.1</b> Typical Carbon Fiber Polymer (CFRP) .....	8
<b>Figure 2.2</b> Typical Aramid Fibers Polymer (AFRP).....	9
<b>Figure 2.3</b> Typical Glass Fibers Polymer (GFRP) .....	10
<b>Figure 2.4</b> Typical Basalt Fibers Reinforced Polymer (BFRP).....	11
<b>Figure 2.5</b> GFRP wrapping configurations .....	15
<b>Figure 3.1</b> Dimensions of the corbel. (Mohammed A. KAMIL 2016) .....	19
<b>Figure 3.2</b> Reinforcement details of the corbel .....	20
<b>Figure 3.3</b> High damaged corbel .....	25
<b>Figure 3.4</b> Low damaged corbel.....	25
<b>Figure 3.5</b> Surface grinding process.....	26
<b>Figure 3.6</b> Using air compressor for removing loose particles .....	26
<b>Figure 3.7</b> Mixing of high viscosity epoxy .....	27
<b>Figure 3.8</b> Filling the side cracks with high viscosity epoxy .....	27
<b>Figure 3.9</b> Crack repair epoxy(Sikadur-52) injection .....	28
<b>Figure 3.10</b> Grinding after injection.....	28
<b>Figure 3.11</b> Surface preparation before gluing the basalt fiber.....	29
<b>Figure 3.12</b> Basalt fiber strips .....	30
<b>Figure 3.13</b> Saturated basalt fiber with low epoxy.....	30
<b>Figure 3.14</b> Configuration steps of bonding surface and applying the Basalt Fiber .....	31
<b>Figure 3.15</b> Grinding after covering of basalt fiber .....	31
<b>Figure 3.16</b> Corbel Specimen Setup.....	32
<b>Figure 3.17</b> Injected and covered corbels with two LVDTs on the testing machine .....	33
<b>Figure 4.1</b> Load-displacement curve of specimen (C1-0.0-250) .....	37
<b>Figure 4.2</b> Specimen (C1-0.0-250) failure before repairing.....	38
<b>Figure 4.3</b> Specimen (C1-0.0-250 ) failure after repairing .....	38

<b>Figure 4.4</b> Load-displacement curve of specimen (C2-0.0-500) .....	40
<b>Figure 4.5</b> Specimen (C2-0.0-500) failure before repairing.....	40
<b>Figure 4.6</b> Specimen (C2-0.0-500 ) failure after repairing .....	40
<b>Figure 4.7</b> Load-displacement curve of specimen (C3-0.0-750) .....	41
<b>Figure 4.8</b> Specimen (C3-0.0-750) failure before repairing.....	42
<b>Figure 4.9</b> Specimen (C3-0.0-750 ) failure after repairing .....	42
<b>Figure 4.10</b> Load-displacement curve of specimen (C4-0.5-250) .....	43
<b>Figure 4.11</b> Specimen (C4-0.5-250) failure before repairing.....	44
<b>Figure 4.12</b> Specimen (C4-0.5-250 ) after repairing.....	44
<b>Figure 4.13</b> Load-displacement curve of specimen (C5-0.5-500) .....	45
<b>Figure 4.14</b> Specimen (C5-0.5-500) failure before repairing.....	46
<b>Figure 4.15</b> Specimen (C5-0.5-500 ) failure after repairing .....	46
<b>Figure 4.16</b> Load-displacement curve of specimen (C6-0.5-750) .....	47
<b>Figure 4.17</b> Specimen (C6-0.5-750) failure before repairing.....	48
<b>Figure 4.18</b> Specimen (C6-0.5-750 ) failure after repairing .....	48
<b>Figure 4.19</b> Load-displacement curve of specimen (C7-1.0-250) .....	49
<b>Figure 4.20</b> Specimen (C7-1.0-250) failure before repairing.....	50
<b>Figure 4.21</b> ; Specimen (C7-1.0-250 ) failure after repairing .....	50
<b>Figure 4.22</b> Load-displacement curve of specimen (C8-1.0-500) .....	51
<b>Figure 4.23</b> Specimen (C8-1.0-500) failure before repairing.....	52
<b>Figure 4.24</b> Specimen (C8-1.0-500 ) failure after repairing .....	52
<b>Figure 4.25</b> Load-displacement curve of specimen (C9-1.0-750) .....	53
<b>Figure 4.26</b> Specimen (C9-1.0-750) failure before repairing.....	54
<b>Figure 4.27</b> Specimen (C9-1.0-750 ) failure after repairing .....	54
<b>Figure 4.28</b> Load-displacement curve of specimen (C10-0.0-250) .....	58
<b>Figure 4.29</b> Specimen (C10-0.0-250) failure before strengthening .....	58
<b>Figure 4.30</b> Specimen (C10-0.0-250 ) de-bonding failure after strengthening.....	59
<b>Figure 4.31</b> Load-displacement curve of specimen (C11-0.0-500) .....	60
<b>Figure 4.32</b> Specimen (C11-0.0-500) failure before strengthening .....	60
<b>Figure 4.33</b> Specimen (C11-0.0-500 ) de-bonding failure after strengthening.....	61
<b>Figure 4.34</b> Load-displacement curve of specimen (C12-0.0-750) .....	62
<b>Figure 4.35</b> Specimen (C12-0.0-750) failure before strengthening .....	62
<b>Figure 4.36</b> Specimen (C12-0.0-750 ) de-bonding failure after strengthening.....	63

<b>Figure 4.37</b> Load-displacement curve of specimen (C13-0.5-250) .....	64
<b>Figure 4.38</b> Specimen (C13-0.5-250) failure before strengthening .....	64
<b>Figure 4.39</b> Specimen (C13-0.5-250) de-bonding failure after strengthening.....	65
<b>Figure 4.40</b> Load-displacement curve of specimen (C14-0.5-500) .....	66
<b>Figure 4.41</b> Specimen (C14-0.5-500) failure before strengthening .....	66
<b>Figure 4.42</b> Specimen (C14-0.5-500 ) de-bonding failure after strengthening.....	67
<b>Figure 4.43</b> Load-displacement curve of specimen (C15-0.5-750) .....	68
<b>Figure 4.44</b> Specimen (C15-0.5-750) failure before strengthening .....	68
<b>Figure 4.45</b> Specimen (C15-0.5-750 ) de-bonding failure after strengthening.....	69
<b>Figure 4.46</b> Load-displacement curve of specimen (C16-1.0-250) .....	70
<b>Figure 4.47</b> Specimen (C16-1.0-250) failure before strengthening .....	70
<b>Figure 4.48</b> Specimen (C16-1.0-250 ) de-bonding failure after strengthening.....	71
<b>Figure 4.49</b> Load-displacement curve of specimen (C17-1.0-500) .....	72
<b>Figure 4.50</b> Specimen (C17-1.0-500) failure before strengthening .....	72
<b>Figure 4.51</b> Specimen (C17-1.0-500 ) de-bonding failure after strengthening.....	73
<b>Figure 4.52</b> Load-displacement curve of specimen (C18-1.0-750) .....	74
<b>Figure 4.53</b> Specimen (C18-1.0-750) failure before strengthening .....	74
<b>Figure 4.54</b> Specimen (C18-1.0-750 ) de-bonding failure after strengthening.....	75

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 General**

As a result of their service aims, industrial buildings are exposed to go through structural damages. When there is a fire, high temperatures can reversely have an effect on the load carrying capacity of elements of the buildings in particular. As a result, a dangerous and risky condition exists for serviceability and safety of the structure whenever fire is potential. The other problem concerning industrial buildings is that when they are demolished, their reconstruction can create problems for the project owners.

Reinforced concrete corbel or bracket is an important structural element in the carrying system of industrial buildings. The corbels are short cantilever structural members that project from the face of the columns, in which they play a crucial role as structural elements due to their function of transferring the coming load from the beams to the supporting columns or walls.

Use of steel fiber in reinforced concrete corbels is on up to date application in the construction sector. Including steel fiber into the concrete corbels may not solitary effect the reduction of reinforcement density and construction difficulties, also it improves the mechanic capacity of the corbels. (Gao and Zhang, 2010).

Strengthening or rehabilitation of reinforced concrete corbels has taken through by relevant theoretical and experimental researches. The researchers investigated several techniques for strengthening corbel behavior and rehabilitate damaged ones.

## **1.2 Repair and Strengthening of Concrete Structures with Epoxy Resin Injection and Fiber Reinforced Polymers**

Restoring the function of damaged and deteriorated components is the fundamental reason of repairing. Rehabilitation of a reinforced concrete structural element can be defined as either the increasing capacity process of damaged components in concrete structures to its original design capacity or an improving over the original strength.

### **1.2.1 Epoxy resin injection**

Epoxy resins are used for surface coating or filling larger cracks or holes. The materials could be easily glued to the concrete and are able to bring back the original structural strength of the cracked concrete, if the epoxy resins are properly applied. In order to inject the cracks suitably, the viscosity of the epoxy resin must be appropriate with the cracks' width. Cracks should be between ~ 0.1 mm and ~ 6 mm in thickness when they are supposed to be injected by epoxy resins. It is still difficult to keep injected epoxy resin in cracks greater than ~ 6 mm in width, although high viscosity epoxies can be used with some success. Epoxy resins cure to form relatively brittle materials with bond strengths exceeding the shear or tensile strength of the concrete. (Guide to Concrete Repair, 1996).

### **1.2.2 Fiber-reinforced polymer (FRP)**

The strengthening with fiber reinforced polymer (FRP) has appeared as an alternative method to conventional techniques in order to rehabilitate the damaged reinforced concrete structural members. These FRP materials, which provide advantages over the conventional repair materials, include carbon, glass and aramid FRP. They are carrying out in terms of better chemical and mechanical performance and much easier constructability (Sim, 2001).

Fire resistance, from another point of view, is also a significant feature when the use of the FRP materials is extended to the building structures' rehabilitation or strengthening. Most of FRP materials rapidly lose their structural capacity whenever they are heated to high-temperatures (Lee, 2002).

Moreover, a material with greater ultimate strain can be suggested to strengthen and repair the deteriorated reinforced concrete structures. Even though the material's strength might be lower, but at the same time it has much greater fire resistance.

Basalt rocks result in basalt fibers throughout a melting process. A form of fibers can possibly be made through the division of the basalt rocks to small particles. Furthermore, from an economical point of view, in basalt fiber producing processes, fibers do not comprise any other additives. The basalt fibers are recognized to be better in tensile strength compared to E-glass fibers, and higher in failure strain than the carbon fibers along with good resistance to impact load, fire and chemical attacks with less toxic fumes as well (Berozashvili, 2001).

In concrete structures, the main purpose of the use of FRP materials, including basalt fibers, is strengthening and repairing. In addition, two typical methods preferred for FRP strengthening which are near surface mounting methods and external bonding, in which they use a sheet or layer material, and a rod type material. (Djamaluddin, 2002). There are mainly two classes of FRP materials to be used for external strengthening of concrete, which are basically available in the form of:

- Plates; rigid thin unidirectional strips made by pultrusion.
- Sheets or Fabric; unidirectional made of fiber at least two distinct directions, pre-impregnated (Sultan, 2012).

### **1.3 Research Significance**

The main motivation of this study is to repair and strengthen of corbels, which are exposed to elevated temperatures and damaged under vertical load, with two different techniques. However, corbels whose various properties are different from each other were studied to determine effect of rehabilitation on them. These properties are steel fiber ratio, shear span and the temperature to which exposed. Epoxy resin injection and Basalt Fiber Fabric BFF were used for rehabilitation.

Many studies have been carried out about the rehabilitation of corbels. However, these studies were focused on the rehabilitation of room temperature corbels, and many types of FRP materials have been used except for basalt fiber fabric. Limited or no studies in literature has been focused on rehabilitation of damaged corbels and utilizing BFF for rehabilitation. Therefore, this research is important to close the gap about damaged concrete corbels which were repaired with epoxy injection and FRP composites through an experimental investigation. In order to overcome the lack of information in this field, this study is necessary.

### **1.4 Research Objectives**

In this research, an experimental work was carried out on rehabilitation of damaged medium strength self-compacted reinforced concrete corbels with epoxy injection and basalt fiber fabric. A wide range of mechanical properties and failure modes of the corbels after repairing of them were studied.

This thesis is devoted to study the mechanical properties of rehabilitated damaged reinforced concrete corbels. The main objectives are as follows:

- To study the ultimate strength and load-deformation characteristics of damaged concrete corbels after repairing.
- To compare the rehabilitation of the corbels by epoxy injection with and without basalt fiber fabric BFF.
- To extract the modes of failure after repairing.
- To evaluate the effects of steel fiber ratio and different degrees of heating on the characteristics stated above.

## **1.5 Thesis Layout**

By carrying out suitable series of tests, the thesis was planned to provide additional knowledge on the structural behavior of rehabilitated corbels under vertical loading with and without basalt fiber fabric. This thesis consists of seven chapters

**Chapter 1:** This chapter provides information about the necessity of rehabilitation. Moreover, it gives brief information on the use of epoxy injection and FRP materials for repairing and strengthening of concrete structures. Objective of the thesis and research significance are also defined within this chapter.

**Chapter 2:** This chapter presents the literature review for repair and strengthening method and materials. In addition to the previous studies made about strengthening for reinforced concrete corbels.

**Chapter 3:** In this chapter details of materials and their properties are presented, which were used in this experimental investigation. Furthermore, the details of the experimental program are also given in the same chapter.

**Chapter 4:** Gives the experimental results, shows the response of the tested corbels, and discusses the failure modes after rehabilitation.

**Chapter 5:** Conclusions are presented with recommendations for further studies.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

The need for strengthening structures to the original or higher performance level becomes common and necessary for economic reasons. The structures are on deteriorating due to mechanical damage, mistakes in design and/or construction works, functional changes or reinforcement corrosion (Shadhan et al., 2011). Concrete structures deteriorate due to reasons including, internal reinforcement corrosion, fire damage, excessive loading and poor initial design. Many structures have no longer considered satisfactory in term of load carrying capacity. In order to maintain efficient highway networks and to keep buildings operational, the damaged structures must be upgraded (Garden and Hollaway, 1998). In the strengthening or rehabilitation of concrete structures, different techniques can adapt as solutions. For instance, the solutions are such as; injection of fresh concrete or epoxy resins, wrapping with steel plates, and bonding techniques with composite materials.

The first recorded strengthening case was in Durban, South Africa, in 1964. Where epoxy-bonded steel plates were used to strengthen concrete beams in an apartment complex. Where part of the reinforcing steel in the building had been accidentally omitted during construction. Furthermore, four bridges were strengthened by using steel plates in 1975 and 1977, respectively at Swanley, Kent, in England (Hollaway and Head, 2001).

The strengthening of reinforced concrete members by externally bonded steel plates has become very popular throughout the beginning of 1970s to the beginning of 1990s (Ahmad and Hamoush, 1991).

The disadvantages of steel plates can be summarized as follows:

- The difficulty of transporting handling and installing heavy plates.
- Deterioration of bond in concrete-steel interfaces because of corrosion of plates.
- Necessity of hard work and difficulty of formatting joints due to restricted transporting lengths.
- During the adhesive cure holding the plates in position required a massive and costly false work.
- Preparation the surface of the steel for bonding take the labor intensive and time.

Since the utilization of steel plates has had several serve detriments, researchers have attempted to find an option material. Fiber reinforced plastic materials have developed at that time. Compare to steel plates FRP materials have better physical and mechanical properties, especially regarding to fatigue and tensile strengths also under an extensive variety of temperatures (Garden and Hollaway, 1998).

The FRP laminates have been typically made of continuous fibers, glass, aramid and carbon, bonded with a polymeric matrix such as epoxy. Regarding the FRP material selection, it has been believed that, given its superior properties over other composites, carbon fiber reinforced plastics (CFRP) has offered highest potential for repairing of concrete structures. By using fiber reinforced plastic material (FRP), many buildings and bridges were strengthened. For example, Kattenbusch bridge in Germany was strengthened by using glass fiber reinforced plastic (GFRP) sheets, Moreover, the tall chimneys in Japan were strengthened by using CFRP tapes and winding strands (Plevris et al., 1995).

## **2.2 Fiber Reinforced Polymer FRP Materials for Strengthening**

The use of fiber reinforced polymer (FRP) materials for structural repair and strengthening has continuously increased during the past years. Several advantages associated with these composites when compared to conventional materials like steel. These benefits include low weight, easy installation, high durability and tensile strength, electromagnetic neutrality and practically unlimited availability in size, geometry and dimension (Barros et al., 2006). FRP materials are lightweight,

noncorrosive, and exhibit high tensile strength. Additionally, these materials are readily available in several forms ranging from factory-made laminates to dry fiber sheets. The laminates of the FRP can be wrapped to conform the geometry of a structure before adding the polymer resin (Setunge and Nezamian, 2004).

Fibers are the effective reinforcement materials, as they satisfy the required conditions and transfer strength to the matrix constituent influencing and enhancing their properties as required. Fibers can be oriented in any direction to enhance the strength and stiffness of the composite in the desired direction. The performance of a fiber composite is evaluated by its length, shape, orientation, composition of the fibers and the mechanical properties of the matrix. (Reddy et al, 2015).

The most common Fiber Reinforced Polymers (FRP), which are on using for strengthening;

### **2.2.1 Carbon Fiber Reinforced Polymer (CFRP)**

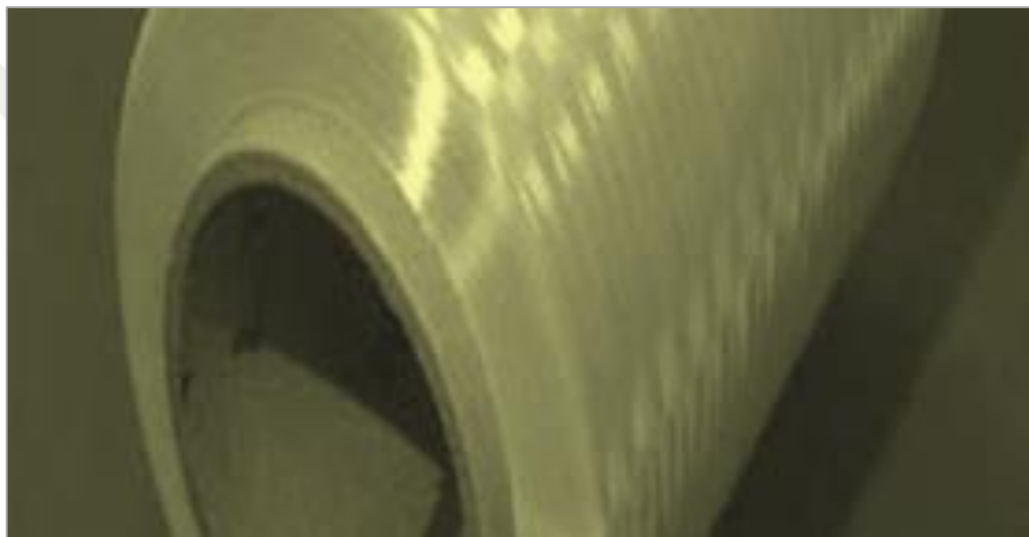
Carbon fibers are anisotropic in nature which is produced at 1300°C. The advantages of carbon fibers can be summarized as; High strength, excellent creep level, resistance to chemical effects, low conductivity, low density and high elastic modulus. Carbon fibers are expensive and anisotropic materials and it has a low compression strength these are the weak sides of carbon fibers (Sultan, 2012). Figure .1 shows the typical carbon fiber polymer.



**Figure 2.1** Typical Carbon Fiber Polymer (CFRP)

### **2.2.2 Aramid Fiber Reinforced Polymer (AFRP)**

Aramid fibers widespread known as a Kevlar fiber in the markets. The structure of aramid fiber is anisotropic in nature and usually are yellow in colors. Aramid fibers are more expensive than glass, moderate stiffness, and good in tension application (Cables and tendons) but lower strength in compression. Aramids have high tensile strength, high stiffness, high modulus and low weight and density. Impact-resistant structure can be produced from aramids. There are five classes Kevlar with the different engineering properties. Kevlar-29, Kevlar-49, Kevlar- 100, Kevlar-119, Kevlar-129 (Günaşlan et al, 2014). Figure 2.2 present typical aramid fibers



**Figure 2.2** Typical Aramid Fibers Polymer (AFRP)

### **2.2.3 Glass Fiber Reinforced Polymer (GFRP)**

Glass fibers are isotropic in nature and most widely used filament. Common types of glass fibers are E-Glass, S-Glass and C-Glass. The characteristic properties of glass fiber are: High strength, low cost, good water resistance and resistance to chemicals (Zhang, 2010). Figure 2.3 shows the typical glass fibers (GFRP)



**Figure 2.3** Typical Glass Fibers Polymer (GFRP)

#### **2.2.4 Basalt Fiber Reinforced Polymer (BFRP)**

Basalt fiber is a relative newcomer to fiber reinforced polymers (FRPs) and structural composites. It has a similar chemical composition as glass fiber, but has better strength characteristics. Basalt fiber unlike most of glass fibers are highly resistant to alkaline, acidic and salt attacks. These properties make it a decent candidate for concrete, bridge and shoreline structures.

Compared to carbon and aramid fibers, basalt fiber has the elements of the more extensive application temperature range  $-452^{\circ}\text{F}$  to  $1,200^{\circ}\text{F}$  ( $-269^{\circ}\text{C}$  to  $+650^{\circ}\text{C}$ ), higher oxidation resistance, higher radiation resistance, higher compression strength, and higher shear strength. (Note that application temperatures of FRPs are limited by the glass transition temperature of the matrix, which is lower than the application temperature of the fibers).

The price of fibers made from basalt is higher than those made of E-glass, but less than S-glass, aramid or carbon fiber and as worldwide production increases, its cost of production should reduce further (Jamshaid and Mishra, 2015). Figure 2.4 show the typical basalt fibers (BFRP).



**Figure 2.4** Typical Basalt Fibers Reinforced Polymer (BFRP)

### **2.3 Adhesives**

Adhesives are used to bond FRP laminate systems to the concrete substrate. The adhesive provides a shear load path between the concrete substrate and the FRP reinforcing laminate. Adhesives are also used to bond together multiple layers of FRP laminates. A suitable adhesive/resin should be selected for a particular FRP strengthening system. This is normally specified by the manufacturer to meet all the requirements regarding the installation system. The bonding agent normally assures the bond between the substrate and the FRP reinforcement. It may have to impregnate „wet lay-up“ types for the FRP system, depending on the type of FRP reinforcement.

There have been many kinds of adhesives such as PVC, PVA, amino-plastics, polyamides, epoxies, etc. These varieties have supplied us to select the material which has more proper properties. Epoxy adhesives have had two components, namely basic resin or just resin and hardener or accelerator. These materials have been mixed with a definite range of temperatures and different volume or weight so as to produce epoxy adhesives (Mazzotti et al., 2015).

Recently, there are a rapid development of adhesive binding to be parallel the development of science and technology as an economical and effective method for the fabrication of various components and assemblies.

The basic characteristics of epoxy resins can be listed in the following

- Outstanding adhesive qualities to such materials as concrete and steel.
- Resistance to a wide range of chemicals.
- Rather vulnerable when the compound has cured and changed from the liquid to the solid state.
- High coefficient of thermal movement compared with concrete.
- High compressive, tensile and flexural strength.
- High rate of gain of strength.

Epoxy resins are a form of thermosetting resins (Setunge and Nezamian, 2004)). The physical properties of a cured epoxy resin have depended upon many factors such as type and amount of curing agent, cure history, type of filler, type of reinforcement etc. (Reddy et al, 2015).

#### **2.4 Factors Effecting Durability of Strengthening System**

The durability of the strengthening system can be affected by many parameters some of them have been presented as follows.

##### **2.4.1 Surface preparation**

The surface of concrete should be roughened by using different techniques such as grinding using a grinding wheel, sandblasting, etc. All loose particles and other laitance can be removed with a vacuum cleaner. If FRP sheets will be used, the sharp corner should be rounded prior to application. In addition, the concrete surface should be dry and age should be minimized at the age 3-6 weeks (Savas, 2001).

##### **2.4.2 Temperature**

During an application of CFRP sheets and plates, temperatures should satisfy some requirements. Otherwise, the application could not be started. In order to start strengthening work dew point should be lower than the substrate temperature. Dew point obtained from dew point table is a function of ambient temperature of the air and relative air humidity. If temperature requirements are not satisfied, the temperature of the air can be increased by heating or the relative air humidity can be decreased by using fans. Besides, the minimum ambient temperature of the air and substrate

temperature should satisfy some conditions. For example, according to SIKA for Sikadur-330 application temperature should be in the range of +15 °C to +35 °C (for substrate and ambient temperature) (Savas, 2001).

## **2.5 Studies on Strengthening of Heat Damaged Reinforced Concrete Structures**

Fire has always been a major threat to buildings and other structures. Lading to consequences that can both affect the safety of people and the usage. Furthermore, it affects in some cases the very survival of constructions, due to collapse mechanisms induced by fire or fire effects (Bontempi F. 2010).

Several methods have been used by the researchers for repairing fire damaged reinforced concrete members. The techniques are included essentially removing deteriorated concrete layers and replacing them with fresh concrete, a few researchers have used ordinary methods.

In 1980 after St. Elizabeth Hospital in Holland being damaged by an intense fire, Lange used epoxy injection and shotcrete repair of damaged concrete surfaces to recover the structural reliability (Lange G, 1980).

Lin et al. (1995) studied the behavior of reinforced concrete columns repaired with fresh cast-in-place concrete after being damaged by fire. The outcomes demonstrated that the majority of repaired columns could reach their original stiffness and strength or much higher than those of unheated columns.

Layers of ferrocement, fibrous grout and fiber-reinforced polymer sheets were used by Haddad et al. (2007, 2008, 2011) to repair heat-damaged shallow beam, T-shape beams and reinforced concrete slabs. From the three researches, it is concluded that both of fibrous grouts, and fiber reinforced polymer composites contribute high flexural capacity and rigidity.

Roy et al. (2014) investigated the effectiveness of different strengthening schemes in strengthening heat damaged reinforced concrete short columns. A progression of 63 heat-damaged specimens were tested under concentric compression after jacketing externally with High Strength Fiber Reinforced Concrete (HSFRC), Ferrocement (FC) and Glass Fiber Reinforced Polymer (GFRP) jackets. It was observed that while the GFRP jacketing entirely effective in improving compressive strength and energy

dissipation, it is not capable of improving stiffness. The specimens which repaired with HSFRC and FC jacketing techniques showed less measure of deformability contrasted with the respective heat damaged unstrengthened specimens. However, the ductility of heat damaged specimens wrapped with GFRP jacket increased significantly, overall GFRP jacketing was observed to be the applicable technique for strengthening fire or heat damaged concrete columns.

## **2.6 Researches on Repaired and Strengthened Reinforced Concrete Corbels**

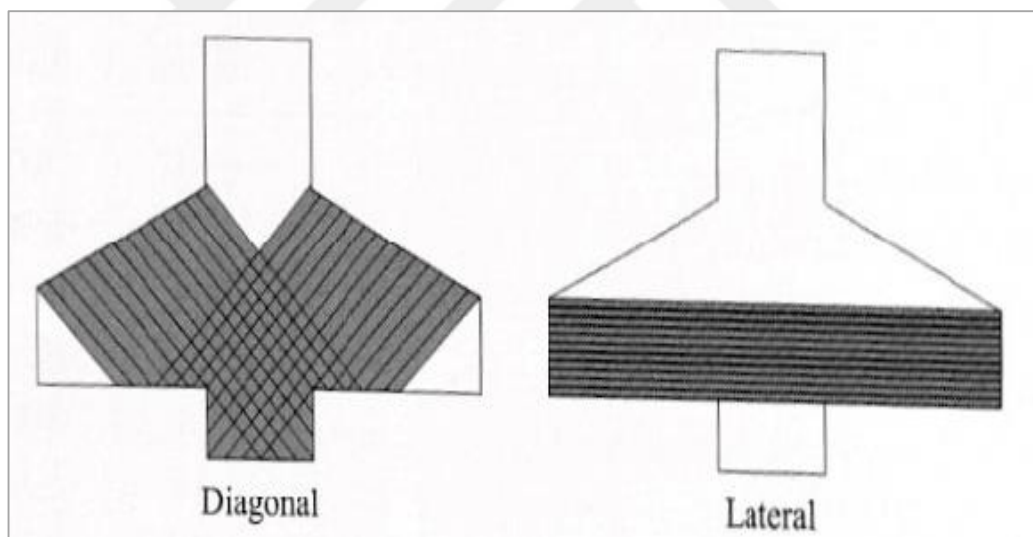
Heidayet et al. (2004) carried out an experimental investigation on 18 damaged reinforced concrete corbels. The specimens were repaired by external steel plates subjected to vertical loads. The studied parameters were the main and secondary reinforcements, the shear span to depth ratio, ( $a_v/d$ ), and the depth of the corbels. At first, the corbels were loaded close to their ultimate capacity and then repaired using externally steel plates, which were fixed by bolts. Finally, the specimens were loaded to failure. Test results showed that the ratio between the strength of the repaired corbel to that of original ones varied from 0.7 to 1.5; it was concluded that this repair technique may be regarded as an effective and economical technique for strengthening existing structures.

Published research work on the behavior of strengthening corbels with FRP fabric is very limited. There were a series of experimental and theoretical tests carried out by Abdul-Wahab (1989), Fattuhi and others (1989-1994), Muhammad (1998), Ridha (2008), Campion and others (2007, 2009), Ahmad and Shah (2009), Yousif (2009), Khalifa (2012) and Gulsan et al. (2015), to investigate the effect of adding steel fibers and chopped carbon fibers to reinforced concrete corbels. Test results showed that the addition of fibers improved the behavior of corbels. This procedure cannot be considered as a strengthening technique to corbels as much as it may be regarded as an improvement to the conduct of those corbels.

Elgwady et al. (2005), carried out an experimental investigation on six corbels strengthened with carbon fiber reinforced plastic (CFRP) strips. Different strengthening configurations were used and the corbels were subjected to monotonic loading. One specimen was considered as a control specimen; the parameters studied were the orientation and amount of CFRP strips. Test results indicated that diagonal

CFRP strips could increase the corbel capacity by about 70% of its control specimen. The other types of strengthening, increased the ultimate load carrying capacity by values ranged from (8-30) %. It was concluded which the specimen with mixed horizontal and diagonal strips showed an apparent delay of cracking. Most of the corbels showed a brittle mode of failure, the stiffness of all specimens were increased and they failed suddenly without adequate warning. The author recommended that the CFRP strips should be stopped before the end of the corbel, where the distance left may be considered as the weaker portion where cracks were propagated.

Ozden and Atalay (2011), investigated the strength and post-peak performance of reinforced concrete corbels strengthened with GFRP overlays. In the experiment 24 specimens were tested to failure under quasi-static gravity loading. The parameters studied were the strength of concrete, the shear span to depth ratio,  $a_v/d$ , the main reinforcement, and the GFRP layers and orientation, the GFRP wrapping configurations are shown in Figure 2.5.



**Figure 2.5** GFRP wrapping configurations

Test results concluded that GFRP wrapping with 45 degrees' fiber orientation (diagonal) was more effective than lateral wrapping. The level of tension steel strain on the onset of failure depends on the type and number of GFRP layers and the tension reinforcement ratio. The results also revealed that the level of strengthening with GFRP wrapping ranges from (40-200) %, depending on the reinforcement ratio,  $A_v/d$  ratio and the orientation and number of GFRP layers used.

Mohamad-Ali and Attiya (2012), carried out an experimental investigation on the shear behavior of reinforced concrete corbels externally strengthened or retrofitted with carbon fiber reinforced polymer (CFRP) sheets. The variables studied were the width, number, length, location and direction of the CFRP sheets. Test results showed that corbels strengthened with inclined strips gave better results compared with specimens strengthened with horizontal strips. It was concluded as well that the external strengthening technique had a significant effect on the first cracking load. The percentage increase in cracking load for the inclined strips was 51%, and the percentage for the horizontal strips was 19%. For the repaired specimen, an increase in the ultimate load was detected; the amount of increase was 57% with respect to the control specimen. Finally, an average decrease in the width of the crack was observed, this decrease was due to the presence of the CFRP strips. The percentage of decrease was 41% and 24% of the control corbels at ultimate load levels for the inclined and horizontal techniques respectively.

El-Maaddawy and Sherif (2014), carried out experimental and theoretical tests to investigate the structural response of concrete corbels reinforced internally with steel rebars and externally with carbon fiber reinforced polymer (CFRP) composite sheets. Nine specimens were tested for this purpose. The specimens were divided into two groups based on whether it was reinforced with main reinforcement only or a combination of main and secondary reinforcement. The strengthening technique included primary longitudinal CFRP reinforcement, parallel to the main reinforcement, secondary longitudinal CFRP sheets, and diagonal CFRP sheets and oriented at 45°. Two U-shaped CFRP sheets were wrapped around the corbel cross section outside the test region, one at each end, to provide an anchorage for the longitudinal CFRP sheets, for the theoretical analysis the FE software ATENA was used.

The results concluded that the load capacity of the corbels was improved by using CFRP as an external strengthening technique. This improvement was decreased with the increase in the amount of primary reinforcement.

The local behavior of RC short corbels strengthened with carbon fiber fabrics was studied by Ivanova et al. (2015). They have studied the main three types of failure for strengthened reinforced corbels; compression failure, flexion failure, shear and fabrics

peeling off the failure with two diagonal cracks, the result showed that increasing in tensile strength failure more than 1.82 by bonding carbon fiber fabric. Also, it concluded that still, the best configuration is strengthening by wrapping. Effect of containment by wrapping provides higher values than those at which the plates are glued directly on the front breaking loads.

Ivanova and Assih (2016), investigated the strengthening of short reinforced concrete corbels under fatigue test. Out of four corbels two of them were strengthened with externally wrapped carbon fiber fabrics and the others were un-strengthened. The corbels were tested under both static and fatigue loading. Different parameters as the influence of cycle, static and dynamic loading on the behavior of the corbels were studied, the cracks and failure modes have been described as well. The results showed that the effect of fatigue on strengthening corbels was a little lower tensile strength by 10% compared to unstrengthen RC short corbel under monotone static test. And also it was resulted that strengthening by bonding carbon fiber fabrics and wrapping the reinforced-concrete corbel improves durability and delays the appearance of cracks.

Ahmad et al. (2013) tested twelve corbel beams to investigate the effectiveness of wrapping of D-region of beam corbels with CFRP. It was shown that by using CFRP wrapping, the loading capacity and energy absorption of corbel beams can be increased and externally adhesive bonded flexible CFRP effect the ultimate shear strength of RC corbels.

In a recent research Shadhan and Kadhim (2015), studied an experimental program on 16 reinforced concrete corbels with various plies of CFRP laminates, 14 of the corbels have been repaired or strengthened. In the experiment some parameters were considered as; damaged ratio, bond type (Using CFRP anchors, full and partial warping), the CFRP pattern scheme (i.e. Number of layers, orientation, and location), and modes of failure as well.

The results showed that the largest influence of increase of ultimate capacity were by the orientation of CFRP strips. The percentage of increasing of ultimate capacity varied from 35% to 71% for horizontal and vertical strips respectively. In an acceptable amount the crack load of the RC corbels increased with respect to the presence of CFRP laminates.

It was concluded that the application of CFRP overlays were not a success for corbels with high damage ratio. It was recommended to use of CFRP anchors to improve the bond strength because de-bonding was the main mode of failure of the experiment.

## **2.7 Conclusion**

Use of various techniques provides considerable advantages for repairing and strengthening of reinforced concrete structures. For instance, they are differently effective on modes of failure, stiffness, ductility as well as the increase of load carrying capacity. The assistances of FRP composite materials throughout the strengthening process, especially for heated and damaged concrete structures require a comprehensive study.

Some of the researchers investigated the strengthening methods for heat damaged reinforced concrete structures such as shallow and T-shape beams, short column and slabs. On the other hand, they compared the effect of using FRP materials with the other techniques. It can conclude from their researches that the load carrying capacity and ductility of heat damaged specimens wrapped with FRP increased significantly.

Although some researchers carried out experimental works to observe physical and mechanical outputs of strengthened reinforced concrete corbels. Many techniques for both of externally wrapped and internally reinforced has been used for strengthening of RC corbels. FRP materials such as (CFRP, GFRP) has selected as proper externally wrapped methods for repair and strengthening of damaged reinforced concrete corbels.

Limited or no data exist in the literature about repair or strengthening of heated and damaged reinforced concrete corbels. The structures that exposed to intense fires, it is necessary to restore their structural integrity. Furthermore, it is a challenge for structural engineers to develop efficient rehabilitation techniques. Therefore, more study theoretical and experimentally required to provide certain information about strengthening for heat and damaged reinforced corbels.

In this thesis an experimental study was carried out for repairing of reinforced concrete corbels with two different techniques. Before the rehabilitation, the corbels were exposed to elevated temperatures, and were damaged with a vertical load.

## CHAPTER 3

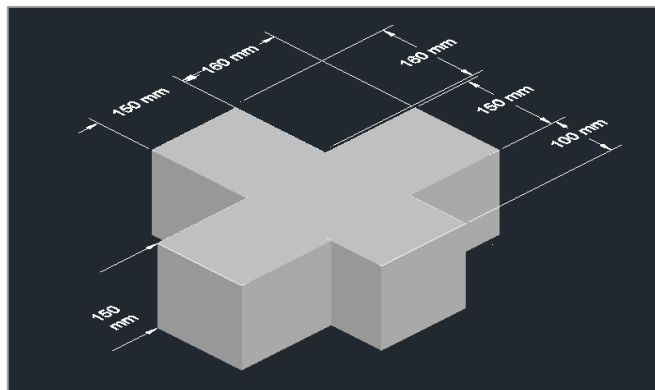
### EXPERIMENTAL PROGRAM

#### 3.1 Introduction

The experimental part of the study is presented in this chapter. There are totally 18 corbels experimented for the thesis with a compressive strength of approximately 50MPa. Nine of them were repaired with epoxy resin injection only and the others were repaired with basalt fiber fabric beside the injection. Before rehabilitation, the corbels were constructed, heated and tested under a vertical load by Khamees Nayyef Abdulhaleem in the laboratory of Gaziantep University. In order to eliminate size and bar diameter effect on the behavior of tested corbels, all corbels had chosen in the same size and same bar diameters. Damaged corbels contain three different amount of steel fiber (0%, 0.5% and 1% of total volume). The corbels had been heated up to three different temperature levels of 250°C, 500°C, and 750°C before the first failure due to vertical loading and they had been loaded on the span of 90 mm and 120 mm before rehabilitation.

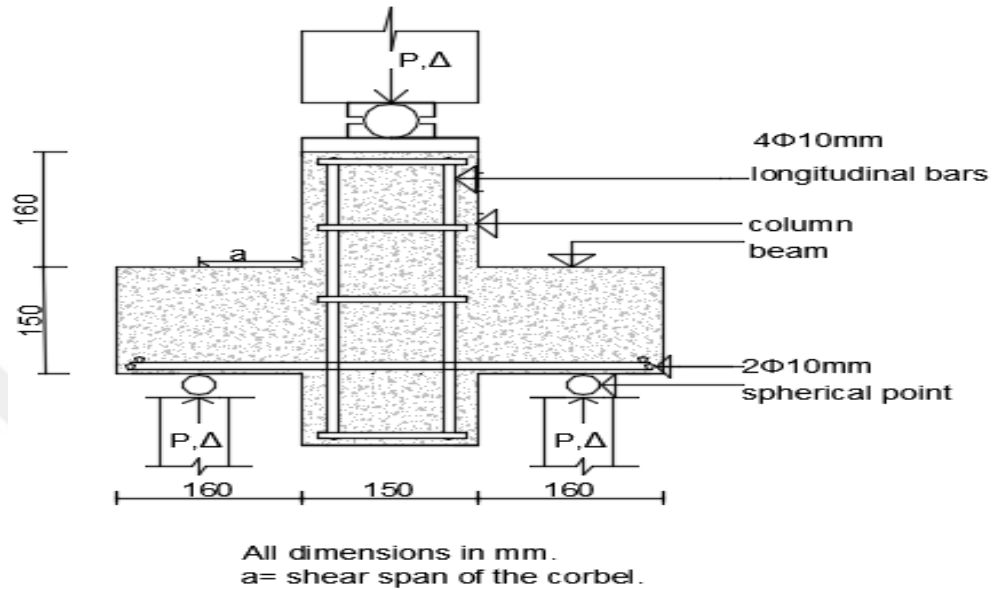
#### 3.2 Description of Test Specimen

The width of the corbels is 150 mm. Both columns and corbels have the same cross section (150 × 150 mm). The stubs of the column are extended by 160 mm from above and 100 mm from below the corbels. Figure 3.1 shows the dimensions of the corbel.



**Figure 3.1** Dimensions of the corbel. (Mohammed A. KAMIL 2016)

The column was reinforced with four vertical bars (10mm in diameter) and 4 stirrup reinforcement had been provided in the form of closed ties at a spacing of 90 mm. The main tension reinforcement of the corbel consisted of two 10mm diameter steel bars. Figure 3.2 shows the details of the reinforcements.



**Figure 3.2** Reinforcement details of the corbel

### 3.3 Materials Properties of Corbels

Portland cement type two according to ASTM with a fineness (295 m<sup>2</sup>/kg), and a specific gravity (3.12) was used totally in all the specimens. Coarse and fine aggregate was used reproducer from crushed stone and crushed with a maximum size (11 mm), a specific gravity (2.65), and water absorptions (0.8%, 1.4%), respectively. To achieve the SCC limitation, fly ash was used as binder additives and silica fume as well. When steel fibers were used, workability of concrete decreased. Therefore high-performance super-plasticizer was added to the mix to increase the workability of self-compacting concrete. To produce hybrid fiber reinforced SCC (FR-SCC), hooked-end steel fiber (SF) and polypropylene fiber (PP) were used. The properties of the PP and SF fibers used in the corbels are shown in Table 3.1.

**Table 3.1** Properties of fibers used in the study

Fiber type	Length (mm)	Diameter (mm)	Density (g/cm <sup>3</sup> )	Tensile strength (MPa)
Steel Fiber (SF)	30	0.75	7.8	1200
Polypropylene fiber (PP)	12	0.02	0.91	450

The properties of steel bar which utilized for reinforcement the corbels shown in Table 3.2.

**Table 3.2** Mechanical properties of steel bars

Diameter ( $\phi$ ) mm	Yield stress (MPa)	Ultimate strength (MPa)
10	455	588

### 3.4 Properties of Repairing Materials

The loosing parts from damaged corbels were replaced with a high viscosity epoxy (TEKNOBOND 200). The epoxy resin based solvent free adhesive with A&B components. It can be used in bonding of FRP sheets on wooden, steel or concrete surfaces, and be used in repairing of damaged concrete, on vertical and overhead applications particularly. Also it can be utilized in filling the gaps that occur due to abrasion. In addition, the epoxy's some benefits can be listed as follows:

- Perfect resistance to chemical attacks.
- Ability of adherence to concrete, steel and wooden surfaces.
- Good adherence to FRP sheets.
- Rapidly gets mechanical strength.
- Can be utilized in over-head applications.
- Long process time.
- High ability to resist abrasion.
- Tension and vibration rooting resistance in the different temperatures.
- Resistant to freeze-thaw cycle.

- Absorbs impact.
- Impermeability to water and other liquids.

Moreover, the properties of the epoxy are shown in Table 3.3.

**Table 3.3** The properties of TEKNOBOND 200 epoxy

Color	Gray
Density	1.5 gr/cm <sup>3</sup>
Consumption	1.5 kg/m <sup>2</sup> for 1 mm thickness
Bond to Concrete	4.0 N/mm <sup>2</sup> (7 days) (TS EN 1542)
Pot Life	30 minutes (at 20°C).
Loading capability	1 day
Full strength	7 days
Application Ground Temperature	(+5°C) - (+30°C)

The fiber fabric and the concrete surface were glued together with a low viscosity epoxy (TEKNOBOND 300). The epoxy is based, solvent free adhesive which consists of two components. It can be used to structurally bond FRP composite sheets and transfer all loads into the fiber composite for structural strengthening. The epoxy's benefits and features can be summarized as follows:

- Consummate adherence to concrete, and FRP sheets.
- Perfect chemical resistance.
- High bonding to composite sheets at initial adhesion.
- Time consuming process.
- High resistance to electric current and freeze-thaw cycle.
- Liquid impermeability.
- Allows transfer of stress to the individual fibers in the composite sheets.

Moreover, this adhesive is penetrating very thin details due to low viscosity. The properties are shown in Table 3.4.

**Table 3.4** The properties of TEKNOBOND 300 epoxy

Color	Component A Light Brown / Component B Transparent
Density	1.15 gr/cm <sup>3</sup> (Component A)-1.05 gr/cm <sup>3</sup> (Component B)
Consumption	2 kg/m <sup>2</sup> for 1 mm thickness
Bond to Concrete	>5.3 N/mm <sup>2</sup>
Pot Life	Approx. 45 minutes at +20°C
Loading capability	1 day
Full strength	7 days
Application Ground Temperature	(+5°C) - (+30°C)

The cracks of damaged corbels were injected with a crack repairing epoxy (Sikadur-52). The epoxy is a two component low viscosity liquid, fast curing and free flowing injection resin. This crack repairing epoxy can be used for injecting and filling cracks in structural components such as industrial structures, bridges, foundations, beams, columns, floors, walls, slabs and water-retaining structures. Furthermore, the epoxy can be used in insitu and precast concrete structures to bond the sections together, in that way restoring the structural integrity of the element. It has the following advantages:

- Solvent-free.
- Appropriate in both, damp and dry conditions.
- Working at low temperatures.
- Shrinkage-free hardening.
- High adhesive and mechanical strengths.
- Not brittle but very hard.
- Very low viscosity.

The characteristics of the epoxy adhesive are shown in Table 3.5.

**Table 3.5** The properties of Sikadur-52 epoxy

Color	Part A: Transparent
	Part B: Brownish
	Part A+B mixed: Yellowish-brownish
Density	Part A: 1.1 kg/l (at +20°C) Part B: 1.0 kg/l (at +20°C) Part A+B mixed (2 : 1): 1.1 kg/l (at +20°C)
Compressive Strength	52 N/mm <sup>2</sup> (7 days at 23°C).
Bond to Concrete	4.0 N/mm <sup>2</sup> (7 days at 23°C).
Pot Life	25 minutes (at 25°C).
Flexural Strength	61 N/mm <sup>2</sup> (7 days at 23°C).
Tensile Strength	37 N/mm <sup>2</sup> (7 days at 23°C).
E-Modulus	1800N/mm <sup>2</sup> (7 days at 23°C).

Basalt Unidirectional Fabric this type of fiber used in this experimental study for several reasons such as; High tensile strength, smooth texture, durability and fire resistance. The properties of the fabric are shown in Table 3.6.

**Table 3.6** The properties of basalt fiber fabric

Tensile Strength (MPa)	Tensile Modulus of Elasticity (Gpa)	Elongation (0/0)	Thickness (mm)	Polyester Yarn Density (tex)	Area weight (g/m <sup>2</sup> )
2100	105	2.6	1.15	5.25	300

### 3.5 Preparation of Specimen Surface Before Repairing

Proper preparation of the concrete surface can affect the behavior of concrete members which strengthened or repaired with FRP systems. However, some of the corbels were damaged extremely as shown in Figure 3.3, while some others were not damaged so much (see Fig. 3.4). Therefore, proper and appropriate surface preparation is required for both of them.



**Figure 3.3** High damaged corbel



**Figure 3.4** Low damaged corbel

Surface grinding process was carried out by grinder machine which was used to clean the surface of corbels. The top four corners of each corbel's beam were rounded to reduce the decrease in strength, to prevent stress concentrations on them and to avoid tearing in basalt fabric (see Fig. 3.5).



**Figure 3.5** Surface grinding process

Before the gluing of basalt fiber fabric, the air compressor was used to remove any loose concrete particles or dust on the surface (see Fig. 3.6).



**Figure 3.6** Using air compressor for removing loose particles

### 3.6 Rehabilitation Methods

Two different methods were used for rehabilitation of damaged corbels:

#### 3.6.1 Injection with only crack repairing epoxy

The high viscosity epoxy was used for substituting the loosening parts from damaged corbels, which is shown in Fig. 3.7, A and B components of the epoxy were mixed in a ratio of 1:1 by weight. A mechanical mixer with 500 RPM was used for mixing the components in a container until a gray color and consistency are achieved (at least 3 minutes).



**Figure 3.7** Mixing of high viscosity epoxy

The high viscosity epoxy was also used for filling the big cracks to prevent the leakage of low viscosity resin from the cracks (see Figure 3.8).



**Figure 3.8** Filling the side cracks with high viscosity epoxy

The crack repair epoxy was mixed according to the technical advice which contained in the adhesive data sheets. When the epoxy was injected into the corbels, the cracks

and voids were filled with it. In injection technique, machine was not used and penetration of the epoxy only depended on gravity (see Fig. 3.9).



**Figure 3.9** Crack repair epoxy(Sikadur-52) injection

After injection process, the corbels were left for 7 days for curing of the epoxy (obtainment of the target strength of the epoxy). Then grinder machine was used to level the bottom surface of the corbel beams (see Fig. 3.10) in order to provide the appropriate setup on the testing machine.



**Figure 3.10** Grinding after injection

### 3.6.2 Injection of crack repair epoxy and wrapping with basalt fiber fabric

In this method, all of the corbels were subjected to the injection method before gluing the basalt fiber fabric on surface of them. The performance of externally bonded FRP can be affected by delamination or fiber crushing of FRP if the crack width is 0.3 mm or higher. Therefore, epoxy can be injected into those cracks that are wider than 0.3mm. Minor cracks require resin sealing or injection to avoid corrosion of the steel reinforcement exists in the damaged concrete members. However, for detailed methods and surface preparation of concrete, relevant criteria and guidelines can be used (ACI Committee 440, 2002). The surface of corbels became rough due to application of epoxy 200 and Sikadur-52 injection on them. Therefore, grinder machine was used to make corbel surfaces smooth and to avoid any delamination between basalt fiber fabric and the concrete surface, as shown in Figure 3.11.



**Figure 3.11** Surface preparation before gluing the basalt fiber

Three strips of basalt fiber fabric were cut in specific dimensions for all corbel specimens (see Figure 3.12). The epoxy hardener and resin were mixed by an electric drill machine according to TEKNOBOND 300 product data sheet. Then the basalt fabric was saturated with the epoxy (see Fig. 3.13),

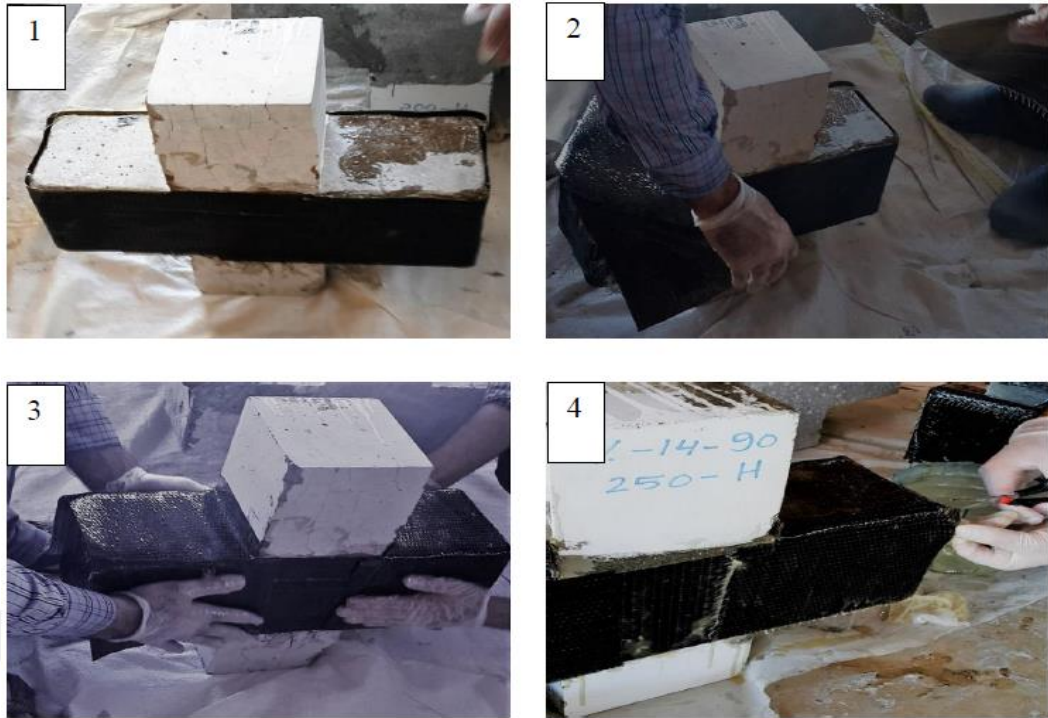


**Figure 3.12** Basalt fiber strips



**Figure 3.13** Saturated basalt fiber with low epoxy

To resist vertical and horizontal stresses the saturated basalt fiber fabrics were glued bi-directionally on the corbels. The fibers were aligned parallel to the axial stresses in a layer, and another layer was wrapped transversally. Afterwards, trowel was used to eliminate air voids and to achieve perfect adhesion between the fabric and surface (see Fig. 3.14)



**Figure 3.14** Configuration steps of bonding surface and applying the Basalt Fiber

At last, grinder machine was used again for levelling of corbels' bottom surface to provide successful simultaneous load transfer mechanism up to both of supports, Figure 3.15



**Figure 3.15** Grinding after covering of basalt fiber

### 3.7 Test Setup

All of the corbels were tested before and after the rehabilitation process under vertical loads. As shown in Figure 3.16, a testing machine with capacity of 500 kN was used to perform loading tests and the load was applied at the top of the column. The machine was operated in displacement controlled mode with the rate of 0.4 mm/min, and the data were recorded at every 0.2 s.



**Figure 3.16** Corbel Specimen Setup.

The deflection was measured using two linear variable displacement transducers (LVDT). These LVDTs were placed at two opposite sides of the corbel-column junction at the tension side of the beams. The corbel specimens were supported on two supports; with one side on a steel roller, whereas the other side was supported on a steel hinge allowing free rotation, but preventing translation in both horizontal and vertical directions. These supports were at a distance ( $a$ ) from face of the column as shown in Figure 3.17. The deflection ( $\Delta$ ) value was obtained as average values of two LVDT readings (for each specimen). Results of loads and deflections with respect to time were recorded in computer to extract load-deflection curves of the specimens. The load was transferred from the loading frame to the corbel by the 15 mm thickness loading plate. Loading plate was produced from a transmission steel to transfer the load effectively and continuously until failure.



**Figure 3.17** Injected and covered corbels with two LVDTs on the testing machine



## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 Introduction

The corbels had been loaded until failure via the testing machine before repairing and strengthening. Three different types of failure were recorded; flexure failure occurred at or close to the column-corbel junction after extensive yielding of the steel reinforcement bars. Diagonal splitting appeared as a line extending from the column-corbel junction toward the bearing plate or the concrete was divided into separate parts, and shear failure occurred between flexure and diagonal-splitting cracks (Fattuhi, 1990).

The failed corbels were repaired by epoxy injection and strengthened with basalt fiber fabric. Most of the corbels' failure patterns were changed after rehabilitation and strengthening. This chapter presents the several responses of each test specimen before and after rehabilitation such as; the load-deflection responses (C.C represents control corbel and R.C represents rehabilitated corbel in the curves), the ultimate load capacity, and failure modes.

#### 4.2 Corbels Repaired with Epoxy Injection only

Nine of the corbels were repaired with only crack repair material in order to study the efficiency of epoxy injection for restoring the capacity of the corbels. The corbels had been loaded on the span of 120mm before and after rehabilitation. The results of injected corbels are shown in Table 4.1. The first column is for name designation of corbels, in which three terms are assigned to each corbel's name; the first term represents the number of the specimen and the remain terms represent steel fiber ratio and degree of heating. The maximum loads carried by control corbels are represented in the second column of Table 4.1. The load values before repairing were affected by many parameters, especially the heating degree and steel fiber ratio.

While increasing the temperature adversely affects the carrying load, the addition of steel fiber increases load carrying capacity as well. The results of each corbel repaired, compressive strength and the ratio of reaching load, are respectively listed in third and fourth columns. It is observed from the results that the ratio of load after rehabilitation to the first failure load varied from 0.67 to 1.28. This big ratio gap is due to the diversity of parameters. Moreover, the load carrying capacity after repairing is significantly affected by the damage ratio of corbels. Micro cracks which could not inject sufficiently effect the effectiveness of rehabilitation process. For example, low resoting capacity exists for the corbels that were damaged on one leg, and also had high number of minor cracks on the other leg. The ability and effectiveness of epoxy for rehabilitation reduces if the crack width is higher. Consequently, the injection technique with low viscosity epoxy was fulfilled more effectively for midium strength corbels which have less damaged ratio. As shown from the results, the average ratio of ( $*P_U/p_u$ ) for repaired corbels with epoxy injection reaches to 0.98 of their initial values. The maximum deflection values of all of the corbels increased after rehabilitation as compared to their deflections before repairing. As represented in fifth and sixth columns of the Table 4.1, the deflection at maximum load for most of the corbels has increased and the average values of maximum deflection before and after rehabilitation are respectively 1.34mm and 1.82mm. Two different modes of failure were observed before repairing which were shear failure and diagonal splitting failure. The modes of failures after rehabilitation had occurred in three manners. As a result of repairing, failure mode for the first group of corbels were changed, the second group's mode of failure were occurred as their previous, and the third group's failure had occurred on the other side of the specimen, however they mentioned as same modes of failure in the Table 4.1. Each corbel's detail, load-deflection curve and the modes of failure are discussed in the following pages of this chapter.

**Table 4.1;** Experimental test results for corbels repaired with epoxy injection

Name	$P_u$	$*P_U$	$*P_U/p_u$	Max.Deflection (mm)		Modes of failure	
				Before repairing	After repairing	Before repairing	After repairing
C1-0.0-250	130	150	1.15	0.736	2.523	Shear failure	Shear failure
C2-0.0-500	80	102	1.28	0.697	1.057	Diagonal splitting	Diagonal splitting
C3-0.0-750	51	43	0.84	1.085	1.672	Shear failure	Shear failure
C4-0.5-250	201	135	0.67	1.718	1.628	Shear failure	Shear failure
C5-0.5-500	117	132	1.13	0.682	0.765	Shear failure	Shear failure
C6-0.5-750	88	80	0.91	2.083	2.157	Shear failure	Diagonal splitting
C7-1.0-250	212	190	0.9	1.221	1.094	Shear failure	Shear failure
C8-1.0-500	136	157	1.15	1.723	2.621	Shear failure	Shear failure
C9-1.0-750	99	80	0.81	1.852	2.868	Shear failure	Diagonal splitting
	Average		0.98	1.34	1.82		

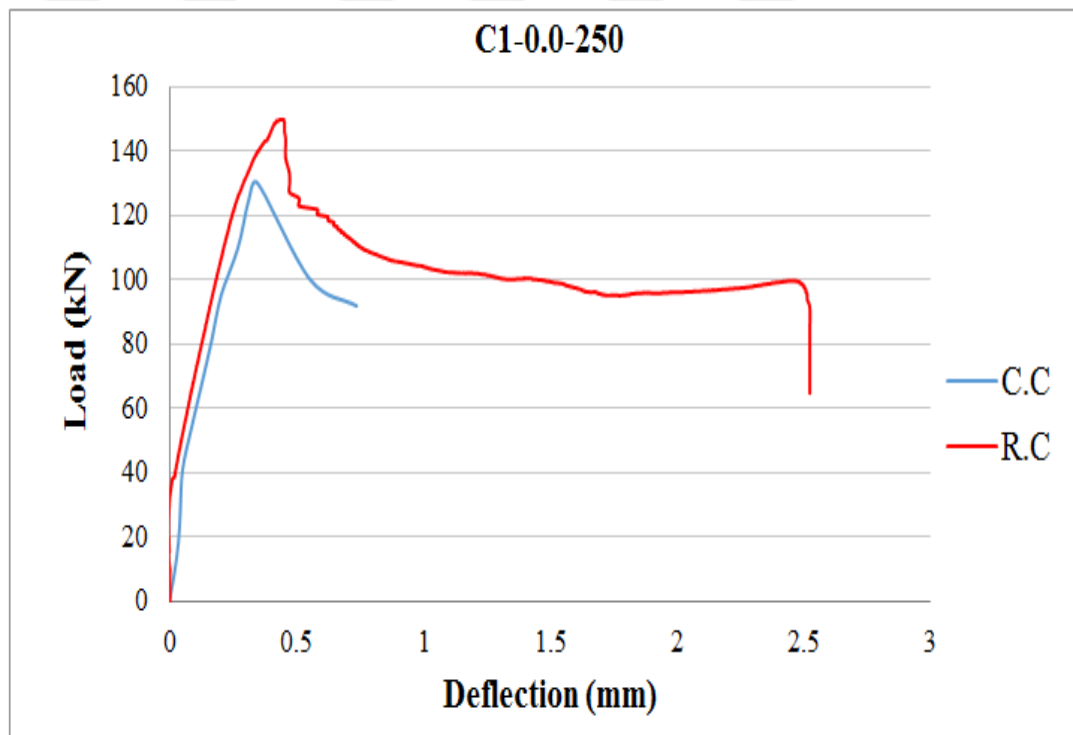
$P_u$ ; peak load capacity before rehabilitation (KN).

$*P_U$ ; peak load capacity after rehabilitation (KN).

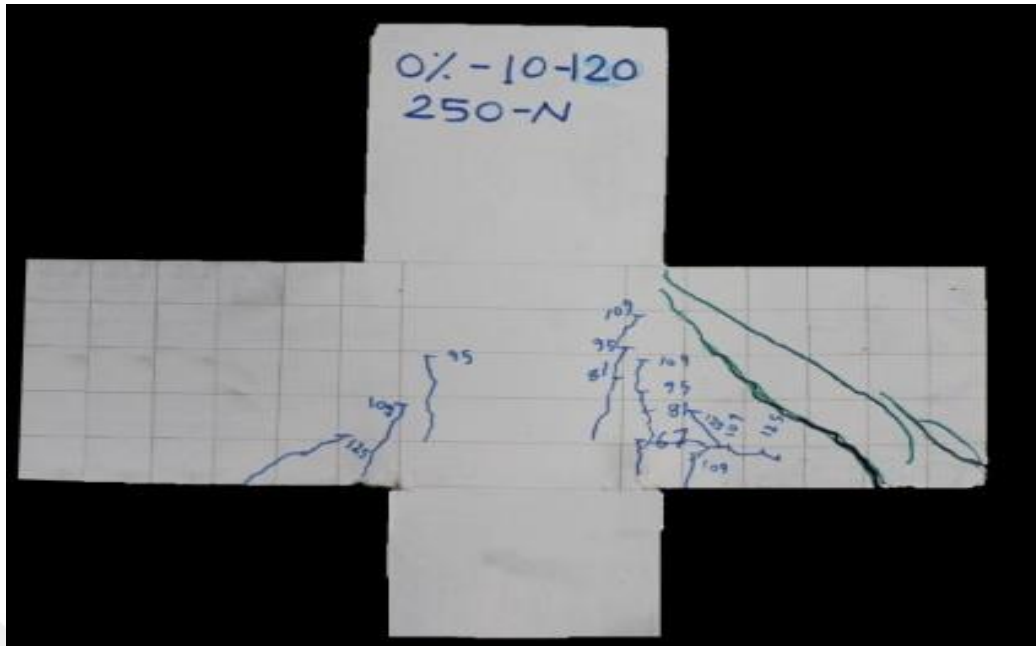
#### **C1-0.0-250:**

This corbel which was reinforced with two  $\phi 10$ mm steel bars for the main reinforcement, and was produced from medium strength self-compacted concrete with compressive strength of 50MPa, was prepared without steel fiber. After  $28 \pm 1$  day of water curing process, the specimen was placed in an electrical furnace and the temperature was increased by a rate of  $5^\circ\text{C}/\text{min}$  till the required temperature of  $250^\circ\text{C}$  was obtained. The corbel was maintained in the desired temperature for 1 hour. After cooling, the corbel having the shear span of 120mm was subjected to a vertical load.

The specimen's ultimate load capacity was 130 kN. The shear failure occurred in the right beam of the corbel, and also very small micro cracks appeared in the right side as shown in Figure 4.2. Whereas the corbel was repaired by only epoxy injection, the load capacity increased in a great amount which was 1.15 of its initial value. After repairing, the mode of failure was the same with the first failure mode which was shear failure as shown in Figure 4.3. As it is shown in the load-deflection curve in Figure 4.1, the deflection at maximum load of the corbel was equal to 0.34 mm before repairing and increased to 0.44mm after rehabilitation. From the curve of R.C (Rehabilitated Corbel), it can be noted that the load capacity reached to its peak value of 150 kN, and the load directly drops to 122 kN due to the development of first cracks. After that, the load gradually decreases to 100 kN until the displacement of 2.5mm at which the corbel collapsed.



**Figure 4.1** Load-displacement curve of specimen (C1-0.0-250)



**Figure 4.2** Specimen (C1-0.0-250) failure before repairing

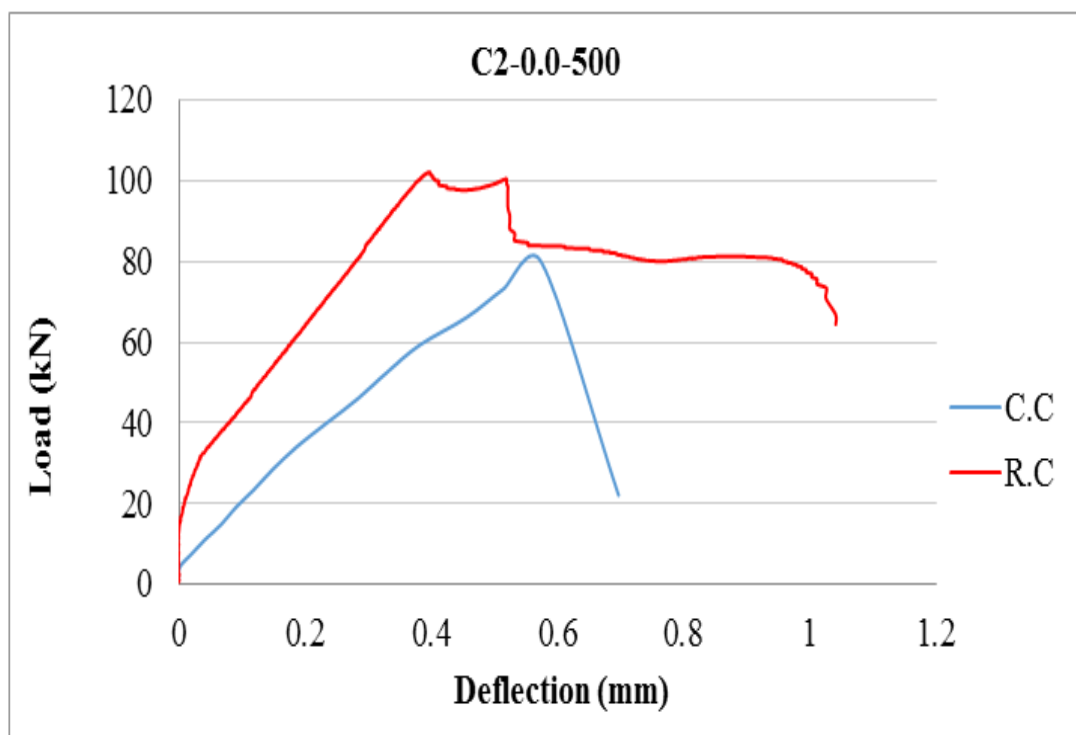


**Figure 4.3** Specimen (C1-0.0-250 ) failure after repairing

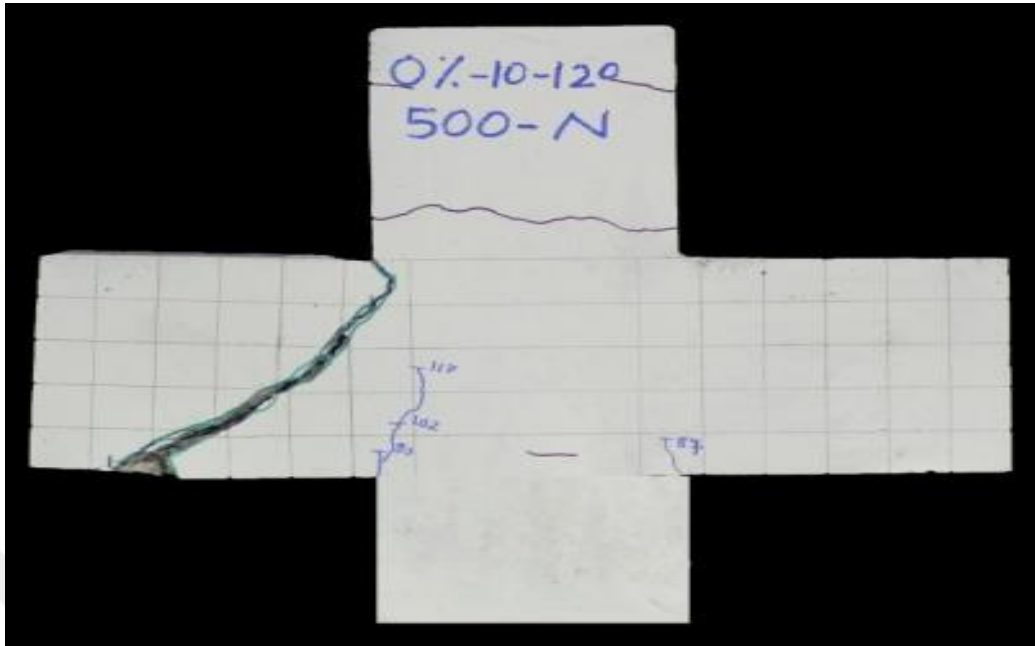
### C2-0.0-500:

This specimen was exposed to the elevated temperature of 500°C and the corbel has the same reinforcement details and shear span with specimen of C1-0.0-250. The ultimate load capacity before rehabilitation was 80 kN with diagonal splitting failure mode in the left side, and a few number of micro cracks on the right side as well, (see Figure4.5). The specimen was repaired by epoxy injection only in order to investigate the effectiveness of restoring the capacity after rehabilitation. The results showed an extremely high improvement in the capacity of the corbel after repairing, where the rate of increasing was 1.28 of the initial value. In other words, absence or lower number of micro cracks provides the corbel to be stronger when only epoxy injection is used for repairing of it. After rehabilitation, the peak load increased to 102 kN with the same failure pattern as shown in figure 4.6. The new diagonal splitting failure crack occurred near the old one on the same side.

As shown from load-deflection curve of the specimen Figure4.4, the deflection at maximum load of the corbel is equal to 0.57mm before repairing and decreased to 0.40mm after rehabilitation. In the displacement of 0.52mm the R.C load dropped down for 82 kN, and the loading continued in a small rate of decrement until it collapsed in 1.04mm.



**Figure 4.4** Load-displacement curve of specimen (C2-0.0-500)



**Figure 4.5** Specimen (C2-0.0-500) failure before repairing

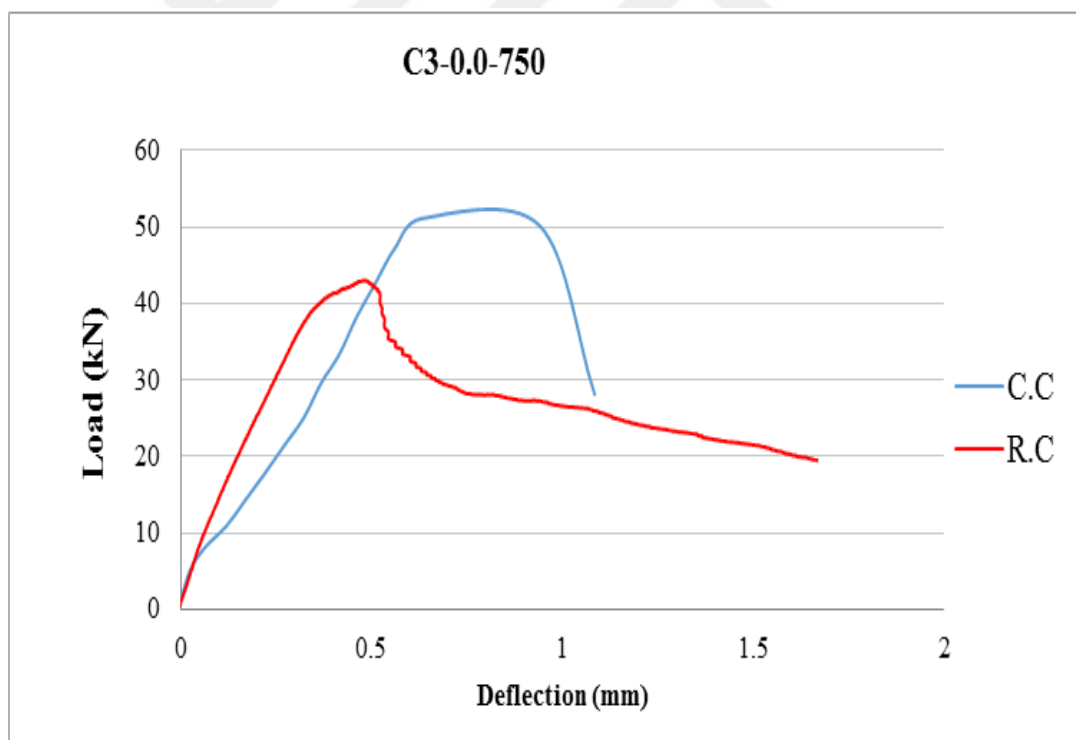


**Figure 4.6** Specimen (C2-0.0-500 ) failure after repairing

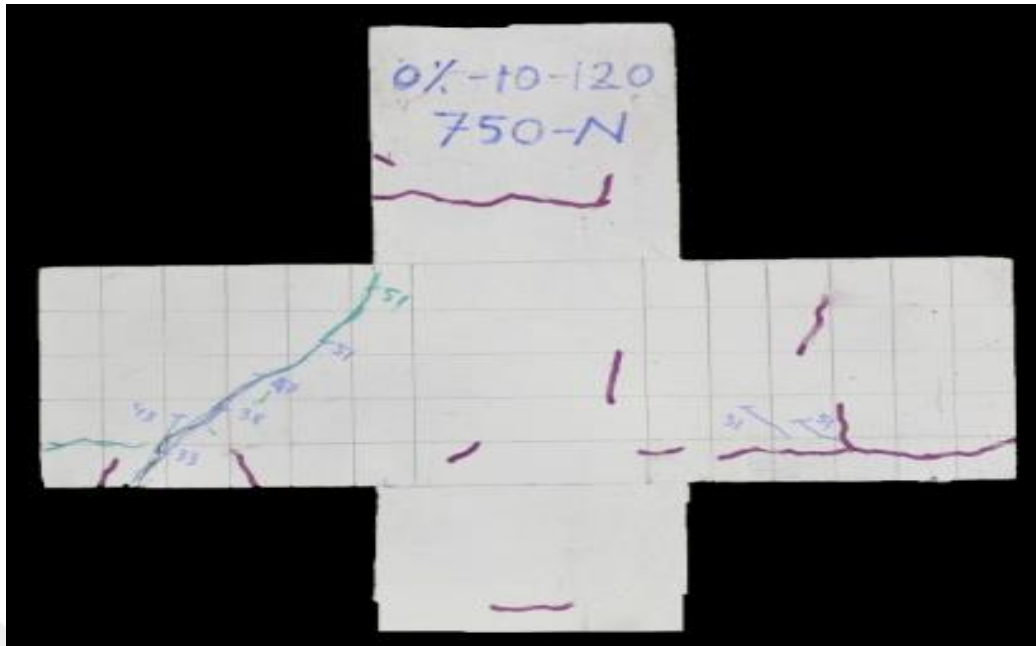
### C3-0.0-750:

This corbel was maintained in an electrical furnace with a temperature degree of 750°C, and was damaged by a vertical load with an ultimate capacity of 51kN. The occurred failure mode was shear failure on the left corbel (see Figure 4.8). After repairing, the specimen was subjected to the vertical load with the same shear span of 120 mm. The specimen's ultimate load capacity was 43 kN with shear failure on the same side of the corbel (see Figure 4.9), where 0.84 of the original load capacity was restored for that heavy damaged corbel. Heating the corbel up to that high elevated temperature had increased the number of micro cracks. Therefore, the epoxy injection could not restore the original load capacity fully.

It can be noted from the load-deflection curve Figure 4.7, at displacement of 0.53mm the R.C load is dropped rapidly. After that, the load gradually decreased until collapse occurred at displacement of 1.66mm.



**Figure 4.7** Load-displacement curve of specimen (C3-0.0-750)



**Figure 4.8** Specimen (C3-0.0-750) failure before repairing

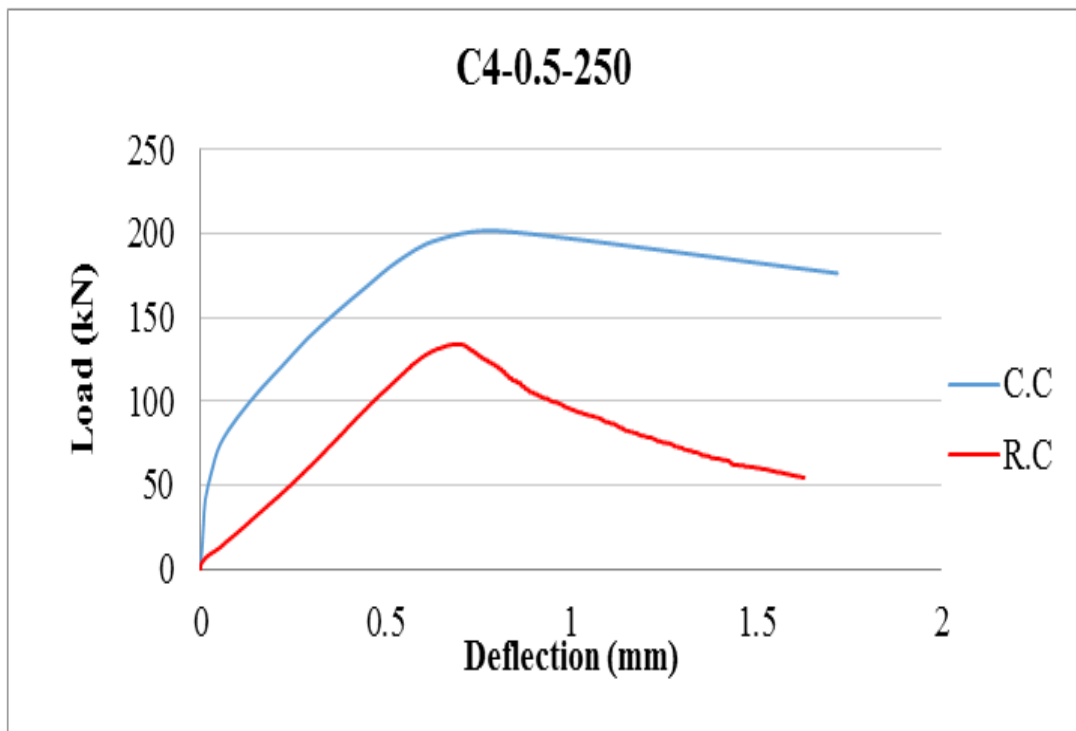


**Figure 4.9** Specimen (C3-0.0-750 ) failure after repairing

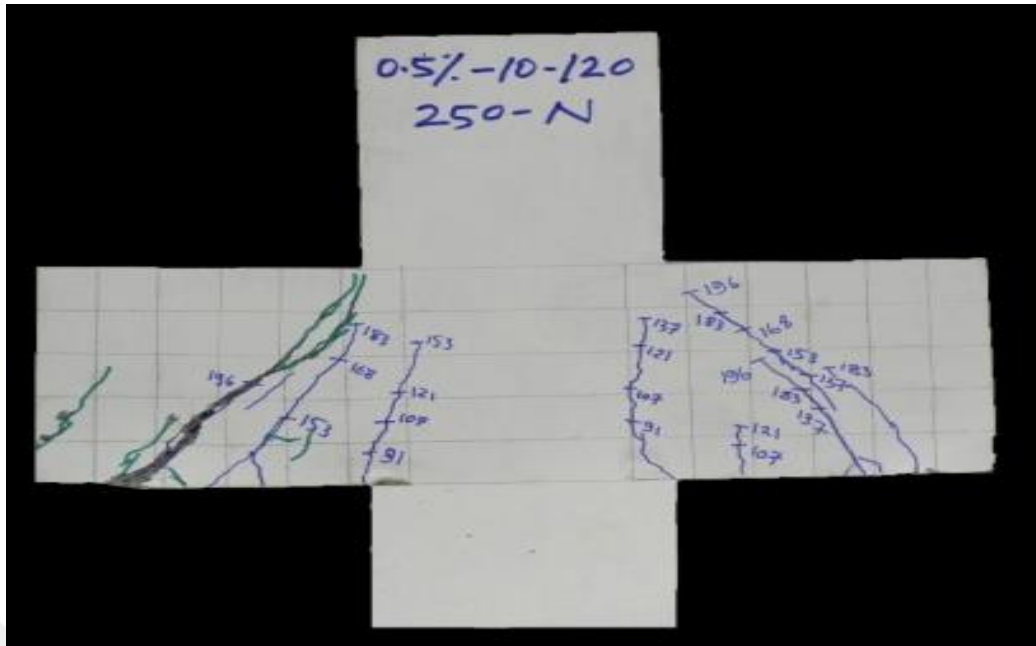
#### C4-0.5-250:

Specimen (C4-0.5-250) is the corbel reinforced with  $\phi 10$  mm steel bars for the main reinforcement of it. Steel fiber with ratio of 0.5% was used in the concrete mix of this corbel. The corbel had been heated until  $250^{\circ}\text{C}$ . After cooling, the corbel was subjected to a vertical load with shear span of 120 mm. The flexural cracks were observed at load of 91 kN on both sides of the corbel, and the cracks extended through the interface between the corbel and column parts. The cracks were also followed by shear cracks at load of 196 kN on the both legs (see Figure 4.11). As a result, the specimen's ultimate load capacity was 201 kN with shear failure on the left side of the corbel.

After epoxy injection was used to repair the damaged corbel, 0.67 of its original load capacity was restored. It can be seen from Figure 4.12, that the failure is apparent on the right beam of the corbel, the side which was neither totally damaged nor perfectly injected due to high presence of micro cracks. Transfer of the failure indicates that the corbel did not fail on the repaired corbel side. Consequently, the rehabilitation process succeeded. As shown from load-deflection curve in Figure 4.10, the displacement at maximum load after repairing is equal to 0.70mm, and the load decreases gradually after peak load due to the existence of steel fiber.



**Figure 4.10** Load-displacement curve of specimen (C4-0.5-250)



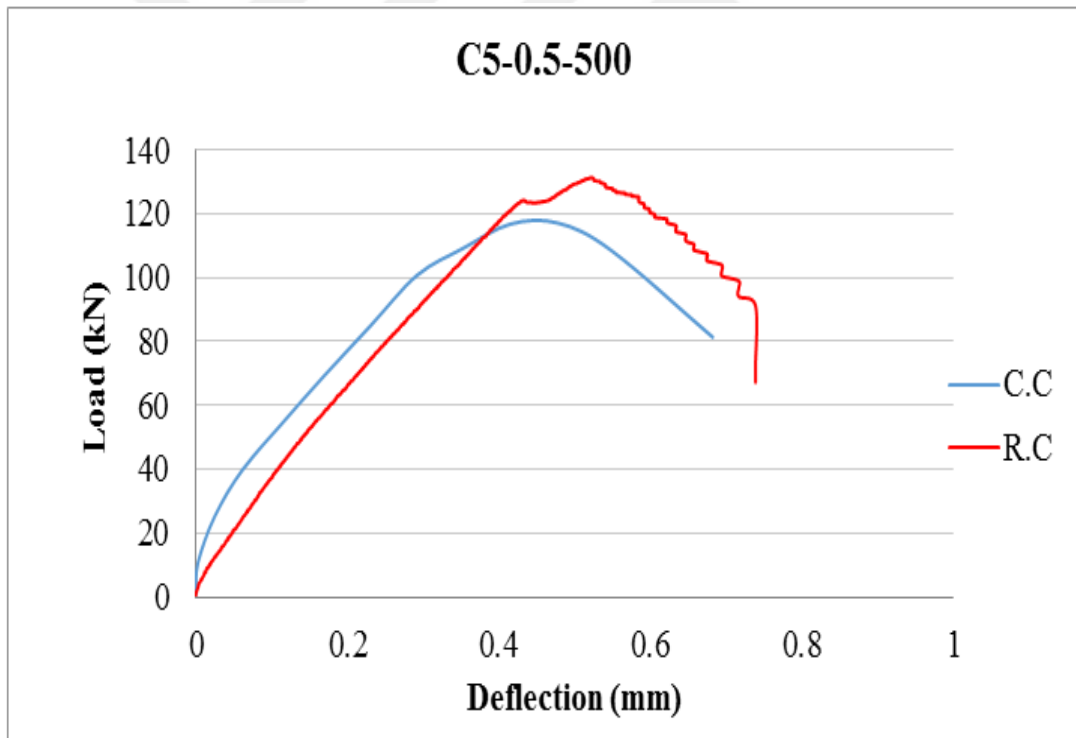
**Figure 4.11** Specimen (C4-0.5-250) failure before repairing



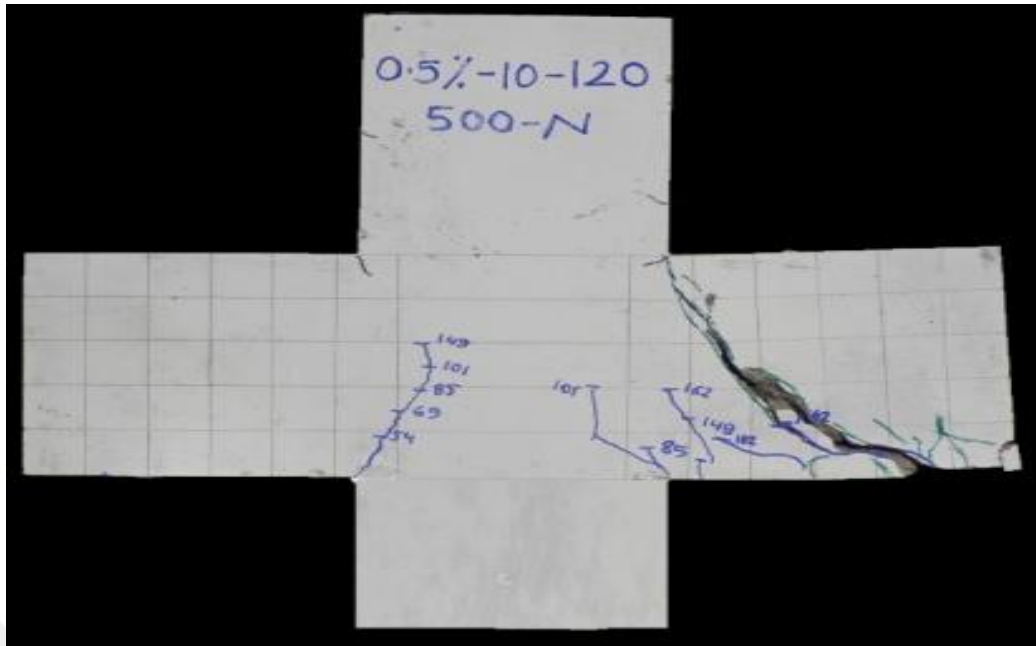
**Figure 4.12** Specimen (C4-0.5-250 ) after repairing

### C5-0.5-500:

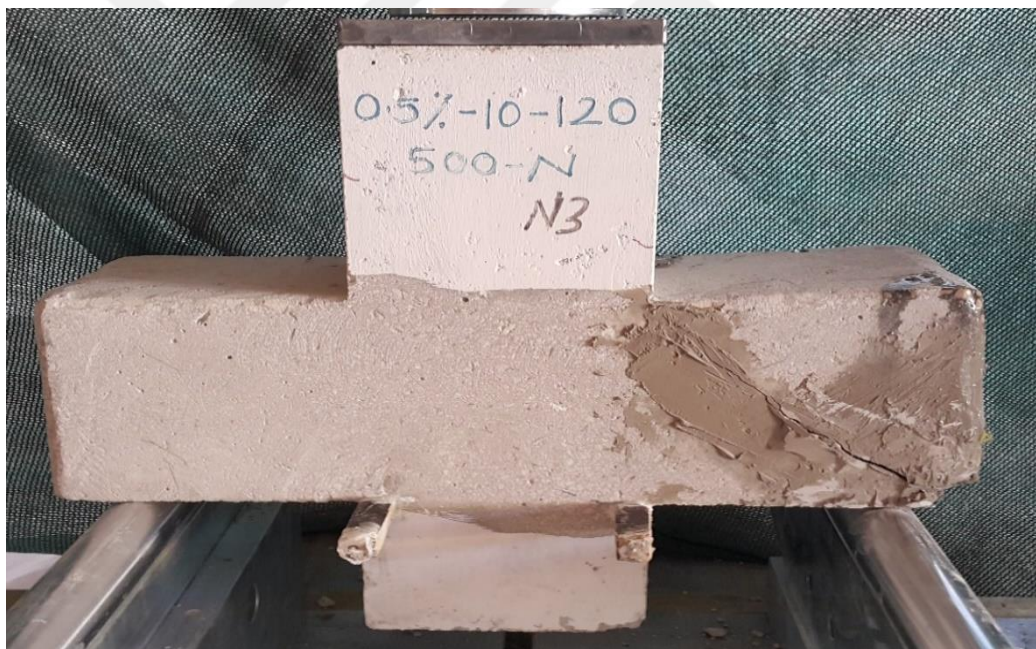
This specimen was exposed to elevated temperature of 500°C and the corbel has the same reinforcement details with C4-0.5-250 specimen with shear span of 120mm. The specimen was repaired by epoxy injection only. After repairing, the results presented a great improvement in the restored capacity of the corbel by 1.13. The peak load, before rehabilitation, was 117 kN with shear failure in the left corbel. After rehabilitation, the load capacity increased to 132 kN with the same failure pattern (see Figure. 4.14 and 4.15). It is shown in Figure 4.13, that the maximum load before repairing is at displacement of 0.47mm, and it is equal to 0.53mm after repairing. It can be noted that the existence of steel fiber provides gradual decrease of the load after the corbel reaches to its maximum value. As a result of failure of one leg of the corbel, the restoring capacity by epoxy injection was very high, even though the specimen was also damaged due to high elevated temperature (500°C.)



**Figure 4.13** Load-displacement curve of specimen (C5-0.5-500)



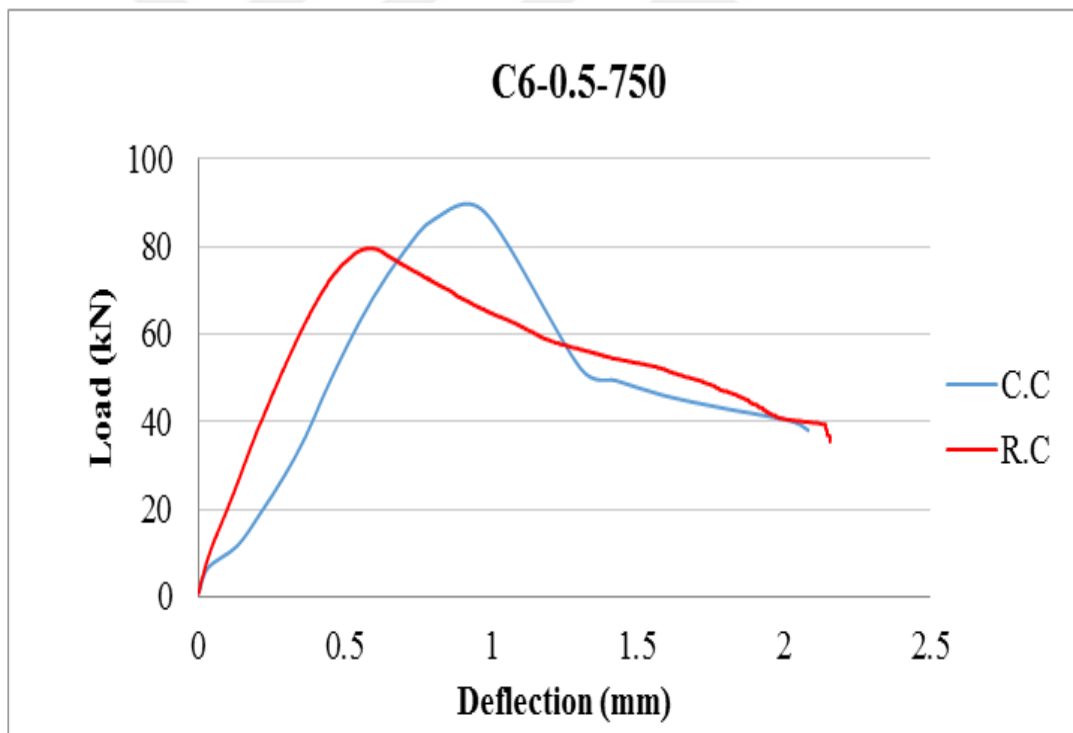
**Figure 4.14** Specimen (C5-0.5-500) failure before repairing



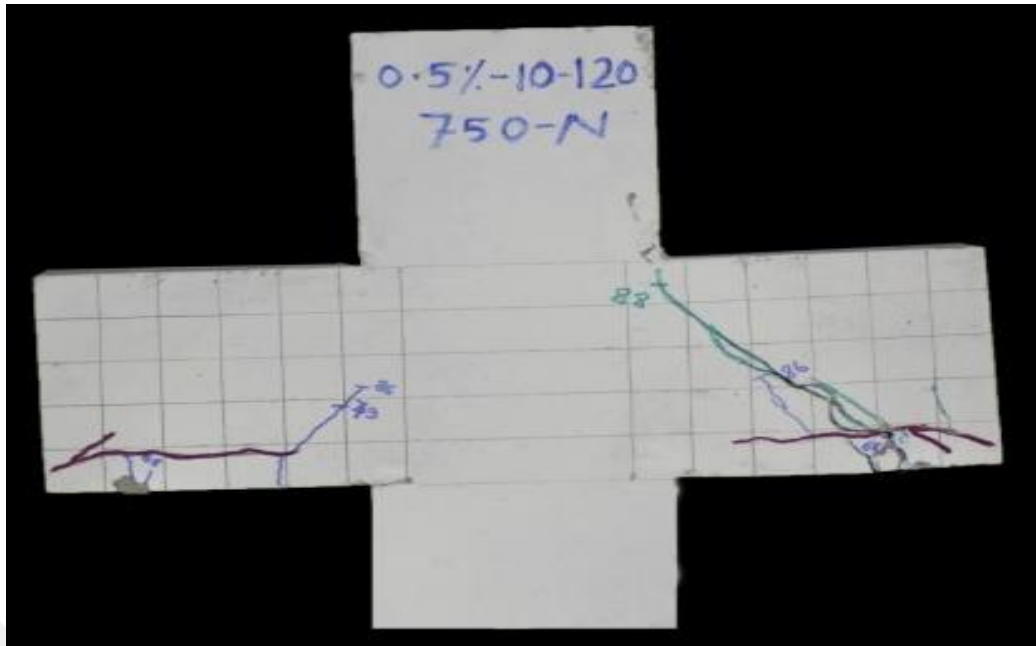
**Figure 4.15** Specimen (C5-0.5-500 ) failure after repairing

### C6-0.5-750:

The characteristics of this corbel was almost equal to C4-0.5-250 corbel, but this corbel was heated up to temperature of 750°C. After use of epoxy injection to repair the corbel, 0.91 of its original load capacity was restored. As it is shown in Figure 14.17, the specimen has shear failure on the left side before rehabilitation. However, when the corbel was repaired and subjected to a vertical load, the failure occurred on the right corbel (see Fig. 4.17). This shows the effectiveness of the epoxy injection for repair of the corbel and also the negative effect of high temperature on the undamaged side of the corbel before rehabilitation. The deflection at maximum load of the corbel was equal to 0.97mm before repairing and decreased to 0.58mm after repairing. The existence of 0.5% steel fiber in the corbel's concrete mix affects the post-peak behavior of the corbel as shown in Figure 4.16. The load decreased gradually up to deflection value of 2.15mm at which the failure occurs.



**Figure 4.16** Load-displacement curve of specimen (C6-0.5-750)



**Figure 4.17** Specimen (C6-0.5-750) failure before repairing

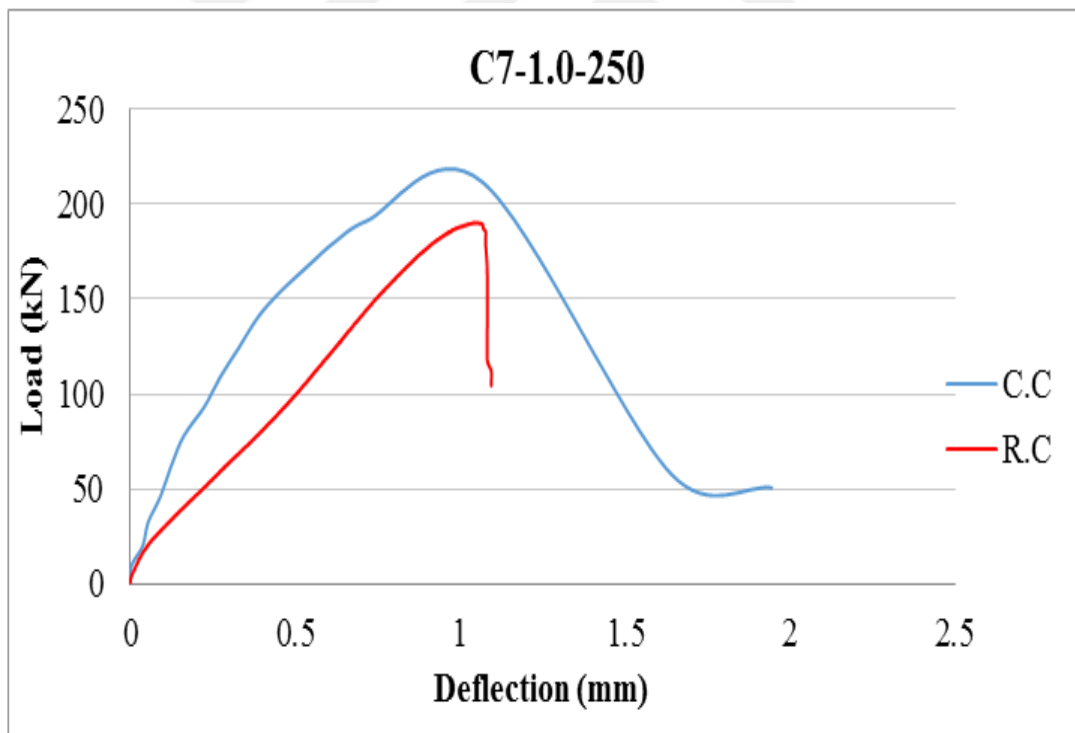


**Figure 4.18** Specimen (C6-0.5-750 ) failure after repairing

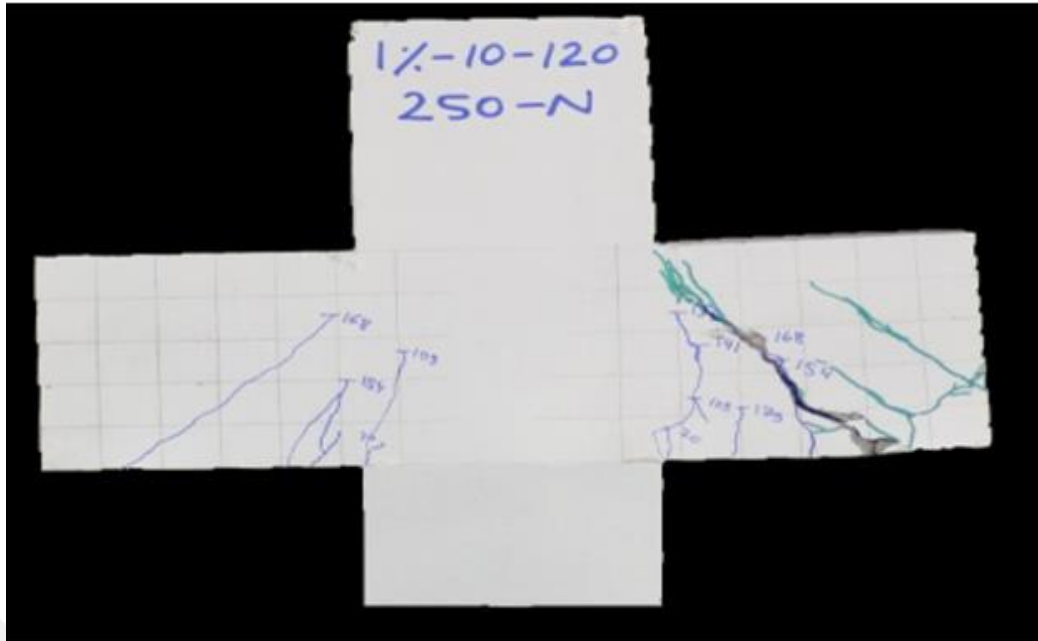
**C7-1.0-250:**

This corbel with shear span of 120mm was repaired by epoxy injection only, which had been maintained in an electrical furnace with temperature degree of 250°C previously. The corbels' concrete mix contains 1.0% (as volumetric ratio) steel fiber. Before the rehabilitation the corbel failed in shear failure existed in the left corbel and its load capacity was 212 kN. However, shear cracks appeared on both of the corbels (see Fig. 4.20). The value of rehabilitation performance for this corbel was found to be 0.90 of the original load capacity before repairing. The damaged left side of the corbel was injected adequately. Consequently, the specimen failed on the right beam with a load of 190 kN. This led to a shear failure near the bearing support (see Fig. 4.21).

Figure 4.19 shows corbel displacements before and after rehabilitation that equal to 1.06mm and 1.05mm at maximum load respectively. It can be noted that when the corbel reaches its peak capacity, the load directly drops due to the shear failure.



**Figure 4.19** Load-displacement curve of specimen (C7-1.0-250)



**Figure 4.20** Specimen (C7-1.0-250) failure before repairing

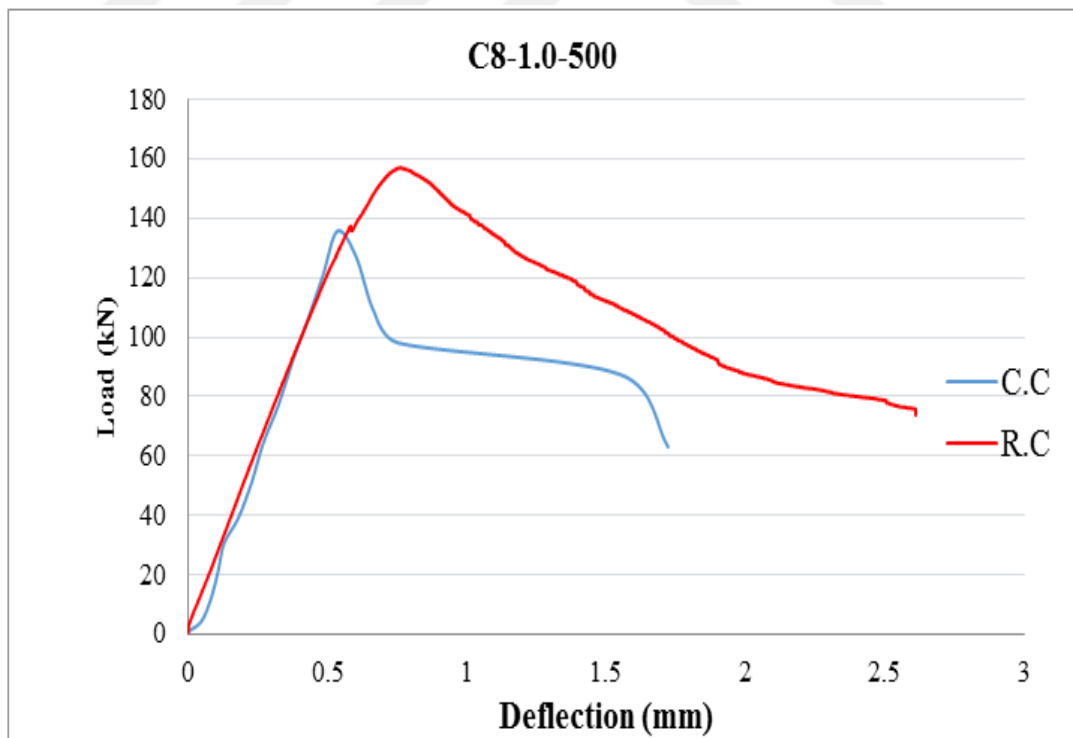


**Figure 4.21;** Specimen (C7-1.0-250 ) failure after repairing

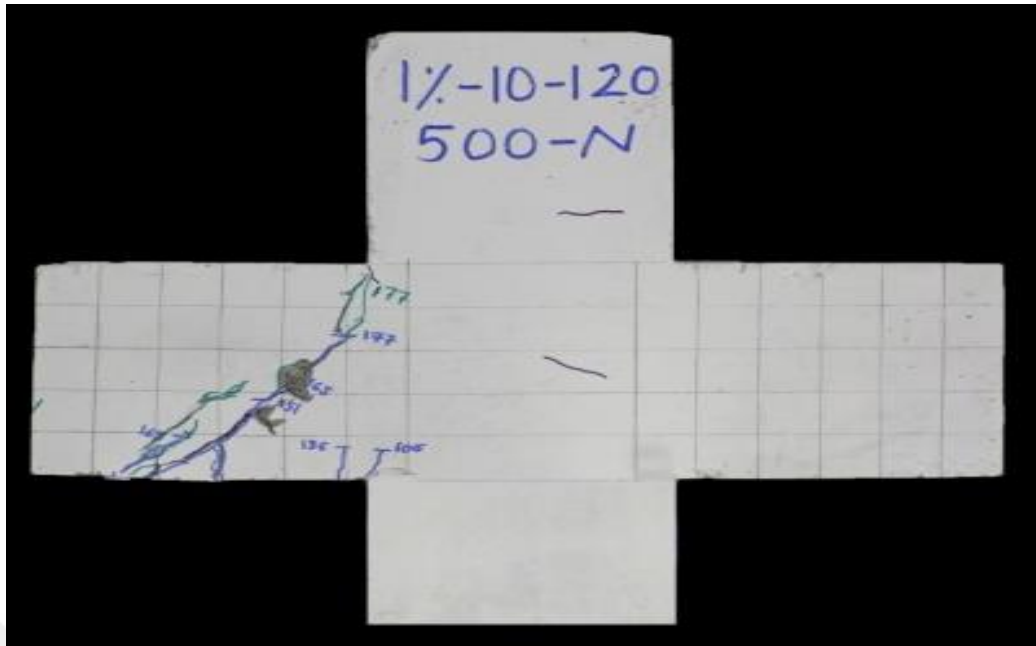
### C8-1.0-500:

The properties of this corbel are almost same with C7-1.0-250 corbel, except elevated temperature of 500°C. The specimen was rehabilitated with epoxy injection only. Significant enhancement was obtained in the capacity was noted which was 1.15 of its original load capacity. Ultimate load capacities before and after rehabilitation were 136 kN and 157 kN respectively. The failure mode for the corbel before repairing was shear failure that existed on the left side. There are no any cracks on the right beam (see Fig. 4.23). The same failure appeared on the other side after rehabilitation process as shown in Figure 4.24. The high performance of the rehabilitation technique is proven in the wake of crack transference from the damaged side to the other side after repairing.

The deflection of the corbel at maximum load before repairing is equal to 0.53mm and increased to 0.76mm after rehabilitation. Presence of 1.0% of steel fiber in the corbels' concrete mix affects the load drop as shown in figure 4.22, in which the corbel gradually comes to colapse at 2.62mm after reaching to its peak capacity.



**Figure 4.22** Load-displacement curve of specimen (C8-1.0-500)



**Figure 4.23** Specimen (C8-1.0-500) failure before repairing

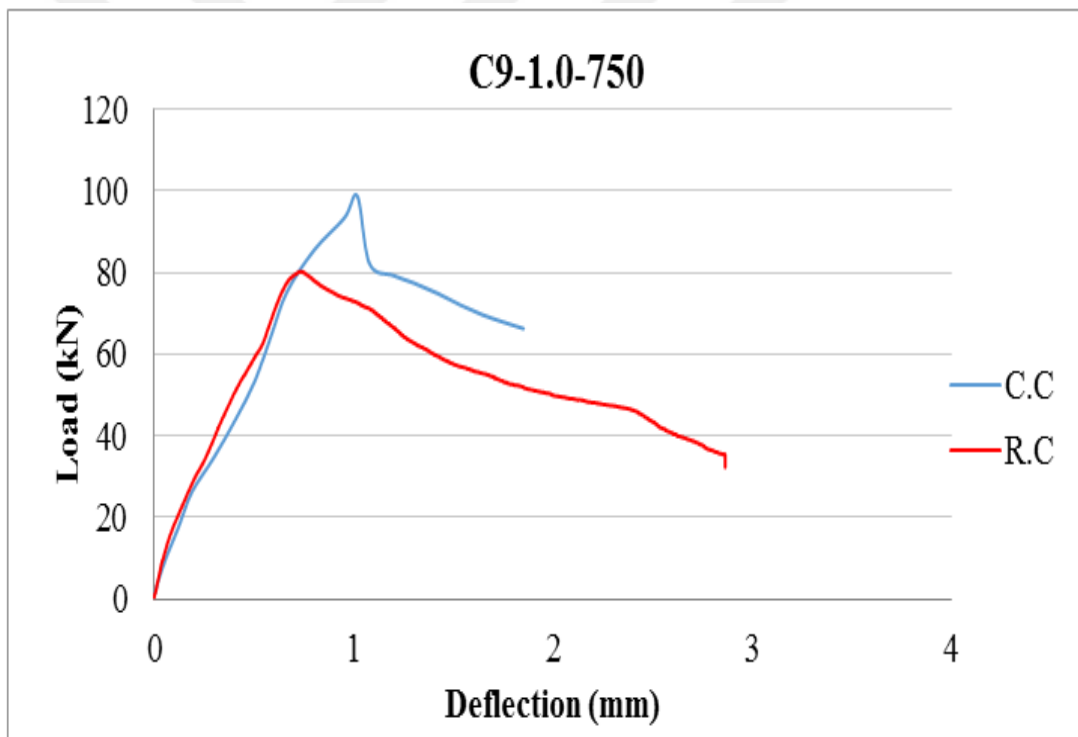


**Figure 4.24** Specimen (C8-1.0-500 ) failure after repairing

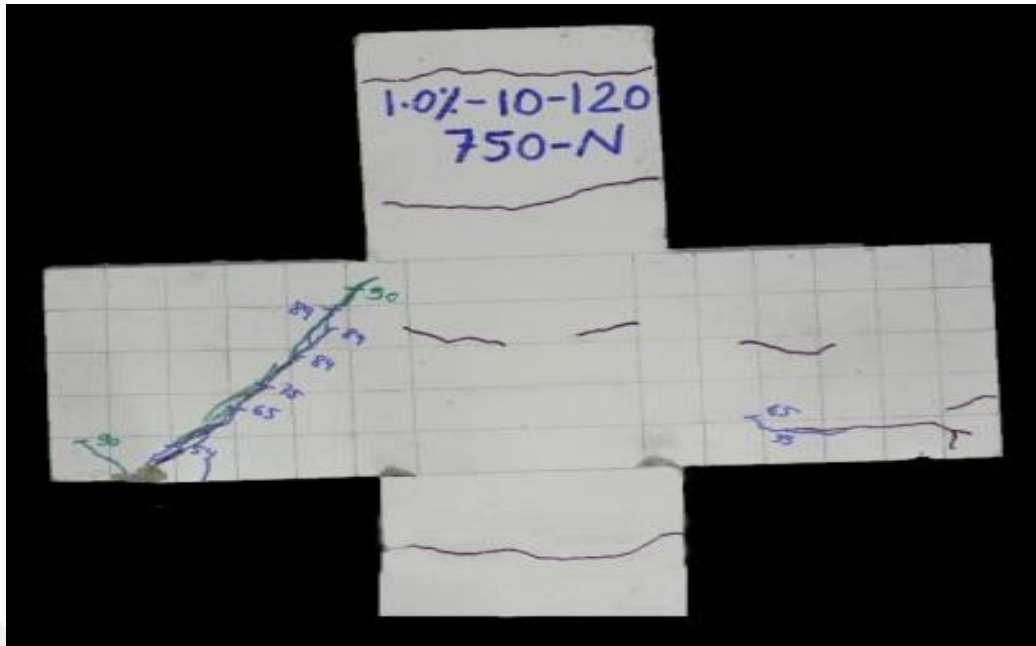
**C9-1.0-750:**

This specimen was maintained in an electrical furnace with temperature degree of 750°C. Sikadur-52 epoxy injection was used for repairing. Before rehabilitation, the load capacity of the corbel 99 kN with shear failure on the left beam (see Fig. 4.26). However, the specimen's ultimate load capacity was 80 kN with shear failure on the opposite side of the corbel after repairing (see Fig. 4.27). 0.81 of the original load capacity was restored for the damaged corbel. Occurrence of cracks and failure on the right side indicates the effectiveness of the epoxy injection.

As it can be noted from the load-deflection curve in Fig. 4.25 that after at displacement of 0.73mm the load on R.C drops gradually from 80 kN to 35 kN. The drop is due to propagation of cracks and its gradual nature is due to the existence of steel fiber.



**Figure 4.25** Load-displacement curve of specimen (C9-1.0-750)



**Figure 4.26** Specimen (C9-1.0-750) failure before repairing



**Figure 4.27** Specimen (C9-1.0-750 ) failure after repairing

### **4.3 Corbels Repaired with Epoxy Injection and Strengthened with Basalt Fiber Fabric (BFF)**

The second group of corbels were injected with crack repair epoxy and covered with basalt fiber fabric. The main purpose of this part of the study is to investigate the effectiveness of use of epoxy injection and basalt fiber fabric together to strengthen heated and damaged reinforced concrete corbels. Test results with all details are shown in Table 4.2. The corbels were constructed of self-compacted concrete with compressive strength of 50MPa. In the main reinforcement of the corbels steel bars in diameter of 10mm were used. Moreover, three different volumetric ratios of steel fiber (0.0%, 0.5% and 1.0%) were used in the concrete mix of the corbels. The specimens were exposed to elevated temperatures of (250°C, 500°C and 750°C). The heated corbels were tested, with shear span of 90mm, under vertical loading until failure. After damaging, the corbels were repaired and tested under the vertical load with same shear span. The table prepared for covered corbels has three more columns to express the increasing rate of energy absorption. The table prepared for covered corbels is same as the one used for the injected corbel group with three more columns to express the increasing rate of energy absorption.

The most important extraction for the corbels rehabilitated with this technique was the increase in the load capacity after rehabilitation. The rate of load capacity increasing ,after rehabilitation, reaches to 1.51 of the initial value. It can be noticed, as shown in Table 4.2, that use of basalt fiber fabric to strengthen the corbels leads to a significant increase in the energy absorption for all corbels. The average maximum deflection enhanced from 1.45mm to 5.72mm which indicates a remarkable high increase in the ductility.

All of the corbels were covered with unidirectional basalt fiber fabric in two directions. This operation makes the fiber to possess much more strength as compared to adhesive epoxy resin. Therefore, all of the failure modes were debonding failure which occurred between the basalt fiber and concrete surface. Moreover, the diverse failure modes before rehabilitation did not cause any change in the failure type after rehabilitation.

**Table 4.2** Experimental test results for BFRP-strengthened corbels.

Name	$P_u$	$*P_U$	$*P_U/p_u$	Max.deflection (mm)		Energy Absorption (J)		Rate of increasing energy absorption after repairing(J)	Modes of failure	
				Before repairing	After repairing	Before repairing	After repairing		Before repairing	After repairing
C10-0.0-250	208	256	1.23	1.186	4.897	164	912	5.5	Diagonal splitting	De-bonding
C11-0.0-500	175	227	1.3	1.102	3.125	122	460	3.7	Shear failure	De-bonding
C12-0.0-750	82	124	1.51	1.054	8.163	57.5	775	13.47	Shear failure	De-bonding
C13-0.5-250	243	278	1.14	1.936	5.51	324	1053	3.25	Shear failure	De-bonding
C14-0.5-500	193	260	1.35	0.913	7.437	77	1728	22.44	Shear failure	De-bonding
C15-0.5-750	119	142	1.19	1.591	6.158	124	675	5.44	Shear failure	De-bonding
C16-1.0-250	247	268	1.09	1.71	2.442	302	433	1.43	Shear failure	De-bonding
C17-1.0-500	207	313	1.51	1.884	6.769	256	1460	5.7	Shear failure	De-bonding
C18-1.0-750	132	185	1.4	1.74	7.034	143	987	6.9	Shear failure	De-bonding
Average			1.31	1.457	5.72					

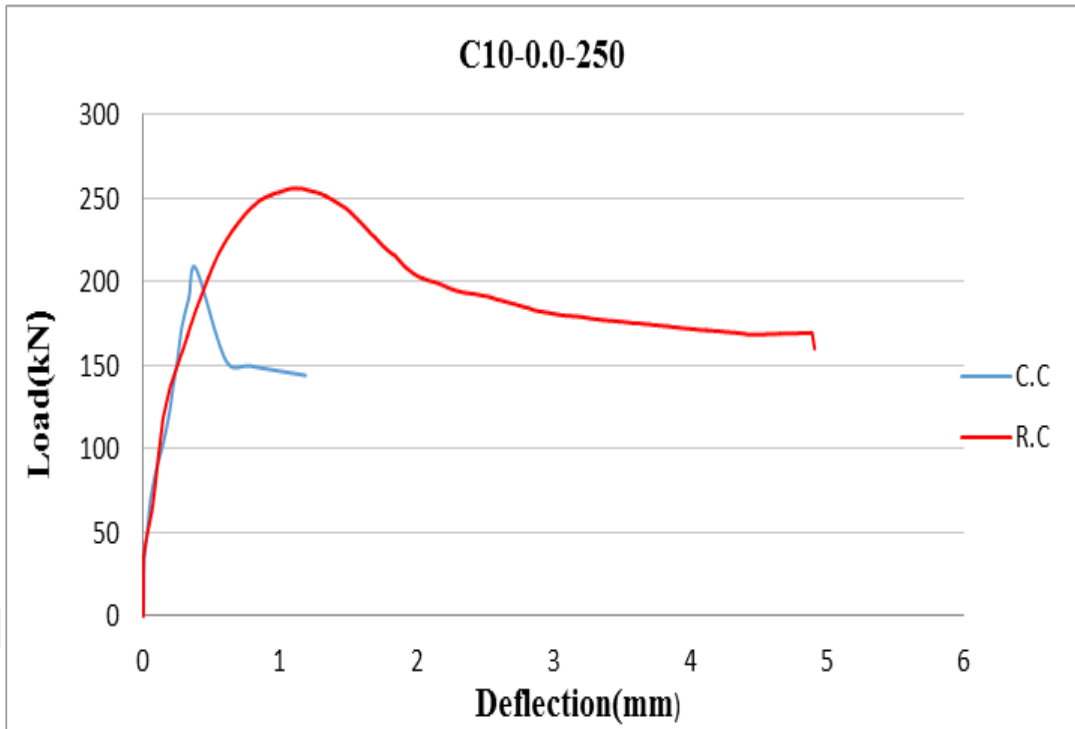
$P_u$ ; peak load capacity before rehabilitation (kN).

$*P_U$ ; peak load capacity after rehabilitation (kN).

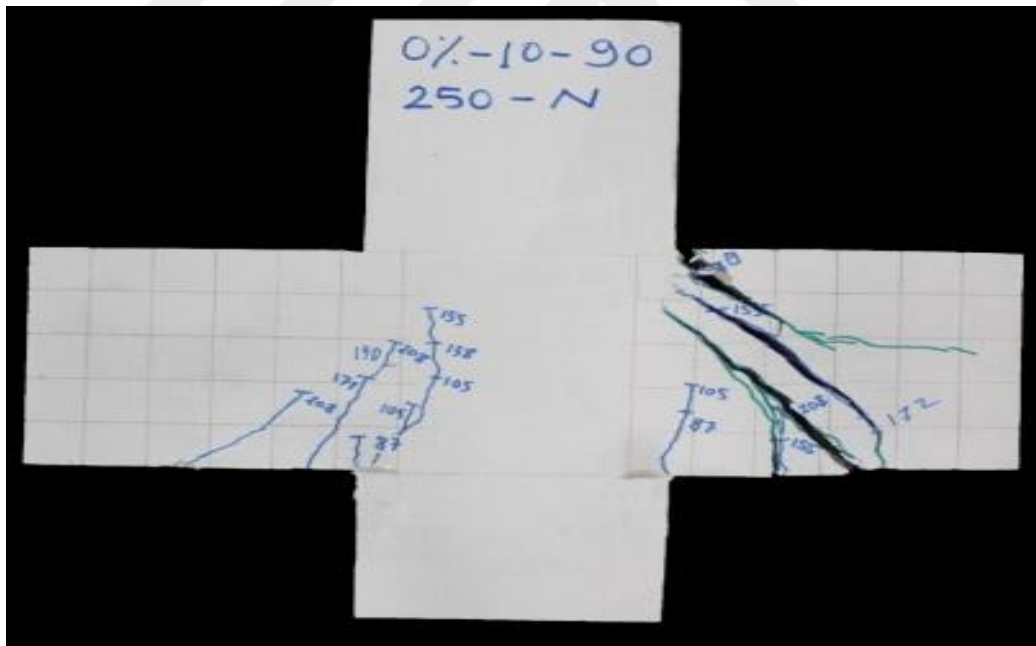
### **C10-0.0-250:**

This corbel was reinforced with  $\phi 10$ mm steel bars for the main reinforcement. Steel fiber was not used in the concrete mix. The compressive strength of the self-compacted concrete was 50MPa. The specimen was placed in an electrical furnace and the temperature was increased up to 250°C. After cooling, the corbel was subjected to a vertical load with shear span of 90 mm. The specimen's ultimate load capacity was 208 kN and failure mode was splitting failure occurred in the right side of corbel (see Fig. 4.29). However, after the corbel was repaired by epoxy injection and was strengthened with basalt fiber fabric BFF, the load capacity increased as the amount of 23% of its initial value. Separation of basalt from the surface of concrete results in debonding failure as shown in Fig. 4.30. The basalt fabric did not tear. Therefore the crack patterns could not be observed during the test.

As it is shown in load-deflection curve (Fig. 4.28) that the maximum displacement of the control corbel C.C before repairing is equal to 1.18mm and increased to 4.89mm after strengthening. From the figure it can be noted that before strengthening, the ultimate load capacity is 208 kN with corresponding displacement of 0.38mm. The corbel failed because of shear failure. After strengthening, the load capacity increases to 256 kN with corresponding displacement of 1.11mm. The load remains constant for a while and drops with a smaller slope until failure that leads to ductile behavior after repairing and strengthening.



**Figure 4.28** Load-displacement curve of specimen (C10-0.0-250)



**Figure 4.29** Specimen (C10-0.0-250) failure before strengthening



**Figure 4.30** Specimen (C10-0.0-250 ) de-bonding failure after strengthening

**C11-0.0-500:**

This specimen was exposed to an elevated temperature of 500°C and the corbel has same reinforcement details with C10-0.0-250 corbel with shear span of 90mm. The ultimate load capacity before rehabilitation was 175 kN with shear failure on the left side (see Fig.4.32). After failure, the specimen was repaired by epoxy injection and was strengthened with basalt fiber fabric (BFF) in order to investigate the possibility of restore and improvement of capacity. The result shows a significant increase in the capacity of corbel after strengthening and the amount of increase is 30% of the original capacity. The strengthening increased the load capacity to 227 kN. De-bonding of the fabric from corbel's surface appeared after the load decreased to 178 kN.

As it is shown from load-deflection curve (Fig. 4.31) that the maximum deflection of the corbel before repairing is equal to 1.11mm, while it increases to 3.12mm after rehabilitation. It means that ductile behavior is achieved in addition to increase in load capacity after rehabilitation.

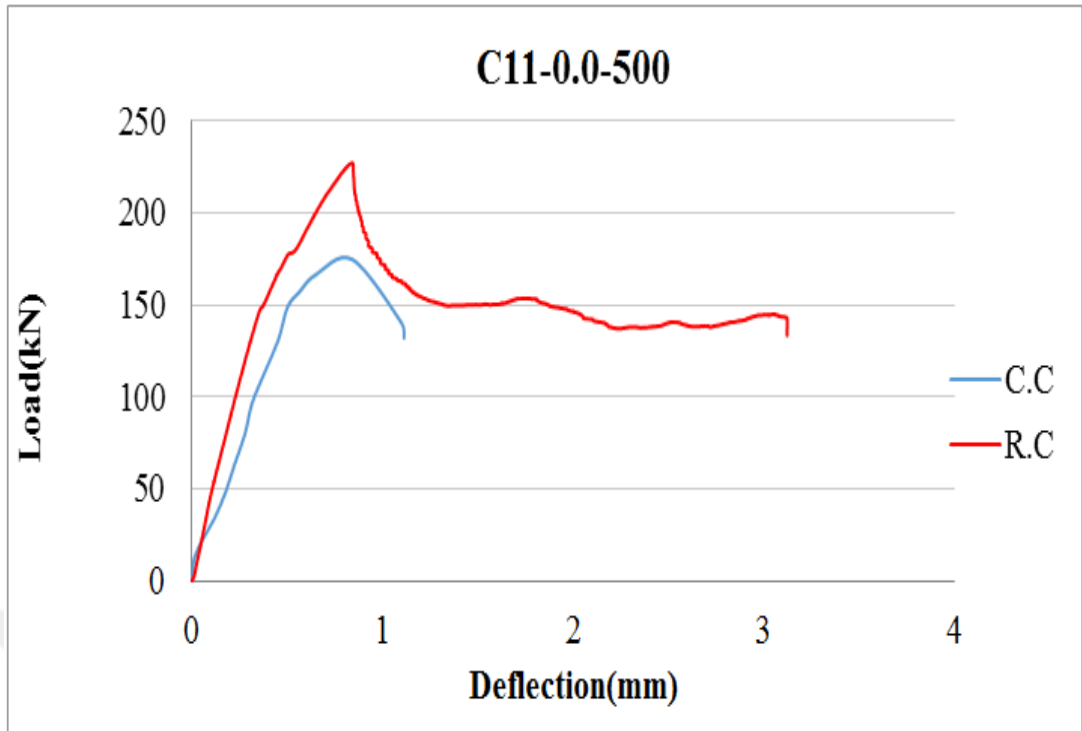


Figure 4.31 Load-displacement curve of specimen (C11-0.0-500)

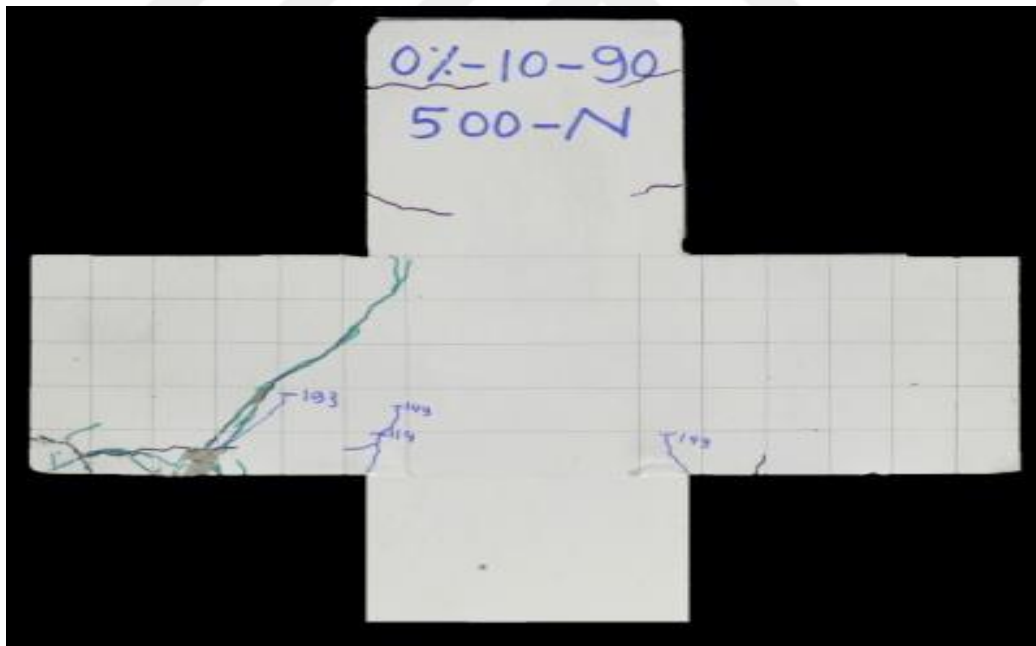
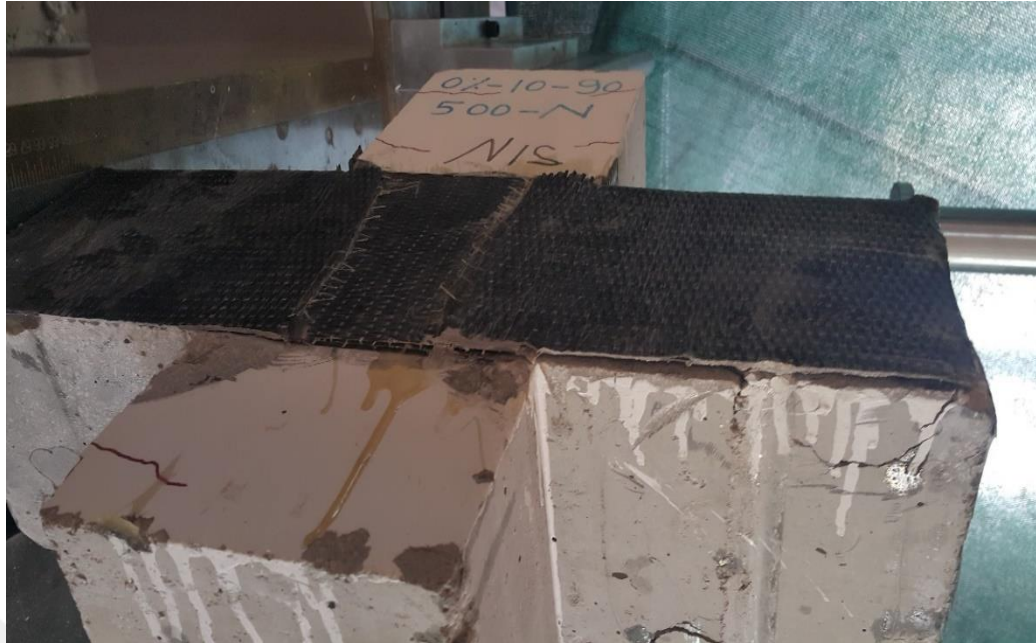


Figure 4.32 Specimen (C11-0.0-500) failure before strengthening



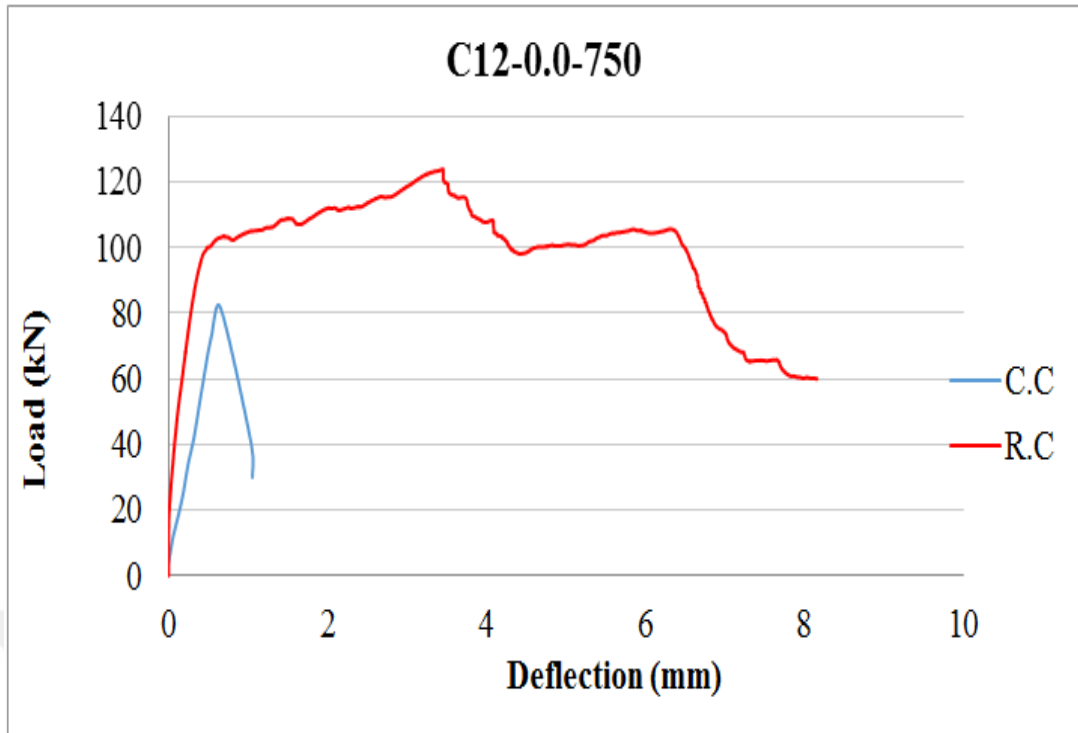
**Figure 4.33** Specimen (C11-0.0-500 ) de-bonding failure after strengthening

**C12-0.0-750:**

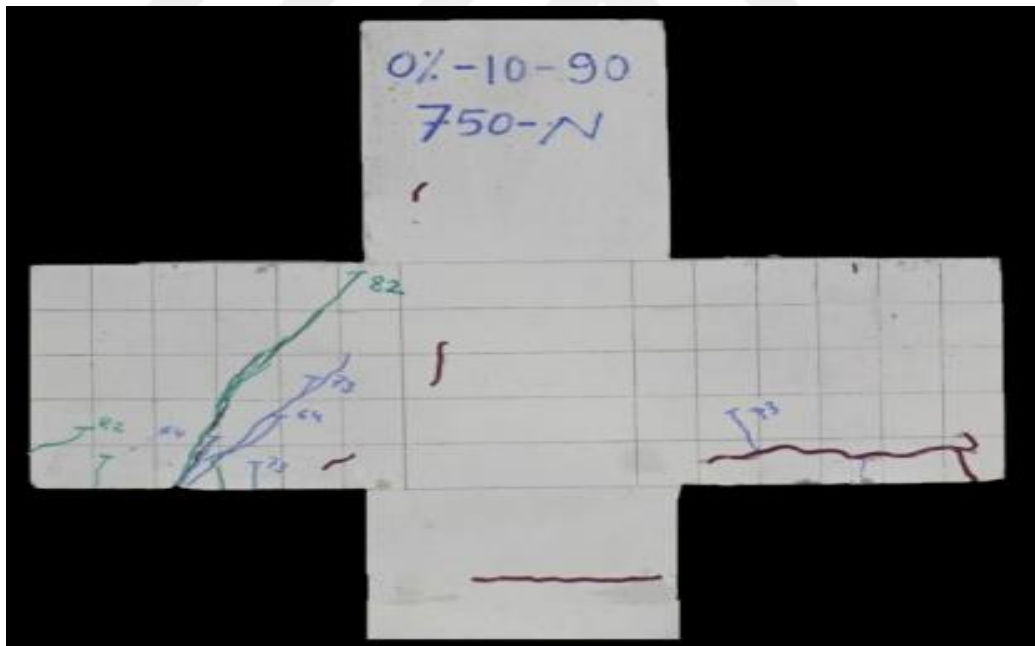
Specimen of C12-0.0-750 was maintained in an electrical furnace until desired temperature of 750°C was obtained. After cooling, the specimen had been loaded vertically with shear span of 90 mm. When the load reached to 64 kN, signs of failure appeared and the shear failure became evident on the left side of the specimen at load of 82 kN (see Fig. 4.35). The specimen was repaired by epoxy injection and was covered bi-directionally with BFF. The result shows high improvement in the capacity of corbel after strengthening, where the amount of increase is 51% of the original capacity.

After rehabilitation the peak load capacity increased to 124 kN with the same failure pattern as previous corbel (see Fig.4.36). De-bonding failure because of difference in the strength between basalt fiber which was placed as two layers in two directions and the adhesive resin.

It is shown in the Figure 4.34 that the displacement is equal to 0.65mm at maximum load before rehabilitation and after strengthening it increased to 3.45mm. It can be noted that the load does not drop directly and the corbel becomes more ductile due to basalt fiber fabric, and the maximum deflection increased to 8 mm from 1.05mm.



**Figure 4.34** Load-displacement curve of specimen (C12-0.0-750)



**Figure 4.35** Specimen (C12-0.0-750) failure before strengthening



**Figure 4.36** Specimen (C12-0.0-750 ) de-bonding failure after strengthening  
**C13-0.5-250:**

The shear span that was used in the loading test was 90mm for this specimen, and value of the shear span-to-depth ratio ( $a/h$ ) was 0.6. A volumetric ratio of 0.5% steel fiber was used in the concrete mix of this corbel. The corbel heated until the temperature of 250°C was obtained. After cooling, the corbel was loaded vertically and the ultimate load capacity was measured as 243 kN at displacement of 0.56mm. In Fig. 4.3.11 it can be seen that the shear failure existed on the right side and also hairline cracks formed on the left side of the corbel.

After the corbel had been repaired with epoxy injection and it had been strengthened with basalt fiber fabric, load capacity increased as the amount of 14% of its original value. After strengthening, the ultimate load capacity increased to 247 kN. Separation of basalt, de-bonding failure, was occurred as shown in Fig. 4.39.

The load–displacement response of the specimen is shown in Fig. 4.37. Maximum displacement rises from 1.9 mm to 5.5mm. It is obvious from the trend of the curve that ductility increases after strengthening. Furthermore, deflection at maximum load is increased from 0.56 mm to 1.13 mm after strengthening. The post-peak (descending) part of the load-deflection curve indicates that load decreases gradually depending on the presence of steel fiber (SF) and basalt fiber fabric.

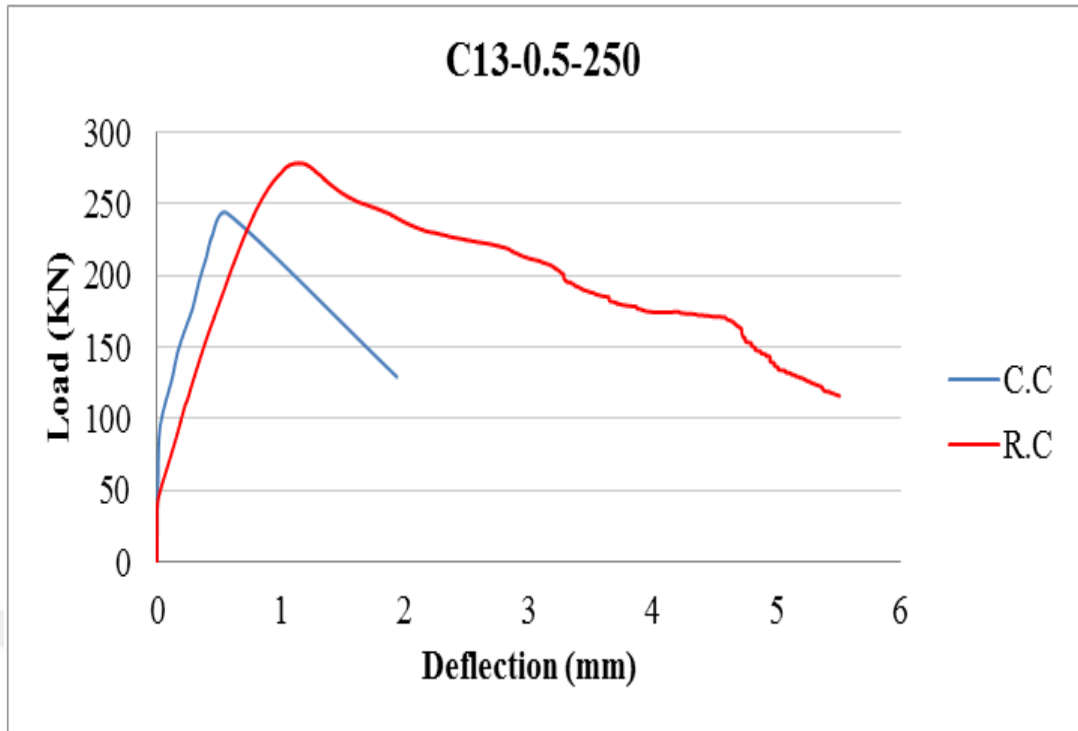


Figure 4.37 Load-displacement curve of specimen (C13-0.5-250)

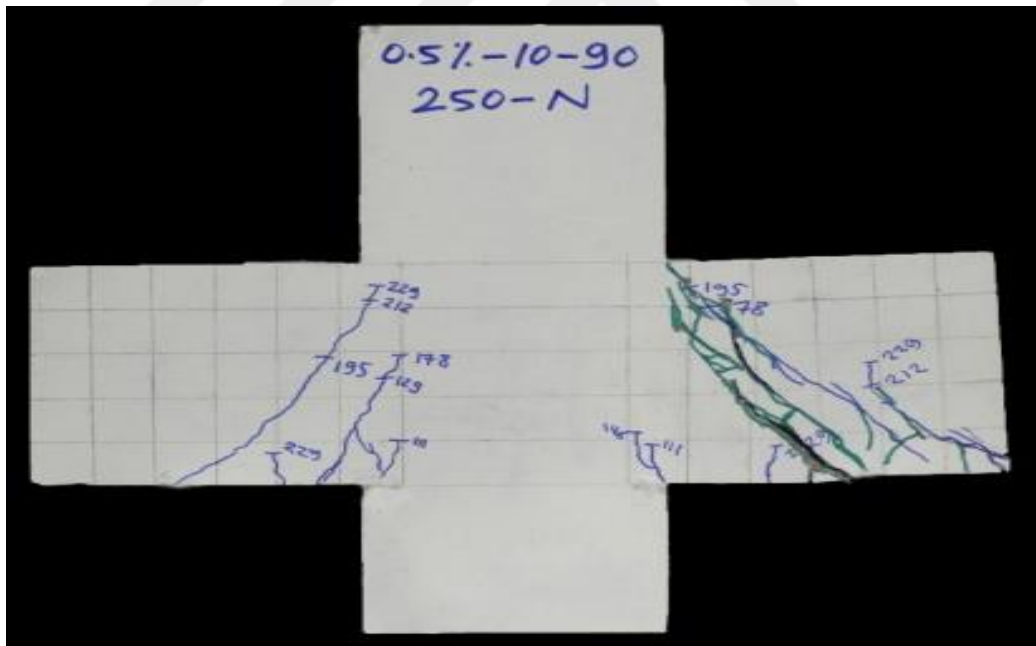


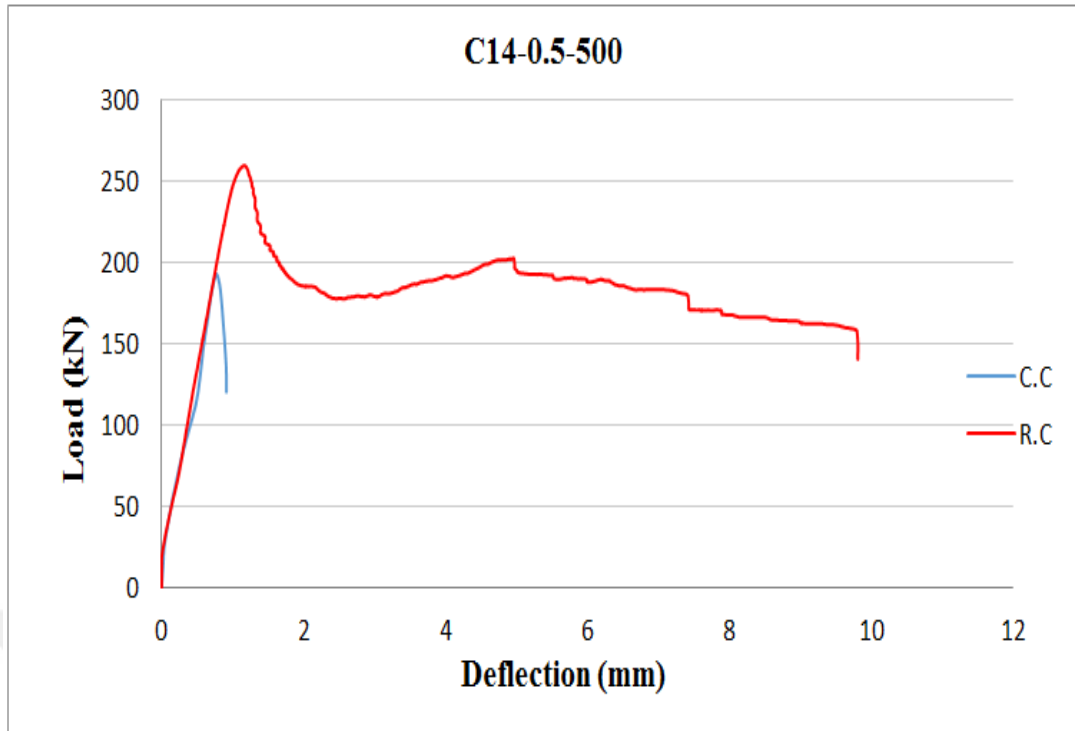
Figure 4.38 Specimen (C13-0.5-250) failure before strengthening



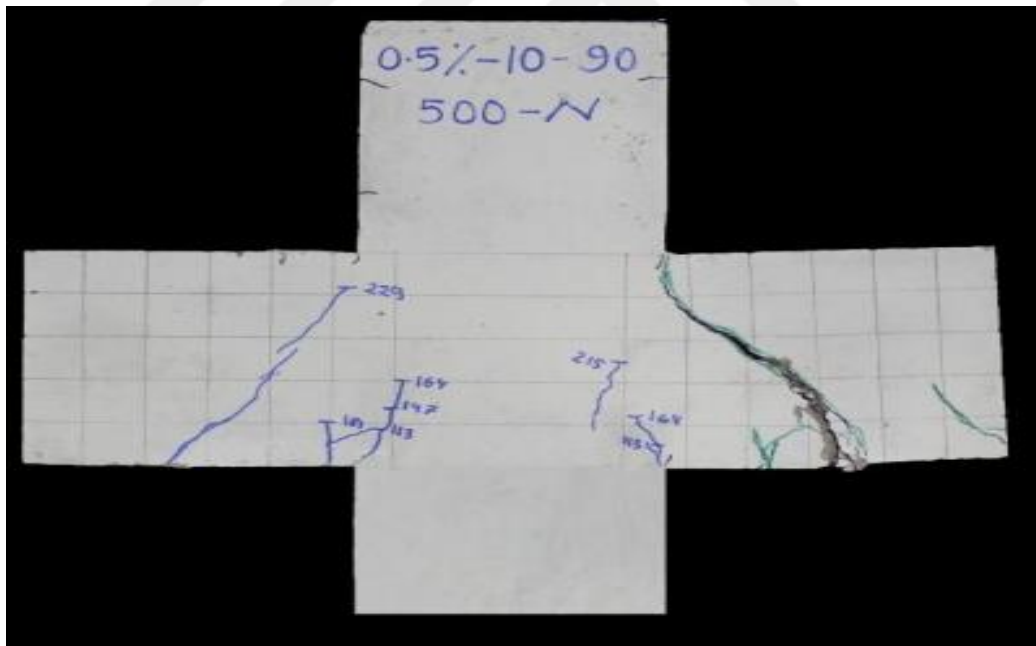
**Figure 4.39** Specimen (C13-0.5-250) de-bonding failure after strengthening  
**C14-0.5-500:**

Specimen C14-0.5-500 contained 0.5% of steel fiber as volume. The corbel was exposed to elevated temperature of 500°C. After cooling, the corbel was tested by vertical loading with shear span of 90 mm (the shear span to the depth ratio ( $a/h$ ) was 0.6). After formation of some hairline cracks on both sides of the corbel, shears cracks appeared on the right corbel close to the support, as shown in Fig. 4.41. The ultimate load capacity of the corbel was 193 kN with corresponding displacement of 0.77 mm.

The damaged corbel was repaired with epoxy injection and was strengthened by externally wrapped basalt fiber fabric. After strengthening, the corbel was tested with the same loading condition and shear span with previous control corbel. The ultimate capacity of the specimen increased to 260 kN with corresponding displacement of 1.15mm and the same failure (de-bonding) occurred (see Fig.4.42). The maximum displacements of the specimen before and after strengthening are equal to 0.91mm and 9.81mm, respectively (see Fig. 4.40). The increase of the maximum displacement as shown in the curve indicates the remarkable improvement in the ductility after strengthening.



**Figure 4.40** Load-displacement curve of specimen (C14-0.5-500)



**Figure 4.41** Specimen (C14-0.5-500) failure before strengthening



**Figure 4.42** Specimen (C14-0.5-500 ) de-bonding failure after strengthening  
**C15-0.5-750:**

This corbel was exposed to very high temperature of  $750^{\circ}\text{C}$ . In addition to main reinforcement the concrete was reinforced with 0.5% steel fiber. The corbel was loaded vertically with shear span of 90 mm. The first hairline crack appeared at load of 80 kN on the left side of the specimen and other cracks formed at load of 105 kN on the other side of the specimen (see Figure4.44). When the load reached to 119 kN, shear failure occurred on the left side of the specimen with corresponding displacement of 0.93 mm (see Figure4.43). The maximum displacement of the sample was 1.59 mm.

After crack repair material had been injected into the corbel and the corbel had been strengthened with basalt fiber fabric, the specimen was loaded vertically. The ultimate capacity increased in amount of 19% of the original value. The failure mode of the specimen, after strengthening, was de-bonding failure and the ultimate load capacity increased to 142 kN. The maximum displacement increases to 6.15 mm and thus the specimen's behavior becomes more ductile as shown from Fig. 4.43.

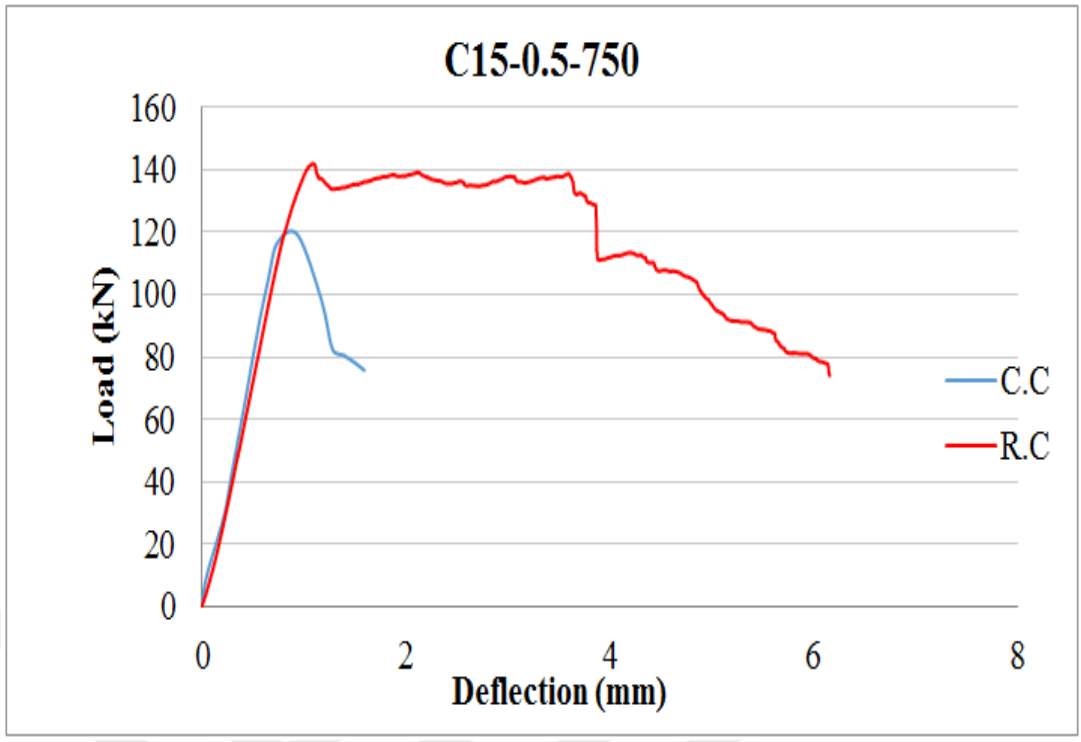


Figure 4.43 Load-displacement curve of specimen (C15-0.5-750)

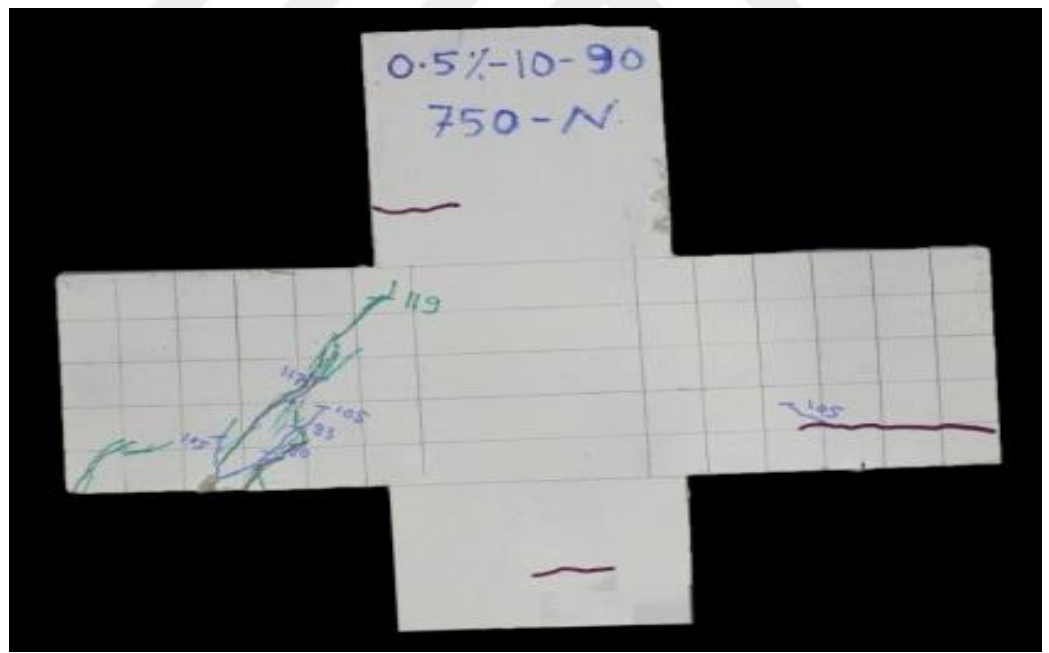


Figure 4.44 Specimen (C15-0.5-750) failure before strengthening



**Figure 4.45** Specimen (C15-0.5-750 ) de-bonding failure after strengthening

**C16-1.0-250:**

This specimen had been maintained in an electrical furnace with temperature degree of 250°C. The corbels' concrete mix contained 1.0% of steel fiber as volume, the shear span to depth ratio ( $a/h$ ) was 0.6 (the shear span was 90mm). The sample had been damaged by vertical loading. The first crack was observed as flexural crack at load of 106 kN on the left side. When the load reached to 141 kN the cracks were appeared on both sides of the corbel, (see Fig. 4.47). The cracks were followed by a shear crack at the load of 221 kN on the left side of corbel. The corbel reached to its ultimate capacity of 247 kN at displacement of 0.66 mm, and also the total displacement of the corbel was 1.71mm.

After failure of the corbel, it was repaired with epoxy injection and was externally strengthened with basalt fiber. After strengthening, the ultimate capacity of the corbel was 268 kN, which means the load increased in amount of 0.09% of its initial value. The existence of high number of micro cracks had negative effect on increasing the load capacity after strengthening. However, the corbel was not exposed to very high temperature as some of other corbels. Like previous rehabilitated and strengthened corbels, the specimen's failure mode was de-bonding, as shown from Fig. 4.48. Even though the corbel's displacement at maximum load decreased, it can be noted from

Fig. 4.48 that the basalt fabric makes the corbel more ductile by increasing the total displacement from 1.72mm to 2.44mm.

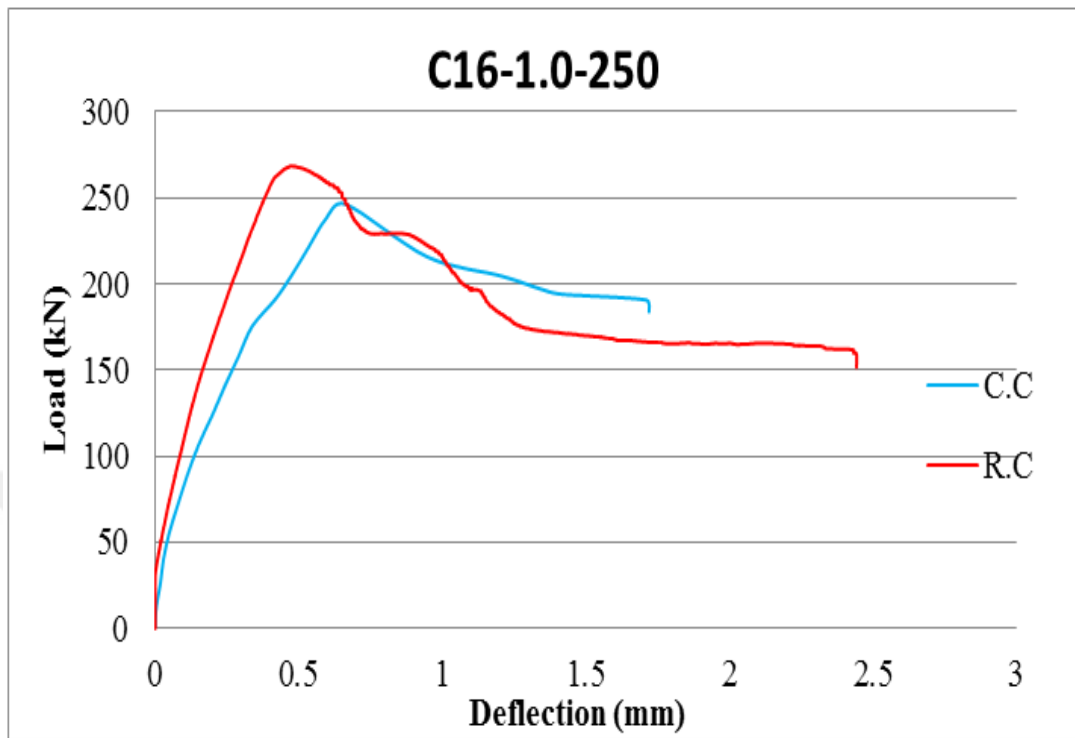


Figure 4.46 Load-displacement curve of specimen (C16-1.0-250)

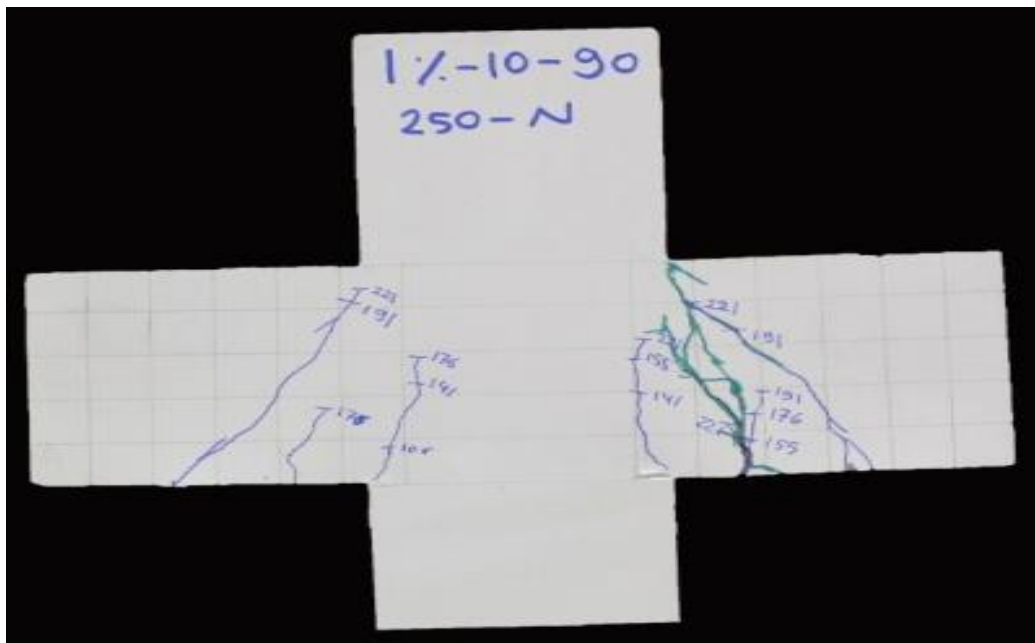


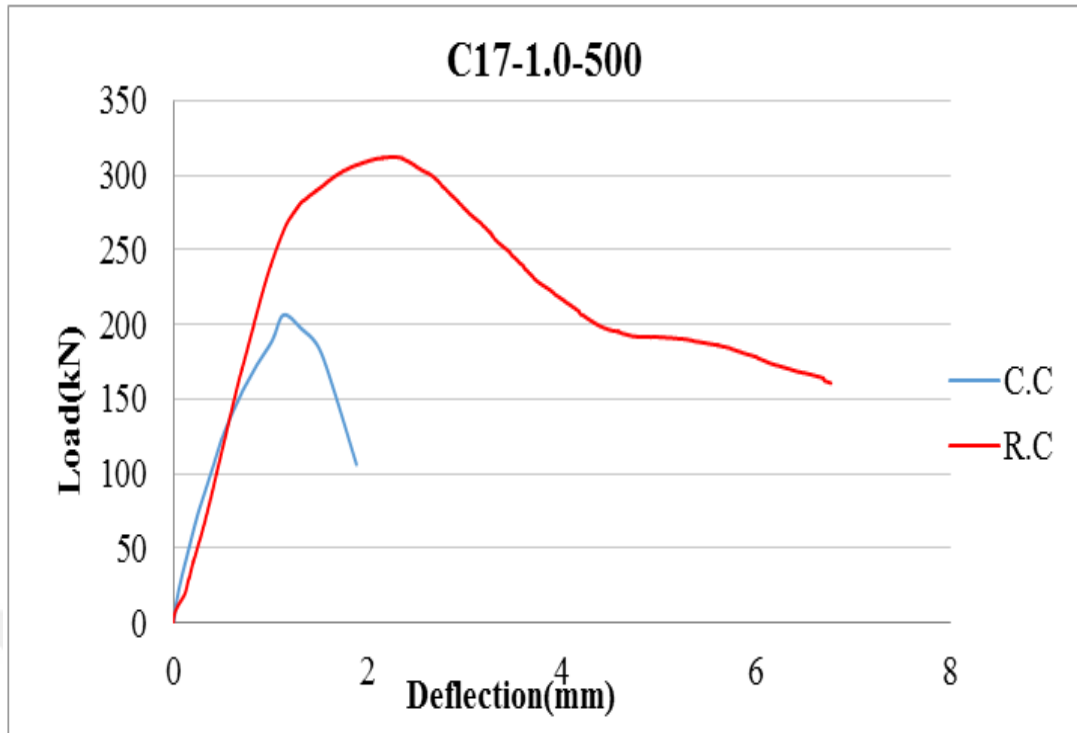
Figure 4.47 Specimen (C16-1.0-250) failure before strengthening



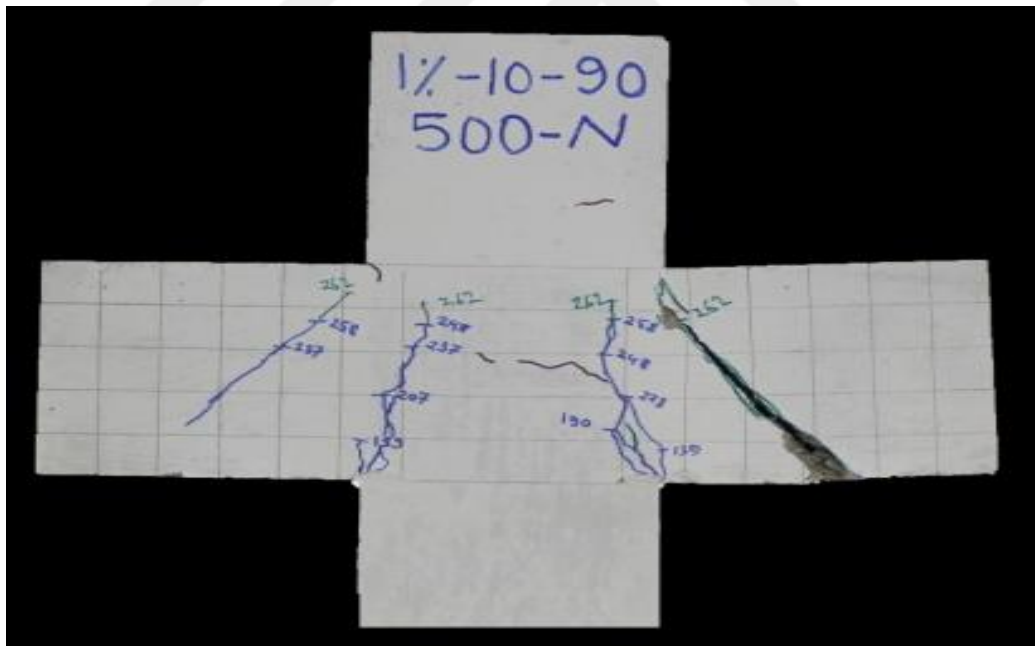
**Figure 4.48** Specimen (C16-1.0-250 ) de-bonding failure after strengthening  
**C17-1.0-500:**

This corbel has same reinforcement details with C16-1.0-250 whose shear span is 90mm, and the specimen was exposed to elevated temperature of 500°C. The ultimate load capacity before rehabilitation was 207 kN with shear failure on the right side (see Fig. 4.50). After failure, the specimen was rehabilitated with crack repair material and was externally strengthened with basalt fiber. The result showed a great improvement in the capacity of corbel after strengthening that the capacity increased to 1.51 times of the original value. The strengthening increased the peak load capacity to 313 kN. After the load arrived to 281 kN, separation between the fiber and corbel's surface occurred (see Fig. 4.51), which indicates that the failure existed due to de-bonding.

It can be concluded from the load-deflection response of the specimen (see Fig. 4.49) that the maximum deflection of the corbel before repairing is equal to 1.88 mm and increased to 6.70 mm after strengthened with basalt fiber. In that way, ductility increase in the corbel is illustrated by the rise in the maximum displacement.



**Figure 4.49** Load-displacement curve of specimen (C17-1.0-500)



**Figure 4.50** Specimen (C17-1.0-500) failure before strengthening



**Figure 4.51** Specimen (C17-1.0-500 ) de-bonding failure after strengthening

**C18-1.0-750:**

This specimen was reinforced with the same amount of steel fiber as the previous specimen which is 1.0% as volume. This specimen was exposed to high temperature of 750°C. The corbel was loaded vertically with shear span of 90mm. The first hairline crack appeared at load of 71 kN on the left side of the specimen, it was followed by another crack at load of 113 kN on the other side of the specimen (see Fig. 4.53). The corbel's maximum load was 132kN with displacement of 0.94mm.

After rehabilitation and strengthening process, the specimen was loaded vertically with same shear span value. The ultimate load capacity, after strengthening, reached to 185 kN with displacement of 2.29mm. Moreover, the load increased in amount of 40% of its original value. The mode of failure was De-bonding, which was occurred due to separation between the basalt fiber and concrete surface (see Fig. 4.54). The sample becomes more ductile since the maximum displacement increases to 7mm, as shown from Figure4.52.

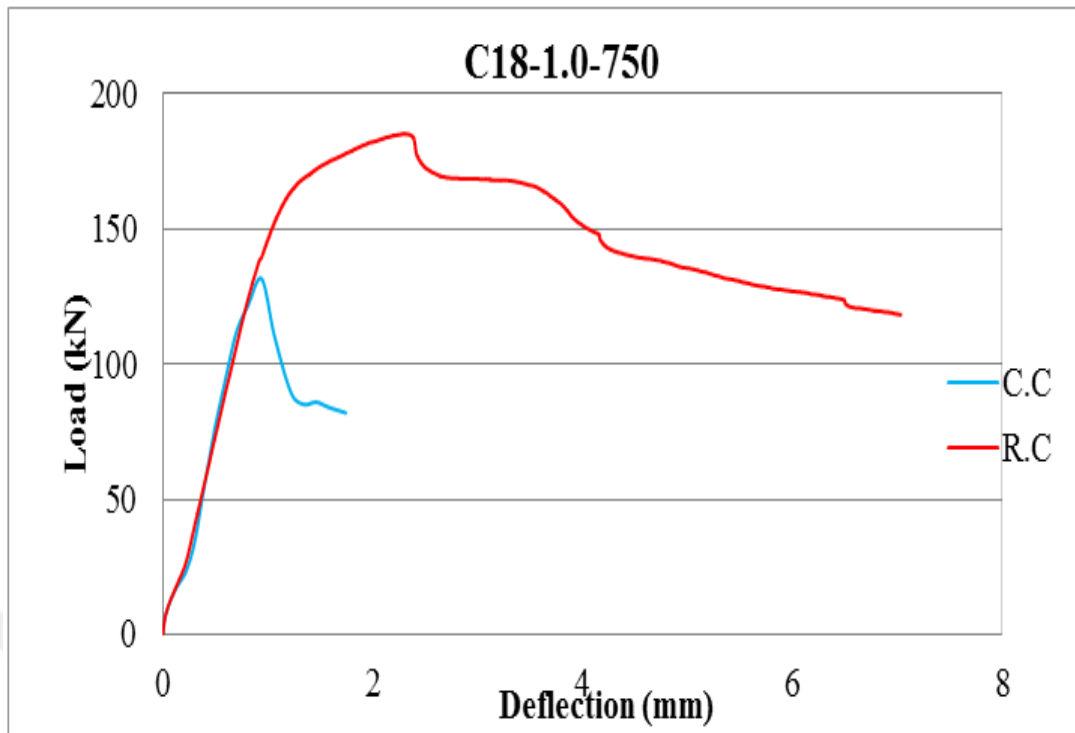


Figure 4.52 Load-displacement curve of specimen (C18-1.0-750)

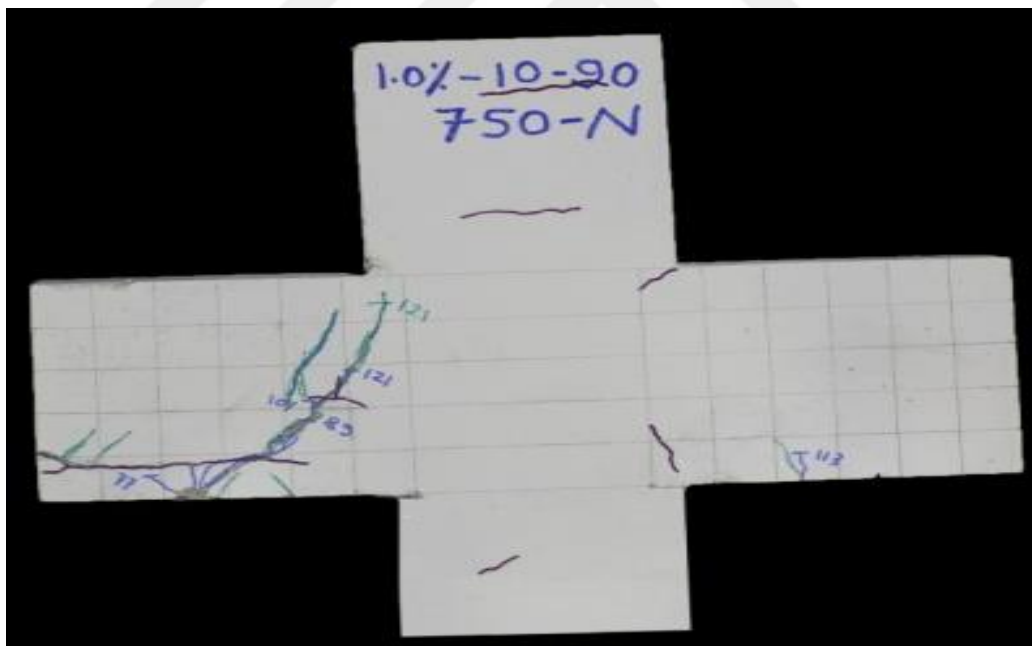


Figure 4.53 Specimen (C18-1.0-750) failure before strengthening



**Figure 4.54** Specimen (C18-1.0-750 ) de-bonding failure after strengthening

## CHAPTER 5

### CONCLUSION

#### 5.1 Conclusion

Corbels play an important role in precast constructions, particularly industrial buildings. While the structures can be damaged because of some reasons, the corbels are generally more prone to damages. Several researchers studied repairing or strengthening of damaged corbels. However, a new technique is investigated for the rehabilitation of damaged corbels in this thesis. Damaged corbels were repaired by crack repair epoxy and strengthened by basalt fiber fabric. The effectiveness of the method was researched for the first time in literature. This is the first experimental investigation that presents and evaluates the response of rehabilitated corbels which were exposed to elevated temperatures and damaged by vertical load. The following subjects are presented in this thesis;

- A detailed literature review on rehabilitation and strengthening methods for concrete structures especially for reinforced concrete corbels.
- An experimental investigation of repairing with epoxy injection for normal strength concrete corbels with shear span of 120mm.
- An experimental investigation of strengthening by epoxy injection and wrapped with basalt fiber fabric for normal strength concrete corbels with shear span of 90mm.
- An analysis of results and discussion of specimens' responses.

Depends on the results of this experimental investigation following conclusions can be drawn.

- According to the results of some of the specimens [(C1-0.0-250), (C2-0.0-500), (C5-0.5-500), and (C8-1.0-500)], it can be said that rehabilitation with epoxy injection only can be successful for the corbels which are exposed to elevated temperatures up to 750°C and damaged as a result of over loading.

- The success of rehabilitation with only injection depends on a proper repairing of both of the legs. For the corbels that have more hairline cracks, the epoxy injection only cannot restore load capacity sufficiently. For instance, rehabilitation result was more successful for (C1-0.0-250), even though it has same degree of heating with (C4-0.5-250) and (C7-1.0-250).
- For the corbels that exposed to 750°C before failure due to vertical load, rehabilitation with injection only is not sufficient. Therefore, extra measures need to be considered.
- Existing of steel fiber play an important role in both of the rehabilitation techniques. For instance, with only injected corbels which had steel fiber in their concrete mix, before and after rehabilitation, the failures were not occurred on the same place.
- Use of basalt fiber reinforced polymer (BFRP) fabric is an effective technique for strengthening of damaged reinforced concrete corbels.
- Existing high number of micro cracks have negative effect on restoring and increasing the load capacity with both of the rehabilitation techniques.
- The de-bonding in the BFRP laminates (which is the main mode of failure) was sudden.
- The corbels strengthened with epoxy injection and basalt fiber fabric, regained up to 1.51 of the control corbel's ultimate load capacity with a significant increase in ductility, and a corresponding increase in ultimate load deflections.
- The basalt much over strengthened as compare to the adhesive, because the corbels were covered bi-directionally.
- These rehabilitation techniques also can be used for one leg corbels.
- Deflection capacity (energy absorption) of all of the BFF-strengthened corbels increased.
- Elevated temperatures do not reduce the effectiveness of rehabilitation on restoring capacity in BFF-strengthened samples as in the case of rehabilitation with epoxy injection only.

## **5.2 Recommendations for Future Research**

Although the results of this experimental research have provided valuable information regarding the use of epoxy injection and basalt fibers, as a composite material, for repairing and strengthening of heated and damaged concrete corbels, there are several related aspects that need further investigation.

Theoretical studies are necessary for understanding the structural behavior of repaired or strengthened heated and damaged concrete corbels. The experimental and theoretical studies need to be performed on similar specimens with different parameters other than reported here. In this thesis, the effect of some variables such as elevated temperature and existence of steel fiber were studied under a vertical load on two different rehabilitation techniques. The study can be extended by the consideration of parameters other than temperature and steel fiber ratio, that affect the mechanical behavior of reinforced concrete corbels.

A combination of vertical and horizontal loading should be used to investigate the variations of shear span and other variables such as steel fiber ratios and different degree of temperature. Furthermore, since only a limited test specimen was carried out with normal compressive strength of self-compacted concrete in this study, the effect of concrete strength on restoring capacity for different strengthening methods is left to other researchers to investigate.

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