إقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Strengthening and Repair of RC Beams with Cementitious Repair Materials

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وإن هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل درجة أو لقب علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

DECLARATION

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification

Student's name: **Yasser M. Owayda**	اسم الطالب: ياسر محروس عويضة
Signature:	التوقيع:
Date:	التاريخ: 15/06/2013

The Islamic University of Gaza
Deanship of Higher Studies
Faculty of Engineering
Civil Engineering Department
Design and Rehabilitation of Structures.

الجامعة اللإسلامية – غزة
عمادة الدراسات العليا
كلية الهندسة
قسم الهندسة المدنية
تصميم وتأهيل المنشئات

Strengthening and Repair of RC Beams with Cementitious Repair Materials

تقوية وإصلاح الكمرات الخرسانية بإستخدام مواد الإصلاح الإسمنتية

Submitted By:
Yasser Mahrosse Owayda

Supervisor:
Prof. Samir Shihada

A Thesis Submitted in Partial Fulfillment of the Requirements for Degree of Master of Science in Civil Engineering -Rehabilitation and Design of Structures

April - 2013

بسم الله الرحمن الرحيم

الجامعة الإسلامية – غزة
The Islamic University - Gaza

عمادة الدراسات العليا

هاتف داخلي: 1150

الرقم ج س غ/35/ Ref
التاريخ 2013/05/29 Date

نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة عمادة الدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **ياسر محروس هاشم عويضة** لنيل درجة الماجستير في **كلية *الهندسة* قسم الهندسة المدنية- تصميم وتأهيل منشآت** وموضوعها:

Strengthening and Repair of RC Beams with Cementitious Repair Materials

وبعد المناقشة التي تمت اليوم الأربعاء 19 رجب 1434هـ، الموافق 2013/05/29م، الساعة العاشرة صباحاً ، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

أ.د. سمير محمد شحادة	مشرفاً ورئيساً	
د. محمد حسني عرفة	مناقشاً داخلياً	
د. مازن طه أبو الطيف	مناقشاً خارجيًا	

وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في **كلية *الهندسة*/ قسم الهندسة المدنية- تصميم وتأهيل منشآت.**

واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

عميد الدراسات العليا

أ.د. فؤاد علي العاجز

ص.ب 108 الرمال، غزة، فلسطين هاتف Tel: +970 (8) 286 0700 فاكس fax: +970 (8) 286 0800 P.O. Box 108, Rimal, Gaza, Palestine
public@iugaza.edu.ps www.iugaza.edu.ps

ABSTRACT

This study investigates the flexural capacity, deflection and crack patterns of reinforced concrete beams repaired by application of four repair materials, Ultra High Performance Concrete, Ultra High Performance Fiber Reinforced Concrete, Ordinary Portland Concrete, and special repair materials for repair of three types of damages that can occur in construction. These include over loading cracks, honeycombing, and spalling of concrete cover due to elevated temperature. It is also intended to assess the feasibility of using these repair materials in repair and strengthening of damaged reinforced concrete beams. A series of four point flexural tests was conducted on both damaged and undamaged reinforced concrete beams to evaluate the performance of the damaged reinforced concrete beams after application of the repair materials. The conducted tests yielded complete load–deflection curves from which the increase in flexural capacity was evaluated. The results show that the repair materials are capable increasing the flexural capacity, deflection and improving crack pattern, and are effective in strengthening and repair of damaged RC beams. The results of the investigation will be used to develop design guidelines governing the use of these repair materials in the field of repair and strengthening of damaged reinforced concrete beams. The cracked beams which were repaired using UHPC, UHPFRC, OPC and SRM developed flexural strengths 8, 19, 3.17, 11% respectively, higher than the undamaged beams. The honeycombed beams which were repaired using UHPC, UHPFRC, OPC and SRM developed flexural strengths 19, 30, 1.50, 27% respectively, higher than the undamaged beams. And the heated beams which were repaired using UHPC, UHPFRC, OPC and SRM developed flexural strengths 1.50, 6.60, 0.00, 3.70% respectively, higher than the undamaged beams.

ملخص البحث

تتناول هذه الدراسة معالجة وتقوية الاحزمة الخرسانية المسلحة باستخدام اربعة مواد معالجة وهي خرسانة عالية الاداء،خرسانة عالية الاداء مضاف لها الياف معدنية،خرسانة عادية ، و مادة معالجة كيميائية جاهزة مصنعة من احد شركات المختصة في مواد المعالجة , لعلاج ثلاث مشاكل في الاحزمة الخرسانية قد تنشأ اثناء التنفيذ وهي ظهور تشققات في الاحزمة, وجود تعشيش في الاحزمة بعد عملية الصب, وتعرض الاحزمة لدرجة حرارة عالية تفقدها الغطاء الخرساني , وذلك للتحقق من مدى تأثير تلك المواد على الاحزمة الخرسانية المتضررة من حيث قوة التحمل في الانحناء ، قيمة الترخيم والهبوط, وتشكل التشققات على الاحزمة الخرسانية المعالجة. تم عمل فحص التحميل ذو الاربع نقاط على الاحزمة المعالجة والاحزمة المرجعية لتقييم تأثير تلك المواد على الاحزمة الخرسانية المسلحة بعد تطبيقها. أظهرت النتائج ان المواد المستخدمة في البحث لها القدرة على تحسين وزيادة قوة تحمل الانحناء وقيم الترخيم والهبوط كما وحسنت شكل التشققات للاحزمة الخرسانية المعالجة. وسيتم استخدام نتائج الدراسة في وضع مبادي يستند اليها في التصميم التي تحكم استخدام تلك المواد في معالجة وتقوية الاحزمة الخرسانية المسلحة. حيث ان الاحزمة الخرسانية التي بها تشققات المعالجة بتلك المواد حسنت قوة التحمل المقطع في الانحناء 8,19,3.17,11%بالترتيب،مقارنةبالكمراتالغيرمتضررة ، بينما ان الاحزمة الخرسانية التي بها تعشيش والمعالجة بنفس المواد حسنت قوة التحمل المقطع في الانحناء 27،30,1.50،19%بالترتيب،مقارنةبالكمراتالغيرمتضررة ، اما الاحزمة الخرسانية التي تعرضت لدرجة حرارة عالية والمعالجة بنفس المواد حسنت قوة التحمل المقطع في الانحناء 1.50، 6.6، 0.00 ، 3.7 % بالترتيب ،مقارنةبالكمراتالغيرمتضررة . .

DEDICATION

This thesis is dedicated to my parents who have supported me all the way since the beginning of my studies.

In addition, this thesis is dedicated to my wife who has been a great source of motivation and inspiration.

Finally, this thesis is dedicated to all those who believe in the richness of learning.

ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my advisor Prof. Samir Shihada for the continuous support during my study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my study.

I am extremely grateful to the staff of the Laboratory of the Engineers Association and the Islamic University Material and Soil Laboratory.

The informal support and encouragement of many friends has been indispensable.

My parents have been a constant source of support – emotional, moral and of course financial – during my postgraduate years, and this thesis would certainly not have existed without them.

My wife Rasha has been, always, my pillar, my joy and my guiding light, and I thank her.

Finally thank my sons, Mahrosse, Mohammed, and Musab who Supported me in my profession and my ambition altitude in this life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ACI	American Concrete Institute.
IUG	Islamic University of Gaza.
UHPC	Ultra High Performance Concrete.
UHPFRC	Ultra High Performance Fiber Reinforced Concrete.
OPC	Ordinary Portland Concrete.
HPFRCC	High Performance Fiber-Reinforced Cementitious Composite.
SRM	Special Repair Materials.
C.B	Control Beam.
FRP	Fiber Reinforced Polymer.
RC	Reinforced Concrete.

CHAPTER 1 INTRODUCTION

1.1. Introduction:

Reinforced concrete is the most frequently applied structural material in the practice of civil engineering. By virtue of its good characteristics such as durability, compressive strength, hardness, fire resistance and workability, it is used in a wide variety of buildings and construction projects. As durable and strong as it is, the commonly held view that concrete is a maintenance-free construction material has been challenged in recent years.

Many reinforced concrete structures may be damaged. Most of them are suffering from various deteriorations, which may be attributed to cracks, spalling, large deflection, etc. Many factors are at the origin of these deteriorations, such as aging, corrosion of steel, earthquake, environmental effects and accidental impacts on the structure. Nowadays, it is necessary to find repair techniques suitable in terms of economy and speed of execution.

In this study, the focus was on three problems that occur frequently in reinforced concrete beams and their repair techniques. The first problem involves excessive cracking due to overloading, which allows aggressive environmental factors to affect concrete. This in turn causes more deterioration such as corrosion of steel and spalling of concrete. The second problem involves honeycombing. The third problem is caused by spalling of concrete cover during exposure to elevated temperatures.

The repair techniques which are to be used for repair of mentined deteriorations include: using Ultra High Performance Concrete (UHPC), Ultra High Performance Fiber Reinforced Concrete (UHPFRC), Ordinary Portland Concrete (OPC), and Special Repair Materials from a certified manufacturer (SRM).

1.2. Problem Statement:

The Rehabilitation and reconstruction of concrete building structures is becoming a major problem worldwide. New materials and improved cost-effective techniques of rehabilitating and strengthening in an innovative manner are urgently sought.

The function of concrete in reinforced concrete beams is to bear the loads in the compression zones and to make a good encasement for steel rebar under normal conditions. On the other hand, the previously stated problem (excessive cracks, honeycombing, and separation of concrete cover) allows for aggressive environmental factors to ingress in concrete to reach steel rebar. This speeds up the process of rusting, which in turn causes separation and loss of adhesion of concrete with steel rebar. This reduces the bearing capacity of RC elements, which may causes in failure and losses in life and property.

Add to this, the abnormal conditions in the Gaza Strip caused by shelling and bombing caused by the Israeli enemy, causes additional damages to structures. This requires suitable repair and strengthening techniques to treat these problems using available and suitable repair materials at the local markets.

1.3. Research Objectives:

The main objectives of the study include the following:

(1) Applying the four-repair technique.

(2) Deciding on the best repair technique in terms of cost and efficiency.

1.4. Methodology:

To achieve the objectives of this research, the following tasks were executed:

1. Conducting literature review related to the subject.
2. Casting a large number of reinforced concrete beam samples, some of the samples are to be cracked through overloading, leaving missing part of the beam (honeycombing), and heating to 250 C^o for 4 hours duration.
3. Applying each of repair techniques on every repair problem, and evaluating the strength of the beams after repair.
4. Conducting a comparison between the results of the control beams and the repaired ones.
5. Deciding on the best repair technique for each of the repair problems.

1.5. Thesis structure:

This thesis consists of seven chapters arranged carefully in the order to make it clear and understandable. This section presents a brief description of these chapters.

Chapter (1): In this chapter statement of problem, objectives of the research, and the methodology adopted in the research are included.

Chapter (2): Provides a general review of relevant previous studies and the main constituent materials.

Chapter (3): Discuses the experimental details, experimental program, dimension of samples that used, materials properties (quantity, quality) that used .

Chapter (4): Discussion and analysis of test results for repair cracked, overview about types of cracks and how to prevent or minimize it.

Chapter (5): Discussion and analysis of test results for repair honeycombing beam, overview about types of honeycombing and how to prevent or minimize it.

Chapter (6): Discussion and analysis of test results for repair heated beam.

Chapter (7): Conclusions and Recomendation.

Chapter (8): Refrences.

CHAPTER 2 LITERATURE REVIEW

2.1. Introduction:

This chapter provides an overview of previous studies related to the subject of this research work. It introduces the framework for the case study that comprises the focus of the research described in this thesis.

It is important to set the context of the literature review work by providing:

- An explanation of its specific purpose for this particular case study.
- Comments on the previous treatment of the broad topic of knowledge sharing.
- An indication of scope of the work presented in this chapter.

The main purpose of the literature review work is to survey previous studies on knowledge sharing. This is done in order to scope out the key data collection requirements for the primary research to be conducted, and it formed part of the emergent research design process.

The approach adopted is in line with current practice in grounded research work. It is now regarded as acceptable for researchers to familiarize themselves with existing research prior to collecting their own data.

2.2. Previous studies related to using UHPFRC as a repair material:

Shamimet et al. [1], studied damaged specimens, which were repaired with fiber-reinforced polymer sheets and wraps, and tested to failure. Companion control specimens were also tested to failure without rehabilitation to provide a basis for comparison and evaluate the effectiveness of the repair techniques. Test results showed that fiber-reinforced polymers (FRPs) were effective in strengthening for flexure as well as for shear. Over-reinforcing in flexure resulted in shifting the failure to shear mode, which in some cases may be undesirable. Strengthening of a member in shear, on the other hand, resulted in increasing the ultimate displacement by more than tenfold and toughness by a factor of more than 26.

Lee and Hausmann [2] investigated the load capacity, ductility and energy absorption aspects of reinforced concrete (RC) beams retrofitted with sprayed fiber-reinforced polymer composites (SFRP). A series of three-point bending tests were conducted on both damaged (precracked) and undamaged RC beams to evaluate the performance of deteriorated RC beams after application of SFRP and to examine the influence of SFRP parameters on the performance of RC beams. The parameters in the experimental program were coating thickness, fiber length, fiber materials and fiber loading. The results showed that SFRP: (1) Coating thickness has a significant influence on the peak load, ductility and energy absorption capacity of RC beams. (2) An appropriate fiber length near 23 mm will maximize the increase in load carrying and energy absorption capacities of RC beams.(3) Moderate volume fraction of fibers (up to 30%) is desirable for increasing the ductility and energy absorption of RC beams. (4) Carbon fibers lead to higher increase in load carry ability and lower increase in energy absorption for both damaged and undamaged RC beams due to their brittle characteristics compared to E-glass fibers. The results indicated that SFRP is capable of substantially increasing the strength as well as the ductility, and is effective in the strengthening and repair of RC structures.

Benjeddou et al. [3] presented the results of experimental studies on damaged reinforced concrete beams repaired by external bonding of carbon fiber reinforced polymer (CFRP) composite laminates to the tensile face of the beam. Two sets of beams were tested in this study: control beams (without CFRP laminates), damaged, and then repaired beams with different amounts of CFRP laminates by varying different parameters (damage degree, CFRP laminate width, concrete strength class). Repairing damaged RC beams with externally bonded CFRP laminates were successful for different degrees of damage. The observed failure modes were peeling off and interfacial debonding. These failure modes depend only on the laminate width. The results indicate that the load capacity and the rigidity of repaired beams were significantly higher than those of control beam for all tested damage degrees. The authors remarked that for a load capacity improvement, reinforcement with a CFRP having about a half width of the beam is satisfactory.

Anugeetha and Sheela [4] attempted to determine the effect of number of layers of wire mesh on the performance of the beams retrofitted using ferrocement. In addition, the effect of number of layers of GFRP on the performance of retrofitted beams was studied. From the experimental investigation it was found that the ultimate load carrying capacity of beams retrofitted with ferrocement having one, two and three layers of wire mesh increased by 6.25%, 50% and 81.25% and that of GFRP retrofitted beams with 1, 2 and 3 layers increased by 50%, 68.75% and 81.25% respectively. The beams retrofitted with one layer of GFRP in the flexural zone showed a higher strength-to cost ratio.

Farhat et al. [5] showed that neither the load carrying capacity of the retrofitted beams nor the bond between retrofit strips and concrete deteriorates with thermal cycling. Retrofitting with thin HPFRC strips bonded to the tension face improved the load carrying capacity and the serviceability of the beam. This configuration of retrofitting can increase the failure load by up to 86%. With thermal cycling, the failure load increased by up to 90% and 87% after 30 and 90 thermal cycles, respectively. No visual deterioration or bond degradation was observed after thermal cycling of the retrofitted beams (the bond between the repair material and the concrete substrate remained intact) attesting to the good thermal compatibility between the concrete and HPFRC. This retrofit material can be successfully used in hot climates.

Yining Ding et. al. [6] analyzed the effect of different fibers on the residual compressive strength, the ultimate load and flexural toughness, the failure pattern and the fracture energy of self-compacting high performance concrete (SCHPC) after exposure to various high temperatures. The micro polypropylene fiber (PP fibre) could mitigate the spalling of SCHPC member significantly, but did not show clear effect on the mechanic properties of concrete. The macro steel fiber (SF) reinforced SCHPC showed higher flexural toughness and ultimate load before and after high temperatures.

The mechanical properties of hybrid fiber reinforced SCHPC (HFSCHPC) after heating were better than that of mono fiber reinforced SCHPC. The failure mode changed from pullout of steel fibers at lower temperature to broken down of steel fibers at higher temperature. The use of hybrid fiber can be effective in providing the residual strength and failure pattern and in improving the toughness and fracture energy of SCHPC after high temperature.

Ombres [7] focused his study on: (i) the strengthening effect of the FRCM system on the flexural behavior of reinforced concrete beams in terms of ultimate capacity, deflections and ductility and (ii) the influence of the fiber reinforcement ratio on the occurrence of premature failure modes. The analysis refers to a FRCM system made by ultra-high strength fiber meshes such as the Polypara-phenylene-benzo-bisthiazole (PBO) fibers; PBO fibers have, in fact, great impact tolerance, energy absorption capacity superior than the other kind of fibers and chemical compatibility with the cementitious mortar. A total of 12 reinforced concrete beams strengthened in flexure with the PBO-FRCM system have been tested. The influence of some mechanical and geometrical parameters on the structural behavior of strengthened beams is analyzed both at serviceability and at the ultimate conditions. The structural performances of reinforced concrete beams strengthened with high performances system made by ultra-strength PBO fibers and cementitious mortar (PBO-FRCM system) was analyzed in the paper. Obtained results presented the following concluding remarks: (1) the use of the PBO-FRCM system improves sensibly the flexural capacity of strengthened reinforced concrete beams. By tests described in the paper the ultimate capacity of strengthened beams increased from 10% to 44% respect to the value relative to un-strengthened beams; (2) the failure modes of FRCM strengthened beams are depending on the percentage of PBO mesh reinforcement. For beams strengthened with one layer of PBO, mesh the failure was due to concrete crushing after internal steel yielding while a perfect bond FRCM-to-concrete was observed in spite of slippage between the PBO net and the cementitious mortar. In presence of higher PBO reinforcement (two or three layers) a premature failure due to intermediate crack de- bonding occurred.

2.3. Previous studies related to using UHPC as a repair material:

Granger et al. [8] investigated self-healing of cracks in an Ultra-High Performance Concrete, considered as a model material. An experimental program is carried out in order to quantify the phenomenon, which has been mainly highlighted by means of water permeability tests. The results of the experimental investigation on the mechanical behavior of healed concrete specimens have been presented. After a controlled pre-cracking phase under three points bending, prismatic specimens are aged, in air or in water, during various durations ranging from 1 to 20 weeks. It appeared that after storage in water exclusively, damaged beams tend to recover their initial global stiffness, and to improve slowly their flexural strength.

Kang and Kiv [9], investigated the effect of fiber orientation distribution on the flexural behavior of Ultra-High Performance Cementitious Composites (UHPCC) and to propose an analytical approach, which enables to predict the flexural behavior considering probabilistic fiber orientation distribution. A three-point bending test with the notched beams was carried out and the help of image analysis process quantitatively estimated the fiber orientation distribution. The measured fiber orientation distributions for two different flexural performances confirmed that the fiber orientation distribution has a strong impact on the deflection hardening behavior in bending. Finite element analyses were performed to predict flexural behavior of UHPCC considering the difference in fiber bridging behavior depending on the fiber orientation distribution. The analytical results were in good agreement with the experimental results.

2.4. Previous Studies related to using OPC & special repair materials as a repair materials:

Diab [10] carried out an experimental program to evaluate the effectiveness of repairing reinforced concrete (R.C.) beams with a layer of sprayed concrete. Nine beams (three series) were tested in total. Series one includes the testing of three reference beams to failure. In series two, three beams were loaded, damaged and repaired by the addition of two reinforcing steel-bar and a layer of sprayed concrete then loaded to failure; the beams of the third series were tested in the same manner as in series (2), except that the reinforcing layer was performed with fibrous concrete., and the result showed (1) the efficiency of the applied technique of strengthening and repairing of reinforced concrete structures. The ultimate load of strengthened beams was slightly lower than that of similar cast beam. This load was also affected by the stage of loading in the first loading test; this effect was within 7%, (2) the stiffness of strengthened beams was lowering than that of similar cast beam. The strengthened beams showed high ductility before failure. The adherence between the sprayed concrete layer and the cast beam was quite enough to ensure the bond between the two layers and no slippage was observed until failure, (3) the addition of metallic glass ribbon fibers to sprayed concrete enhanced the crack pattern of strengthened beam. It also enhanced the ultimate capacity, (4) the sand blasting process for beams before repair ensures a sufficient bond between the new sprayed concrete and the old concrete surface. However, the difference of strength between repaired and casted beams might be explained by the beginning of cracking in the repaired beams.

Kumar et al. [11] carried out a study to generate experimental data on residual flexural strength of heated RCC beams and their strengthening using various repair techniques. 25 RCC beams were cast with similar cross sectional details, length and grade of concrete and clear cover. Twenty beams were meant for fire exposure and the remaining five were used as companion beams. The beams were heated in two stages. In the first stage, two beams were kept at each temperature for 3 h between 100°C and 1000°C, in increments of 100°C. Beams exposed to temperature ranging between 100 and 500°C were repaired by applying paint. The beams exposed to temperature ranging between 600 and 1000°C were repaired for spalling. In the second stage, all repaired specimens were again heated. These test specimens were tested for flexural strength after bringing them to room temperature. The variation of flexural strength of repaired RCC beams with increase in temperature has been studied and the flexural strength of beams before and after the repair was compared. The following conclusions have been drawn from this investigation: (1) the normal-strength concrete could sustain up to 500°C without any visible distress. (2) The weights of the beams were reduced when heated to higher temperatures. The loss of water at elevated temperatures contributes to a decrease in flexural strength.(3) Visible thermal cracks were formed beyond 600°C and they increased in width at increasing temperatures. Spalling of cover concrete was observed in beams exposed to 1000°C before repair. Severe spalling of concrete was observed in the temperature range 700–1000°C, in beams that were heated after repair. (4) The beams exposed to temperatures between 100 and 500°C failed in flexure. Shear cracks were predominant and the beams failed in shear beyond 600°C. (5) The residual strength in the beams between temperatures 100 and 400°C was unclear. The strength was found to decrease almost linearly beyond 400°C. (6) Increased flexural strength was observed at temperatures between 100 and 600°C in the case of beams repaired by applying paint. (7) Unheated, repaired beams exhibited improved flexural strength. They failed to show the same performance when exposed to 600–1000°C.

Ahmad et. al. [12] presented the results of an experimental investigation on the strengthening of existing cracked RC members. The proposed technique consists of applying locally available polymer modified mortar in cracked beams to increase the load carrying capacity. Six full-scale RC beams were constructed with the same material using the same mix and water cement ratio. Initially, beams were tested until the development of cracks with width reached a limiting value of 1mm. The beams were then repaired with the application of polymer modified mortar technique. After 3 days of water curing the beams were tested again and loaded until the failure. An improvement in the load carrying capacity was observed in the beams after the retrofitting. Results clearly demonstrate the effectiveness of the proposed technique in repairing the RC members for strengthening the existing structures. On the basis of the results obtained from this study, RC beams can be strengthened by repairing the existing flexural and shear cracks with PMM application and this can lead to a considerable (36%) increase in the load carrying capacity.

Hashemi and Al-Mahaid [13] investigation of the flexural behavior of FRP-strengthened reinforced concrete beams using cement-based adhesives. It is concluded that the use of cement-based bonding materials is a promising technique in FRP applications for structures located in hot regions or in danger of fire. Compared to CFRP fabric, CFRP textile is more compatible as well as more efficient with cement-based mortar. The ultimate load achieved by using CFRP textile-cement mortar is around 80% of what was achieved by using CFRP fabric with epoxy adhesive.

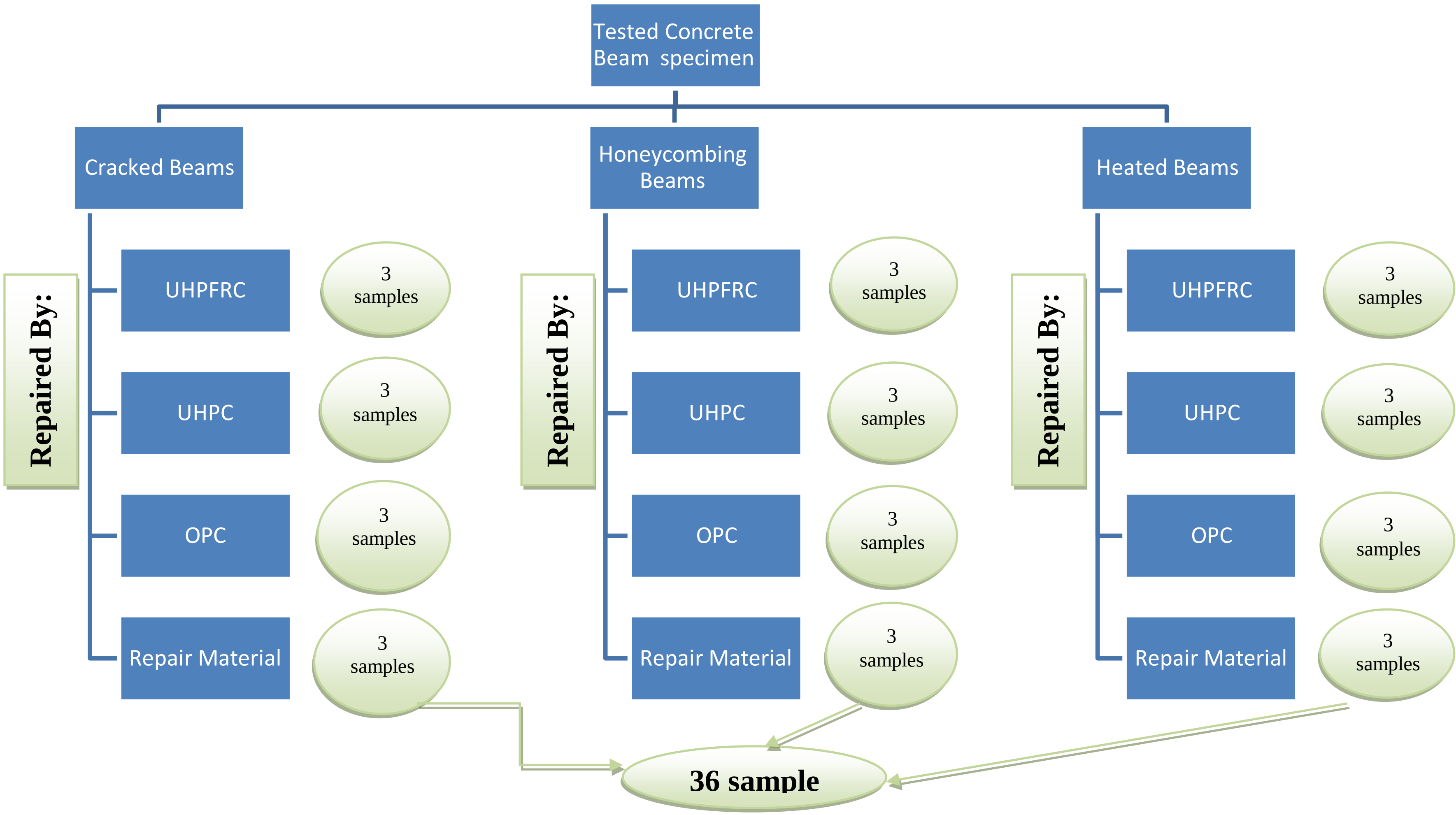
Kim and Yun [14] , presented experimental and analytical studies on the cracking behavior and flexural performance of reinforced concrete beams repaired with strain-hardening cement-based composite(SHCC). Test results demonstrated that RC beams repaired with SHCC showed no concrete crushing or spalling until final failure, but showed a great number of hair cracks, while non-repaired RC beam failed due to crushing. It was noted that the SHCC matrix can improve crack-damage mitigation and the flexural behavior of RC beams, such as moment strength, ductility after peak load and energy dissipation capacity. In the fiber section analysis, the idealized tensile stress–strain curve for the SHCC based on a four-point model was similar to the test result, and it was confirmed that monotonic analytical moment–curvature curves were well fitted to the experimental moment–curvature curves. Based on the parametric analysis results, it was noted that the curvature of the RC beam was more affected by the matrix ductility of the SHCC than the moment strength. The repair effect of SHCC on the flexural behavior of RC beams was evaluated. From the experimental and analytical results, the following conclusions are drawn: (1) RC beams repaired with SHCC showed no concrete crushing or spalling until final failure but showed a great number of hair cracks, while CBN failed due to crushing. However, for the CBF-L series, delamination along interface of the bi-material was observed near the support region after peak load. (2) For RC beams repaired with SHCC, only cracks smaller than 0.2mm wide were found until reinforcement yielding. Damage class II (crack width range 0.2–1.0mm) then lasted until the peak loading, where as the CBN reached damage class III before peak loading. These results indicate that the SHCC matrix can delay decrease in residential capacity of the RC beam.

CHAPTER 3   EXPERMENTAL PROGRAM

3.1. Introduction:

The main objective of the executed testing program is to apply the four repair techniques for each of three stated repair problems on the reinforced concrete beams. The proposed testing program includes testing of 39 reinforced beams that are to be designed, constructed, repaired and tested under flexure to achieve the research objectives. Three of the beam samples are to be tested as control beams, twelve beam samples are tested for cracking repair, (as shown in Figure 3-2), twelve beam samples for honeycombing as shown in Figure 3-3, and twelve beams for concrete cover separation repair as shown in Figure 3-4. The beam dimensions are designed in accordance with ACI 318-08, preventing shear failure through using ɸ8mm stirrups @50mm. The testing program is also summarized in Figure 3-1.

Figure 3-1: Testing Program Flow Chart



3.2. Material Properties:

There are many repair materials that are used all over the world for repairing and strengthening reinforcing concrete structures.

The repair techniques which will be used in this study include: (1) using Ultra High Performance Concrete, (2) Ultra high performance fiber reinforced concrete, (3) Ordinary concrete, and (4) special repair material made by a certified manufacture.

3.2.1. UHPC Properties:

UHPC constituent materials in this study include High Strength Portland Cement CEM I 52.2R. Nesher Cement, Inc. of Israel, which conforms to ASTM CI 50 (2009), quartz sand and basalt aggregate, manufactures this cement. The nominal size of crushed basalt ranges from 0.6 to 6.3 mm, while that of quartz sand is in the range of 0.2 to 0.4 mm. The specific gravity is 2.80 and absorption is 1.48% for basalt. For quartz , the specific gravity is 2.66 and the absorption is 0.62%. Crushed quartz sand of a maximum size of 150 µm is used as very fine aggregate. The very fine particles have sizes ranging from 0.1 to 10 µm to the gaps between the cement grains, while the larger particles have sizes ranging from 10 to 150 µm to fill the gaps between the fine aggregate grains resulting in much denser matrix. Gray silica fume with SiO_2 as main chemical component (95%), which conforms to the requirement of ASTM CI 240-05 (2005) . In addition, a superplasticizer PLAST_B101P, delivered from YASMO MISR Company of Egypt is used to ensure suitable workability. The mix design is shown in Table 3-1.

Table 3-1: UHPC composition

Materials	Quantity (kg/m^3)
Cement CEM I 52.2R	600
Water	180
Silica fume	93
Quartz powder (0.0 - 0.15 mm)	300
Quartz sand (0.15 - 0.4 mm)	315
Basalt aggregate (0.6 – 1.18 mm)	460
Basalt aggregate (2.36 – 6.3 mm)	530
Super plasticizer	18

The previous materials are used in preparing UHPC, which can achieve a compressive strength of 120 MPa, and a volume of 1 cubic meter.

3.2.2. UHPFRC Properties:

UHPFRC constituent materials used in this research include Portland cement which meets the requirements of ASTMC150 (2009) quartz sand and basalt aggregate. The nominal size of crushed basalt ranges from 0.6 to 6.3 mm while that of quartz sand is in the range of 0.2 to 0.4 mm. The specific gravity is 2.8 and absorption is 1.48 % for basalt. For quartz sand, the specific gravity is 2.66 and the absorption is 0.62 %. Crushed quartz powder of a maximum size of 150 μm is used as ultra-fine aggregate. Silica fume, which conforms to the requirements of ASTM C 1240, (2010), is used. In addition, a super plasticizer is used to ensure suitable workability. Properties of steel fibers used in the testing program are shown in Table 3-2.

Table 3-2: properties of steel fibers.

Diameter, mm	Aspect ratio	Yield strength, MPa
0.32 mm	65	1700

The mix design is shown on Table 3-3.

Table 3-3: UHPFRC composition

Materials	**Quantity (kg/m^3)**
Cement	600
Water	180
Silica fume 15.5% cement wt.	93
Quartz powder	300
Quartz sand (0.2-0.4 mm)	315
Basalt aggregate (0.6-1.18 mm)	460
Basalt aggregate (2.36-6.3 mm)	530
Steel fiber % volume, 65 aspect ratio	0.50
Super plasticizer	19.8

The previous materials are used in preparing UHPFRC, which can achieve a compressive strength of 134 MPa, and a volume of 1 cubic meter.

3.2.3. OPC Properties:

OPC constituent materials used in this research include Portland cement which meets the requirements of ASTMC150 (2009), sand and different sizes of aggregate see Table 3-4. The compressive strength of this matrix is about 25 MPa .The mix design is shown in table Table 3-4.

Table 3-4: OPC composition

Materials	Quantity (kg/m^3)
Cement CEM I 52.2R	300
Water	188
Sand	640
Aggregate (Semsem)	320
Aggregate (Adase)	400
Aggregate (Foule)	520
Super plasticizer	18

3.2.4. Special Repair Materials:

In this research, a repair material named **BETONREP 250**, High Quality Repairing Mortar manufactured by YASMO MISR Company, was used.

The compressive strength, at 3 days was 220 kg/cm^2, and at 7 days was 300 kg/cm^2, with water ratio is 10 % that is all according to ASTM C-109.

3.3. Cracked beams

The application of the repaired techniques is aimed at strengthening the damaged RC beams to increase load-carrying capacity.

3.3.1. Beam geometry:

Semi full-scale tests are performed on 1.10 m long beams with a depth of 200 mm and a width of 150 mm as shown in Figure 3-2. Three beams are cast and reinforced with two bottom longitudinal rebar's (Φ= 12 mm), two top longitudinal rebar's (Φ= 8 mm) and stirrups at the beam ends, having a diameter of 8 mm and a spacing of 50 mm. The ends of the bottom longitudinal- rebar were anchorage to guarantee a good bonding and to avoid slipping out during loading.
The beams are cast with concrete having a nominal cubic compressive strength of 250 kg/cm^2.

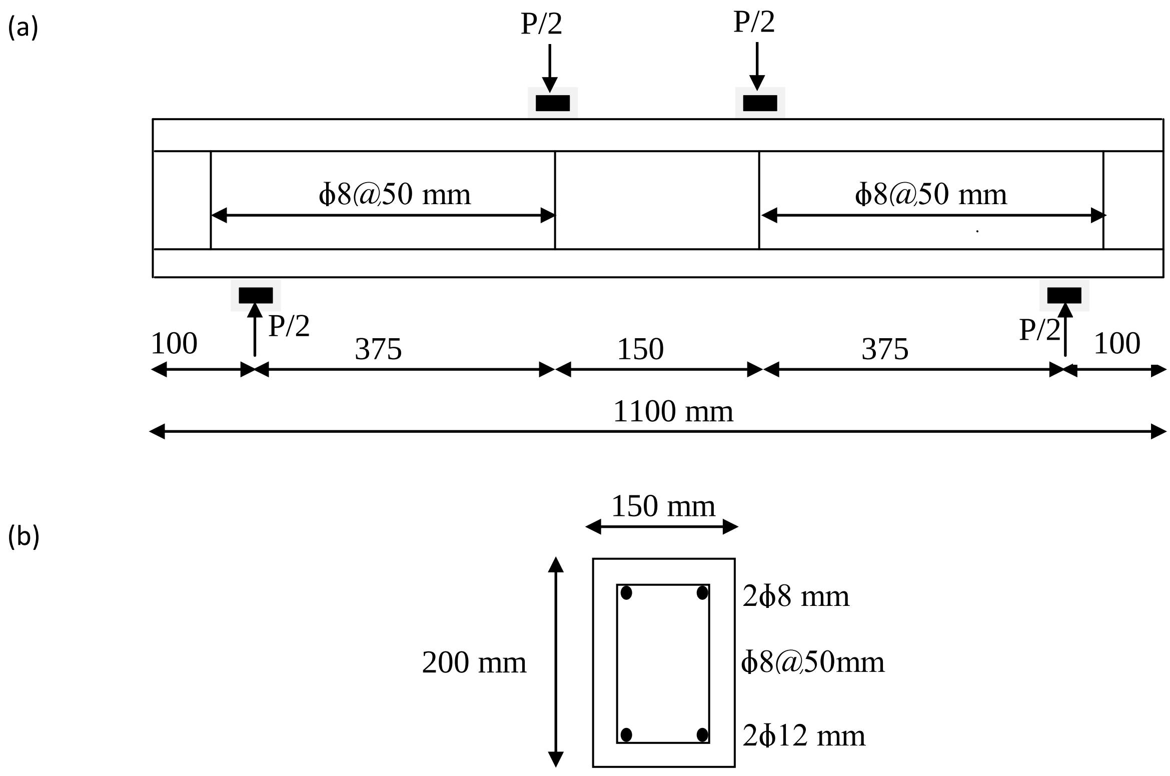


Figure 3-2: Cracked Beam (a) layout and (b) Cross section

3.3.2. Calculation of flexural capacity of the beam section:

Available data :

Concrete strength fc = 250 kg/cm^2 steel yield strength = 4200 kg/cm^2

Width of beam = 15 cm thickness of beam = 20 cm , concrete cover = 2 cm

Bottom steel = 2 Φ12 mm steel stirrup = Φ 8 mm @ 5cm

Analysis of section:

Assume the section is <u>tension controlled</u>

A_s = 2.27 cm^2

From the force diagram , T = C

a = $\frac{As\ x\ fy}{0.85\ x\ b\ x\ f_c} = \frac{2.27\ x\ 4200}{0.85\ x\ 15\ x\ 250}$ = 3 cm.

c = $\frac{a}{\beta}$, $\beta = 0.85$ c = 3.35 cm

from strain diagram, $E_s = \frac{(d-c)x0.003}{c} = \frac{(16.6-3.35)x0.003}{3.35}$ = 0.0118> 0.005

so assumption of tension controlled section is true.

Φ = 0.90

$M_u = \phi(As)(f_y)\,\frac{d-a}{10^5} = (0.9)(2.27)(4200)(\frac{16.6-3}{10^5})$= 1.17 ton.m

M_u=($\frac{Pu}{2}$) 0.375 $P_u = \frac{2(1.17)}{0.375}$ = 6.24 tons.

3.3.3. Number of tested samples:

- 3 samples are used as control beams.
- 3 samples repaired by UHPC.
- 3 samples repaired by UHPFRC.
- 3 samples repaired by OPC.
- 3 samples repaired by specialized repair material.

3.3.4. Testing procedure:

The semi full-scale beams are tested under flexure in a four-point loading. The beams are placed on a 0.90 m span and loaded at two points located at a distance of 0.375 m from the supports (shear span is equal to 0.95), as shown in Figure 3-2 :

1. Ready the 4-point loading frame and examine all parts of it to make sure it is in a good condition.
2. Cast all samples and keep it in water for 28-day to achieve full strength.
3. Test the control beams by applying the load and increasing it slowly to reach its load capacity.
4. Compare the load capacity obtained from the test and the load capacity, which is obtained from theoretical calculation.
5. Apply the load on the other samples and increase the load slowly to reach the value of 2/3 P_u = 4.16 ton, where the beam is to fail at serviceability limit state and crack pattern appears.
6. Draw the crack pattern.
7. Grove the cracks as letter (V) to apply the four repaired materials as (3 samples for each case).
8. The samples are left for 28 days after repair to achieve the repair material its strength.
9. Apply the load and increase until failure under flexure.
10. Record the value of the load where the beam has failed.
11. Draw the crack pattern for each case.
12. Compare the values obtained from the control beams with the values obtained from the repaired samples.
13. Compare the crack patterns of control beams with those for other repaired beams.
14. Decide on the best suitable repair material.

3.4. Honeycombed Beams

The application of the repaired techniques is aimed at strengthening the damaged RC beams to increase load-carrying capacity.

3.4.1. Beam geometry

Semi full-scale tests are performed on 1.10 m long beams with a depth of 200 mm and a width of 150 mm, at mid of span in tension zone the section is empty from concrete by dimension (50mm width, 100mm highest, 150mm depth) as shown in Figure 3-3. Three beams are cast and reinforced with two bottom longitudinal rebar's (Φ= 12 mm), two top longitudinal rebar's (Φ= 8 mm) and, at the beam ends, stirrups having a diameter of 8 mm and a spacing of 50 mm. The ends of the bottom longitudinal- rebar were anchorage to guarantee a good bonding and to avoid slipping out during loading.
The beams are cast with concrete having a nominal cubic compressive strength of 250 kg/cm^2.

(a)

(b)

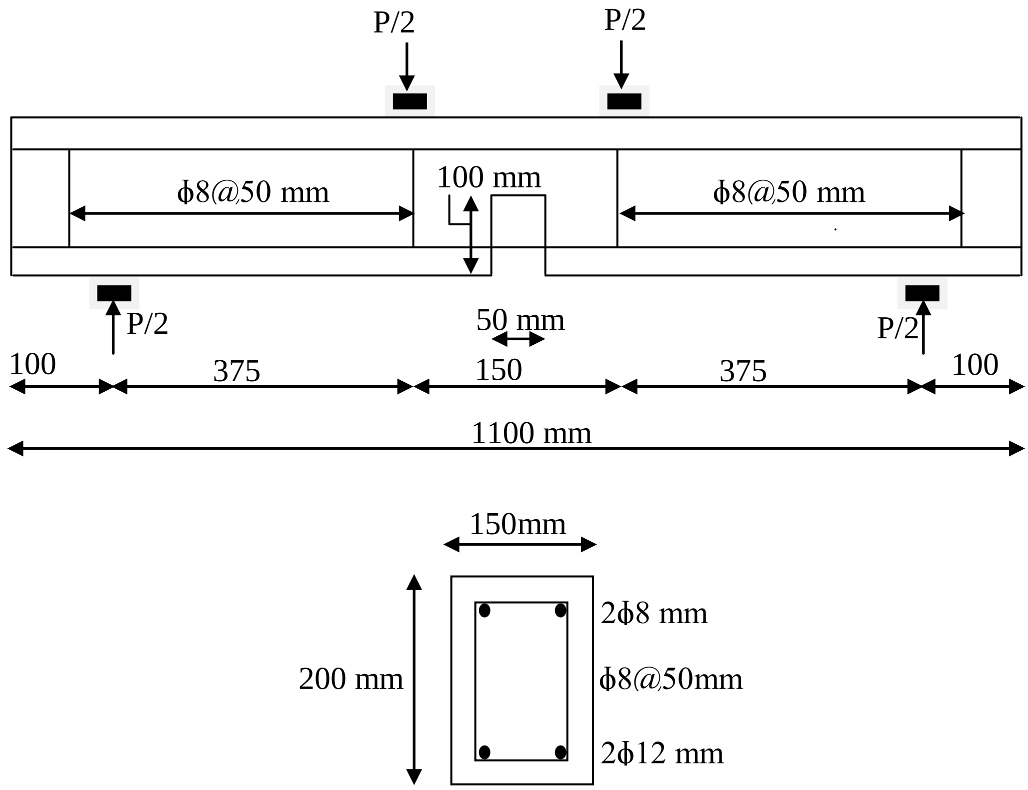


Figure 3-3: Honeycomb Beam (a) layout and (b) Cross section

3.4.2. Calculation of flexural capacity of the section:

Is same as in section 3.3.2.

3.4.3. Number of tested samples:

- 3 samples are used as control beams.
- 3 samples repaired by UHPC.
- 3 samples repaired by UHPFRC.
- 3 samples repaired by OPC.
- 3 samples repaired by specialized repair material.

3.4.4. Testing procedure:

The semi full-scale beams were tested under flexure in a four point bending scheme. The beams were placed on a 0.90 m span and loaded at two points located at a distance of 0.375 m from the supports (shear span equal to 0.95) as shown in Figure 3-3.

1. Ready the 4-point machine and examine all parts of it to make sure it in a good condition.
2. Cast all samples leaving a missing a part of beam without concrete with dimension 50x100x150 mm, located at mid span at tension side of beam, and keep it in water for 28-day to achieve full strength.
3. The control beams where also tested.
4. Compare the load capacity of test and the load capacity that obtained from theoretical calculation.
5. Chisel and roughen the surface of honeycombing to improve bond between existing concrete and the repair materials.
6. Apply the four-repaired material (3 samples for each case).
7. Draw the crack pattern for this case.
8. Apply the load and increase it until failure under flexure.
9. Record the failure value of load of the beam.
10. Draw the crack patterns.

11. Compare the values of the control beam with values obtained from each case of other repaired samples.
12. Compare the crack patterns of control beams with the repaired beams that obtained from each case.
13. Decide on the best suitable repair material.

3.5. Heated Beams

The application of the repaired techniques is aimed at strengthening the damaged RC beams to increase load-carrying capacity.

3.5.1. Beam geometry and material properties

The heated beam geometry and its materials propertied as shows in section 3.3.3, except that the beam length is 0.50 m as shown in Figure 3-4.

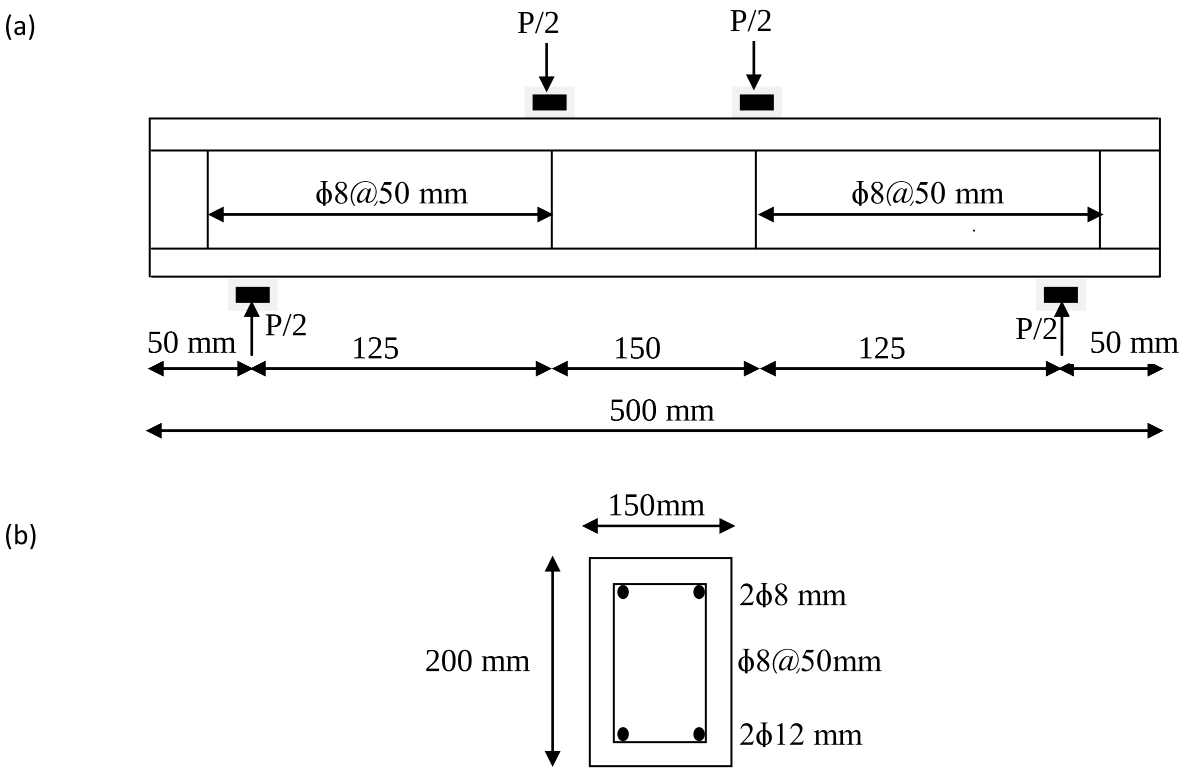


Figure 3-4: Heated Beam (a) layout and (b) Cross section

3.5.2. Calculation of flexural bearing capacity of the section:

Available data:

Concrete strength fc = 250 kg/cm^2 steel yield strength = 4200 kg/cm^2

Width of beam = 15 cm thickness of beam = 20 cm concrete cover = 2 cm

Bottom steel = 2 Φ12 mm, steel stirrup = Φ 8 mm @ 5cm

Analysis of section:

Assume the section is <u>tension controlled</u>

A_s = 2.27 cm^2

From the force diagram , T = C

a = $\frac{(As)(fy)}{0.85\ b\ f_c} = \frac{(2.27)\ (4200)}{(0.85)(15)(250)}$ = 3 cm.

c = $\frac{a}{\beta}$, $\beta = 0.85$ c = 3.35 cm

from strain diagram, $E_s = \frac{(d-c)x0.003}{c} = \frac{(16.6-3.35)x0.003}{3.35}$ = 0.0118> 0.005

so assumption of tension controlled section is true.

Φ = 0.90

Mu = $\phi(As)(f_y)\frac{d-a}{10^5}$ = $(0.9)(2.27)(4200)(\frac{16.6-3}{10^5})$= 1.17ton.m

$M_u = \frac{Pu}{2}$ x 0.125,   Pu = $\frac{2x(1.17)}{0.125}$ = 18.72 tons.

3.5.3. Number of tested samples:

- 3 samples are used as control beams.
- 3 samples repaired by UHPC.
- 3 samples repaired by UHPFRC.
- 3 samples repaired by OPC.
- 3 samples repaired by specialized repair material.

3.5.4. Testing procedure:

The semi full-scale beams were tested under flexure in a four point bending scheme. The beams were placed on a 0.40 m span and loaded at two points located at a distance of 0.125 m from the supports (shear span equal to 0.35) as shown in Figure 3-4.

1. Ready the 4-point loading frame and examine all parts of it to make sure it in a good condition.
2. Cast all samples, and keep it in water for 28-day to achieve full strength.
3. The control beam where also tested.
4. Compare the load capacity of test and the load capacity that obtained from calculation.
5. Put the samples in electric Oren and heat it to $250C^0$, for four hours.
6. Pull out the samples and cool them slowly in normal air condition.
7. After the samples are cooled chisel the bottom concrete cover and roughness the bottom surface for better bond between existing concrete and the repair materials.
8. Apply the four-repaired material (3 sample for each case).
9. Draw the crack pattern on this situation.
10. Apply the load and increase it until failure in flexure.
11. Record the value of load where the beam has failed.
12. Draw the crack pattern for each case.
13. Compare the value of control beam with values obtained from each case of other repaired samples.
14. Compare the crack pattern of control beam with repaired beams that are obtained from each case.
15. Decide on the best solution or the suitable repaired material.

CHAPTER 4 REPAIR OF CRACKED BEAMS

4.1. Introduction:

Cracks in concrete are extremely common but often misunderstood. When an owner sees a crack in a slab or wall, especially if the concrete is relatively new, we assumes that there is something wrong. This is not always the case. Some types of cracks are inevitable. The best that a contractor can do about it is to try to control the cracking. This is done by properly preparing the sub grade, assuring that the concrete is not too wet, utilizing reinforcement where needed, and by properly placing and spacing crack control joints and expansion joints. However, sometimes cracks happen in spite of any precautions taken.

The American Concrete Institute addresses this issue “Even with the best floor designs and proper construction, it is unrealistic to expect crack-free and curl-free floors. Consequently, every owner should be advised by both the designer and contractor that it is normal to expect some amount of cracking and curling on every project, and that such occurrence does not necessarily reflect adversely on either the adequacy of the floor’s design or the quality of its construction.

Excessive cracking is one of the most common causes or damage in concrete structures and results in huge annual cost to the construction industry. Current design procedures to control cracking using conventional steel reinforcement are overly simplistic and often unreliable.

For a concrete structure to be serviceable cracking must be controlled and deflection must not be excessive. Service load behavior depends primarily on the properties of the concrete and these are often not known reliably at the design stage. In the design of concrete structures, it is necessary to check the serviceability of the structure particularly in the post-cracking range. The effects of several factors, which are difficult to assess from purely analytical considerations, complicate the behavior in this range. Of prime importance are the effects of tension stiffening, the random developments of primary cracks and secondary cracks in regions between the primary cracks and around the reinforcing bars, and the degree of bond breakdown.

The width of a crack depends on the quantity, orientation and distribution of the reinforcing steel crossing the crack and the cover to the reinforcement. It also depends on the bond characteristics between the concrete and the reinforcement bars at and in the vicinity of the crack. A local breakdown in bond immediately adjacent to a crack complicates the modeling.

4.2. Control beam sample testing:

Control beam samples are tested under 4-point load and increasing the load slowly until failure to get the flexural capacity of section, crack pattern and deflection. The average load obtained from the three tested samples is 6.30 ton. This value is very close to the theoretical value of the section, which is 6.24 ton. The experimental results, together with the sample geometry, are reported in Table 4-1 and
Figure 4-2.

Crack patterns were taken and drawn to make a comparison with the repaired beams and shown in Figure 4-1.

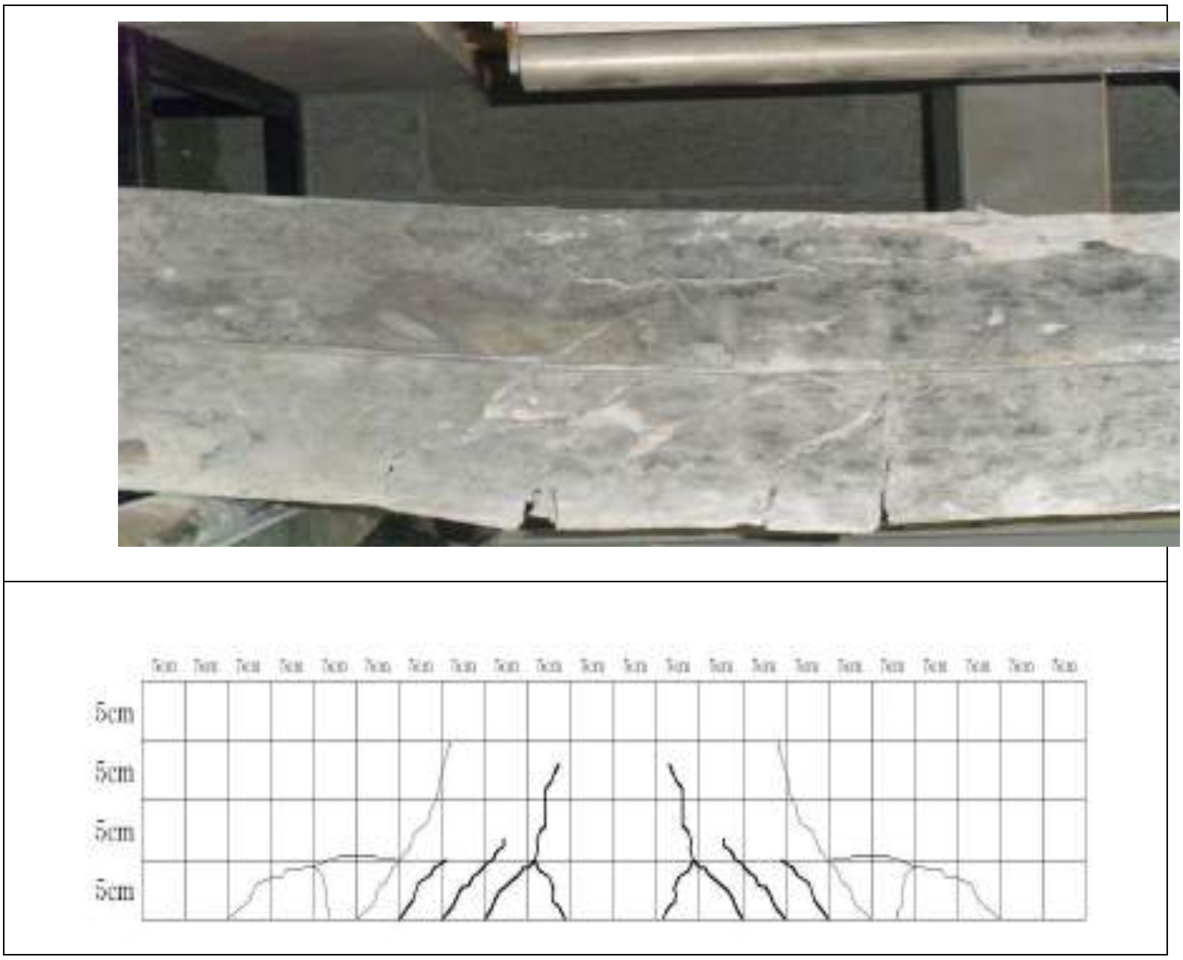


Figure 4-1: Crack pattern of the control beams

Table 4-1: Control beam deflections

Load (KN)	Deflection (mm)
4.5	1.6
9	2.4
13.5	3.1
18	3.7
22.5	4.2
27	4.7
31.5	5.1
36	5.6
40.5	6
45	6.5
49.5	7
54	7.4
58.5	7.9
63	8.6

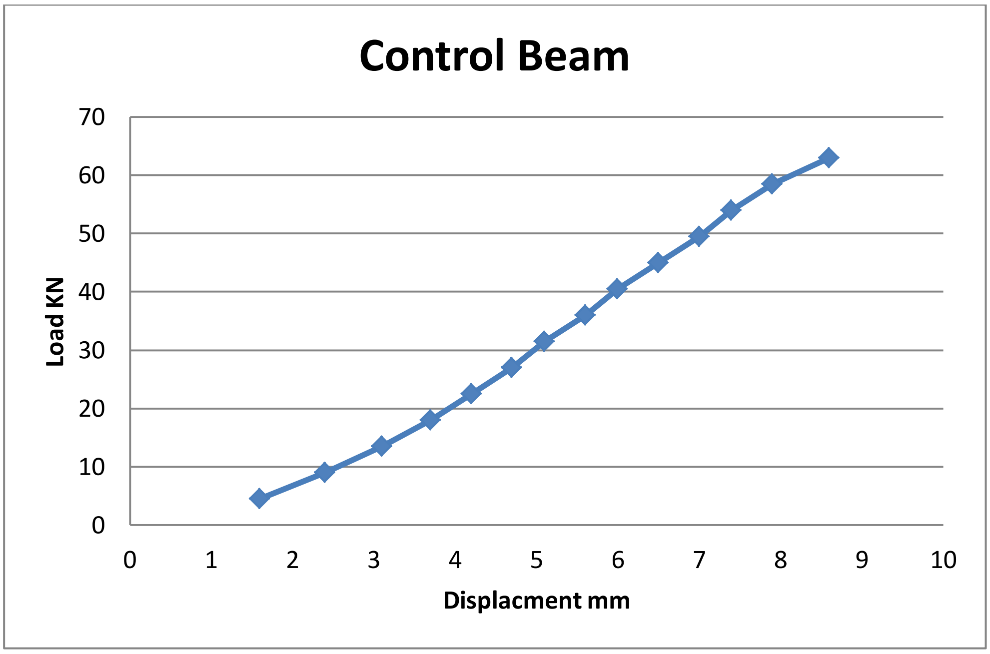


Figure 4-2: Mid - Span displacement

4.3. Cracked beams after repair:

Before stating the process of repairing techniques on RC beams, the samples are loaded to 80% of the flexural capacity of the section, (this value is equal to 5.00 tons). The steps are summarized as follows:

1st Cast the samples and cure it for 28 days.

2nd Apply 80% of the factored load to the samples to cause cracking as shown in Figure 4-3:

Figure 4-3: Sample being cracked

3rd Mark the cracks on the samples, widen the widths of the cracks to make it ready for applying the repair materials as, shown in Figure 4-4:

Figure 4-4: Crack Groves

4th Wash the samples, shown in Figure 4-5.

Figure 4-5: Cleaning Samples by Water

5thPrepare the samples to receive the four cementious repair materials.

4.3.1. Repairing the cracked beams using UHPC:

Ultra High Performance Concrete (UHPC) is one of the latest developments in concrete technology. The UHPC refers to materials with a characteristic compressive strength in excess of 120 MPa. The UHPC is made by using coarse, fine and ultrafine aggregates, very low amounts of water, silica fume and high amounts of cement. Silica fume is an ultrafine powder whose particle sizes are 50 to 100 times finer than cement and can fill up the voids created by the free water in the cement matrix. Chemically, it reacts with Calcium Hydroxide (CH) to produce additional Calcium silicate Hydrate (CSH). The reaction between hydrated Portland cement compounds and Silica fume produces a very dense microstructure and thus improves the bond between the cement and the aggregates.

The procedure is summarized in the following section:

6thprepare the required material quantity of UHPC that enter in mixing, to be ready for application, see Figure 4-6:

Figure 4-6: Applying UHPC matrix to the Cracked beams

7^{th}Cure the samples after applying the UHPC matrix for 7 days.

8^{th}Test the samples repaired by UHPC and record the results, bearing capacity, crack pattern and deflection. (See Figure 4-7):

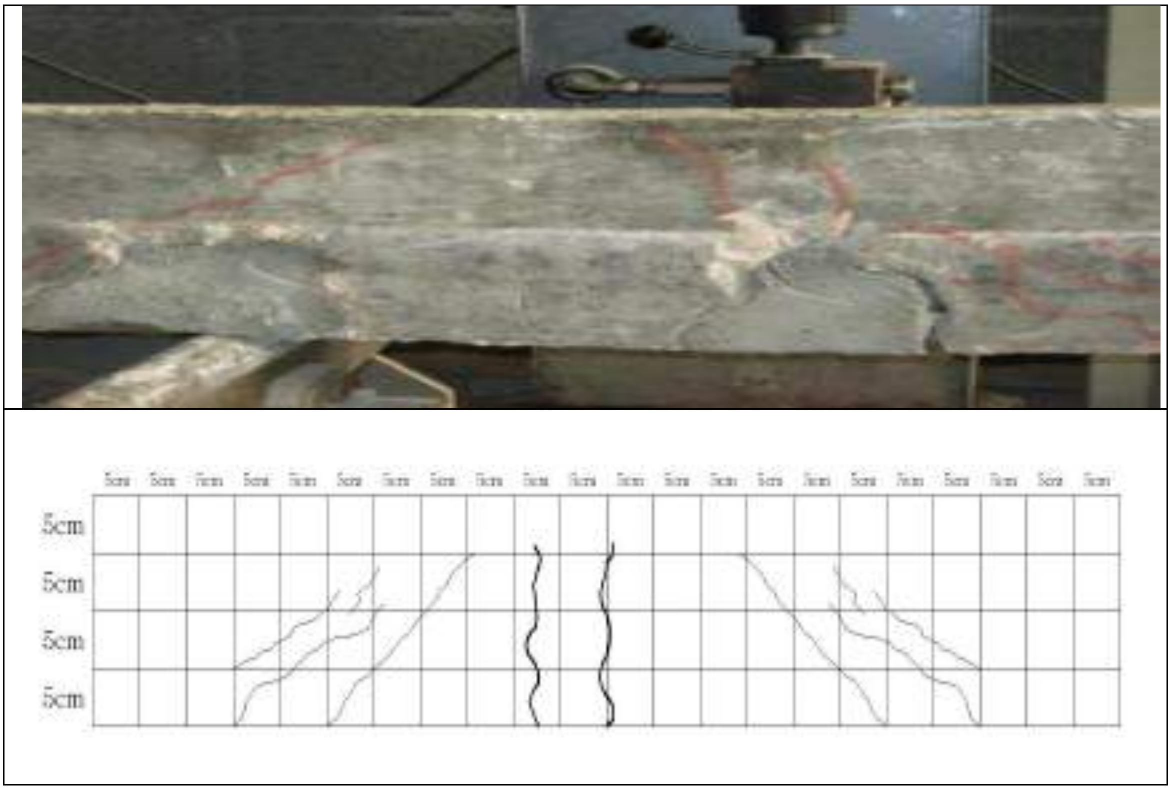


Figure 4-7: Cracked beam repaired by UHPC and its Crack Pattern

Beams repaired using UHPC were tested under 4-point load and increasing the load slowly to failure to get the maximum capacity of section, crack pattern and deflection. The average value obtained from three tested samples is 6.8 ton, and the deflection values are recorded in Table 4-2 and Figure 4-8.

Table 4-2: Deflection of UHPC repaired samples

Load (KN)	Deflection (mm)
4.5	1.2
9	1.8
13.5	2.325
18	2.775
22.5	3.15
27	3.525
31.5	3.825
36	4.2
40.5	4.5
45	4.875
49.5	5.25
54	5.55
58.5	5.925
63	6.45
67.5	6.9

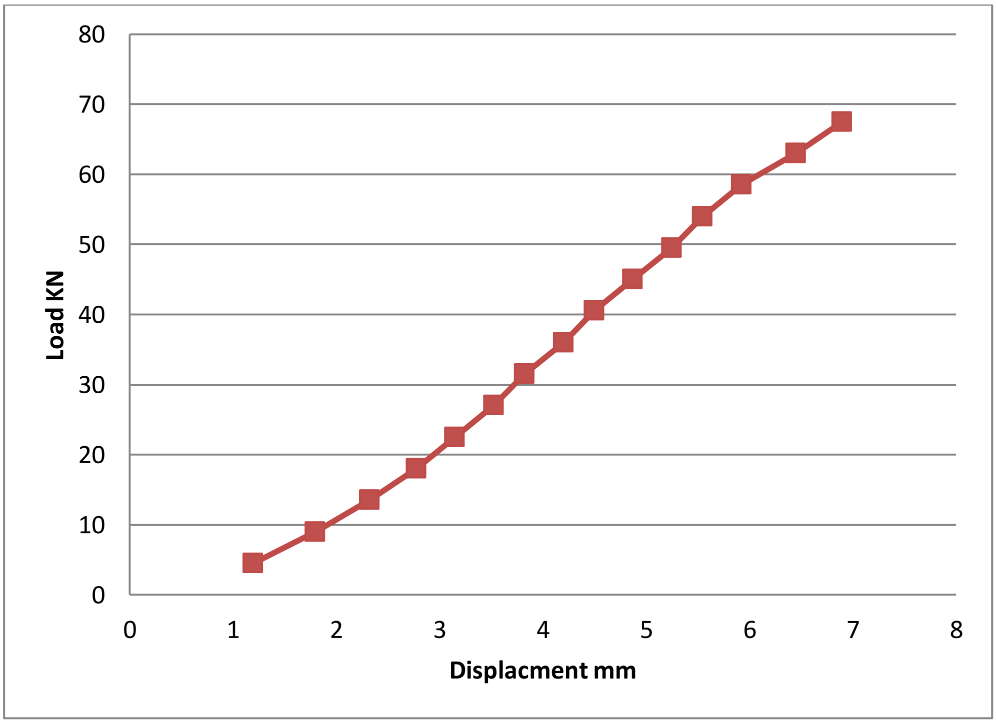


Figure 4-8: Displacement – load curve for cracked beams repaired using UHPC

4.3.2. Repair of cracked beam by using UHPFRC:

FRP are composed of unidirectional fibers (primarily glass or carbon) in an environmentally durable epoxy resin. FRPs have desirable engineering properties (e.g., high strength and stiffness, low density, long fatigue life, and high resistance to corrosion) and offer great potential for cost-effective retrofitting of concrete structures. Among these, continuous fiber-reinforced laminates have been widely used to strengthen and rehabilitate concrete beams and columns and many researchers have reported improvements in strength and stiffness of the retrofitted structures. The continuous FRP fiber-reinforced laminates exhibit relatively small strains at rupture and behave in a linear manner to rupture. In addition, anchorage is generally needed to obtain a good bonding between the composites and concrete structures. On the other hand, the addition of steel fibers have a positive impact on splitting tensile strength and flexural strength of concrete.

The following steps summarize the procedure:
6^{th}Prepare the required material quantity (see Figure 4-9):

Figure 4-9: Applying UHPFRC matrix to cracked beams

7^{th}Cure the samples after applying the UHPFRC matrix for 7 days.

8^{th}Test the sample repaired using UHPFRC and record the results, maximum capacity, crack pattern, and deflection. (See Figure 4-10).

Figure 4-10: Cracking pattern of cracked beams repaired by UHPFRC

Cracked beams repaired using UHPFRC were tested under 4-point load by increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average load value of testing is 7.50 ton, and the deflection values are recorded in Table 4-3 and Figure 4-11.

Table 4-3: UHPFRC sample Deflections

Load (KN)	Deflection (mm)
4.5	0.83
9	1.25
13.5	1.6
18	1.9
22.5	2.2
27	2.5
31.5	2.6
36	3
40.5	3.1
45	3.4
49.5	3.6
54	3.8
58.5	4.1
63	4.5
67.5	5.05
72	5.5
74.997	6.15

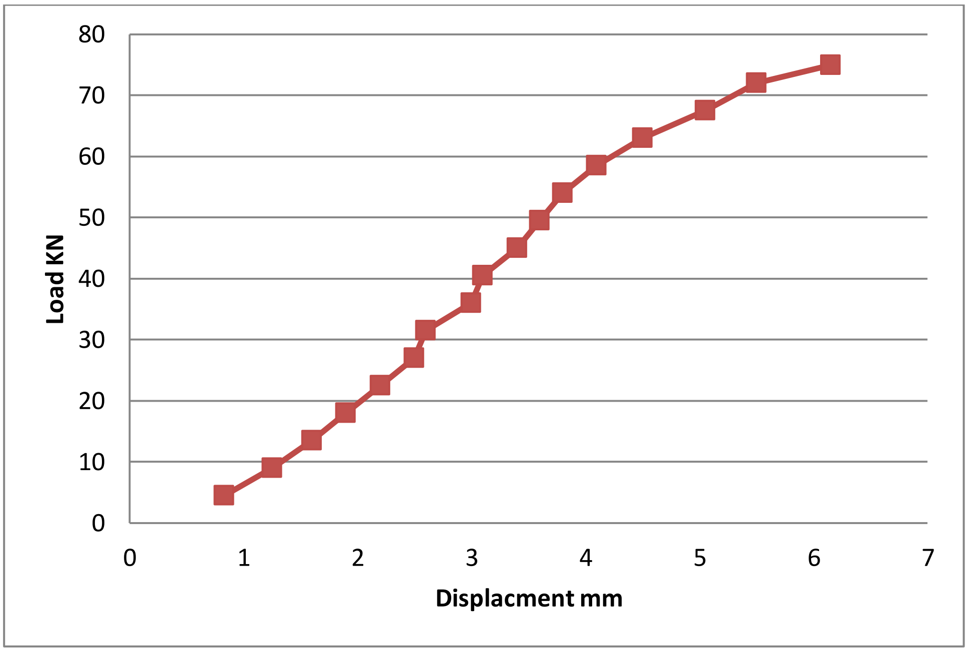


Figure 4-11: Displacement – load curve for cracked beam repaired by UHPFRC

4.3.3. Repairing cracked beams using OPC:

Concrete as a material has been used for many years to build a wide variety of structures from houses to bridges. A period of dynamic growth in its use came during the 1960s because of chronic shortage of housing. It was not until signs of decay started to appear, only 10 years later, that research on the durability of such concrete structures was implemented. The beams were repaired using, OPC.

The procedure is summarized as follows:

6thPrepare the required material quantity of OPC (see Figure 4-12)

Figure 4-12: Applying OPC matrix to Cracked beams

7th Cure the samples after applying the OPC matrix for 7 days.
8th Test the samples repaired using OPC and record the results, bearing capacity, crack pattern, and deflection. (See Figure 4-13).

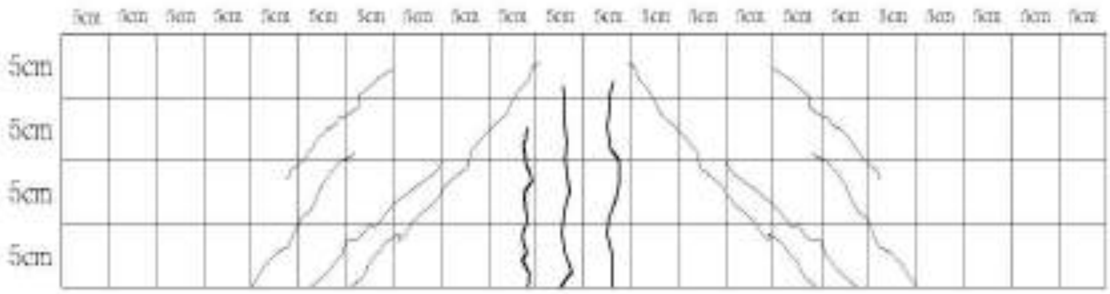


Figure 4-13: Cracking Pattern for cracked beams repaired by OPC

Cracked beams repaired using OPC were tested under 4-point load by increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average load value of testing samples is 6.10 ton, and the deflection values are recorded in Table 4-4 and Figure 4-14.

Table 4-4: OPC Deflection

Load (KN)	Deflection (mm)
4.5	1.5
9	2.3
13.5	2.9
18	3.5
22.5	4
27	4.5
31.5	4.8
36	5.3
40.5	5.7
45	6.2
49.5	6.6
54	7
58.5	7.5
63	8.2

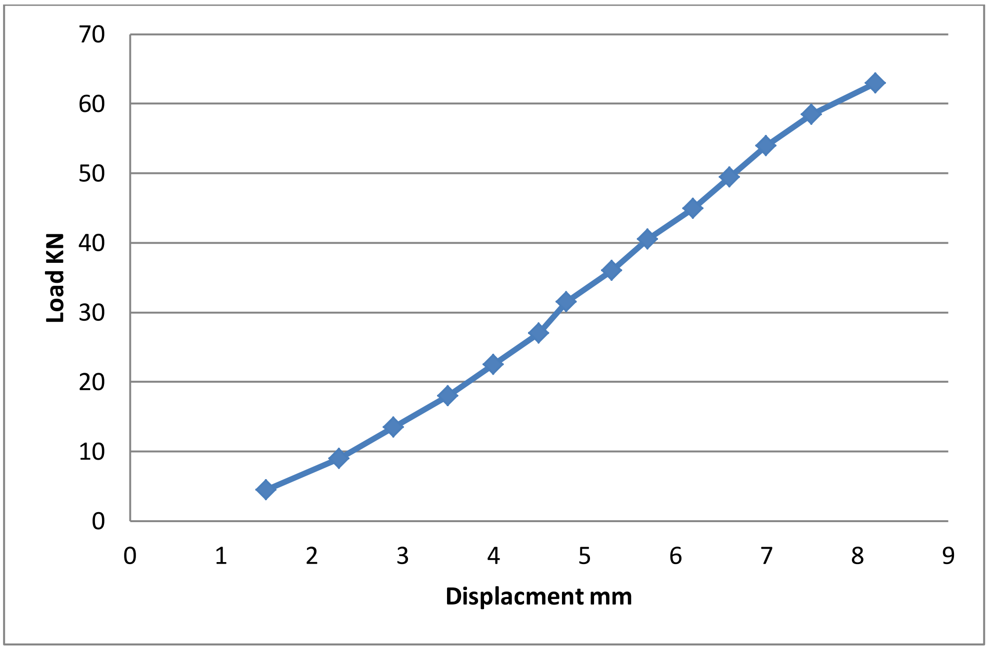


Figure 4-14: Displacement – load curve for cracked beam repaired by OPC

4.3.4. Repairing cracked beams using special Repair Material (SRM):

The procedure is summarized as follows:
6th Prepare the required material quantity of SRM (see Figure 4-15):

Figure 4-15: Applying RM matrix to Cracked Beams

7thCure the samples after applying the SRM matrix for 7 days.
8thTest the samples repaired using SRM and record the results, bearing capacity, crack pattern, and deflection.(See Figure 4-16)

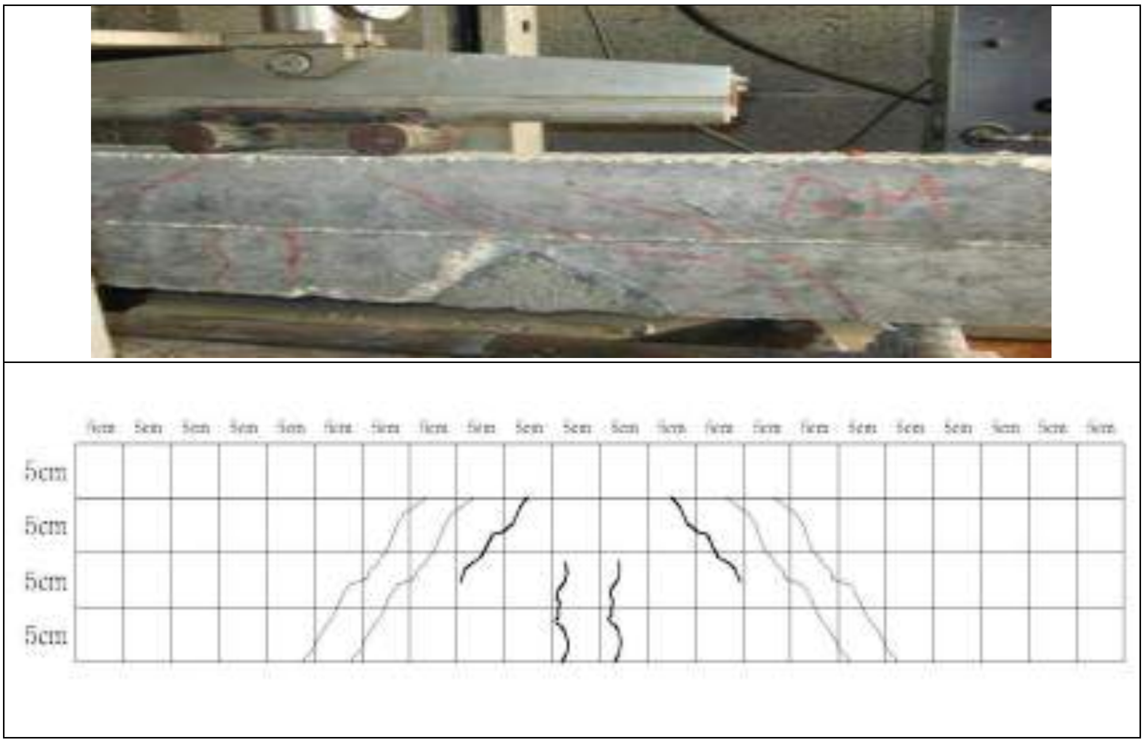


Figure 4-16: Cracking Pattern for cracked beams repaired by SRM

Cracked beams repaired using SRM were tested under 4-point load by increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average load value of testing three samples is 7.00 ton, and the deflection values are recorded in Table 4-5 and Figure 4-17.

Table 4-5: SRM Deflection

Load (KN)	Deflection (mm)
4.5	1
9	1.5
13.5	2
18	2.3
22.5	2.6
27	3
31.5	3.2
36	3.5
40.5	3.8
45	4.1
49.5	4.4
54	4.6
58.5	5
63	5.4
67.5	5.95
69.9975	6.6

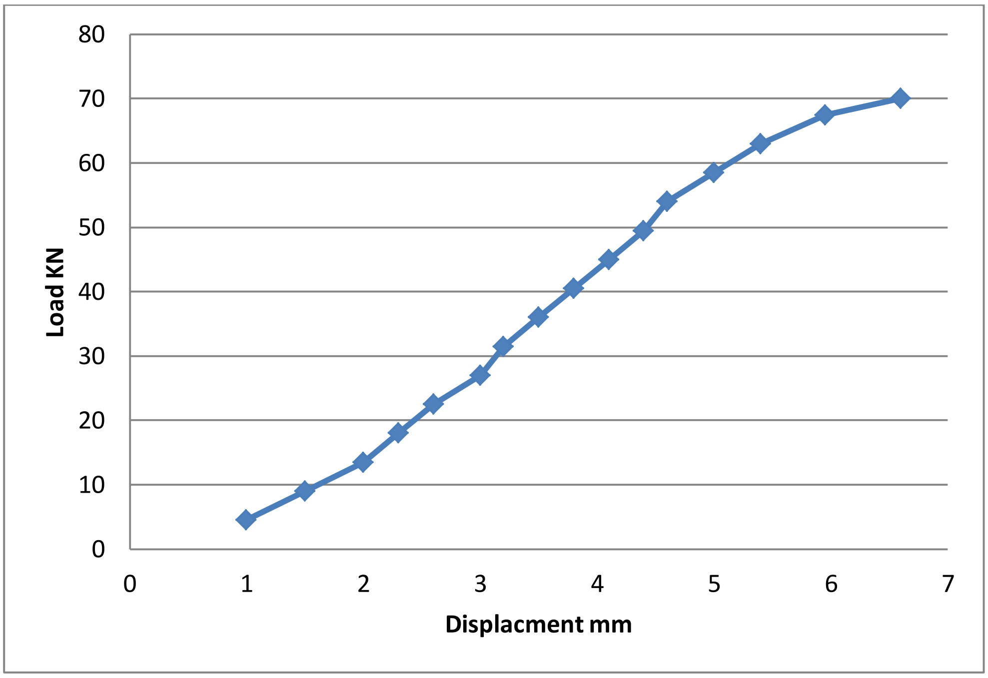


Figure 4-17: Displacement – load curve for cracked beam repaired by SRM

4.4. Results and Discussion:

4.4.1. Flexural capacity

Table 4-6 shows that there are differences between the capacities of the repaired beams and the control ones. This demonstrates that usual repair process that occur to damaged beam has a significant result on the section and load bearing capacity. It also shows that the repair of cemetituous materials formed good materials for repair beam cracks.

Comparing the repaired beams with the control ones, it is clear that the repair process restored the bearing capacity of the section when tested after 1 week after the application of the repair material, except for the beams which were repaired by OPC yielded very close results compared to the control beam.

The beams, which were repaired by UHPC achieved flexural strengths 8% larger than those of the control beams. In addition, beams that were repaired by UHPFRC developed flexural strength 19 % larger than those of the control beams. On other hand, beams repaired by OPC had flexural strengths 3.17 % smaller than those of the control beams. Beams that were repaired by SRM developed flexural strength 11 % larger than those of the control beams.

Failure of all Beams did not occur in the repair zone but was a sudden explosive collapse in the compression zone of the beam with no apparent sign of reduced bond.

Table 4-6: Flexural capacity comparisons

Beam code	No. of beam	Load capacity (KN)	Average load (KN)	Percentage of Improvement over the control beam
Control beams C.B	C.B 1	62.0	63.0	-
	C.B 2	63.0		
	C.B 3	65.0		
Cracked beams repaired by UHPC	UHPC 1	67.5	68.0	7.94 %
	UHPC 2	68.8		
	UHPC 3	67.3		
Cracked beams repaired by UHPFRC	UHPFRC 1	77.0	75.0	19 %
	UHPFRC 2	76.0		
	UHPFRC 3	72		
Cracked beams repaired by OPC	OPC 1	60.0	61.0	-3.17 %
	OPC 2	60.5		
	OPC 3	62.0		
Cracked beams repaired by SRM	RM 1	69.0	70.0	11 %
	RM 2	71.0		
	RM 3	70.5		

4.4.2. Mid-Span deflections:

The deflections at mid-span were recorded and plotted against the load as shown in *Figure* 4-18. Given that deflection is related to stiffness, it can be stated that the process of repair has a major effect on stiffness. But it can be noticed that lower deflections were recorded for the repaired beams when compared with the control ones. The repair material was applied at the area of highest bending moment, which has got the bending reinforcement overlapped. Given that the original cracked, concrete was defined prior to repair, the decrease in deflection of repaired beams shows that the repair process develop full anchorage between reinforcement bars.

The repaired beams on the other hand showed four broad categories. The first is beams repaired by UHPC which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, while decrease deflection of about 73% from the control beam (See Table 4-7). The second is beams repaired by UHPFRC that exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, while decreases the deflection of about 51% from control beam. The third is beams repaired by OPC which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, while semi deflection value of control beam. The fourth is beams repaired by SRM, which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, while decreases the deflection of about 63% from control beam.

The curves in *Figure* 4-18 on the other hand can easily establish the four stages including the plastic one. This enhanced flexible behavior may be attributed to the lower modulus of elasticity of the repair material used.

Table 4-7: Mid-span comparisons

Load (KN)	Deflection (mm) of control beam (C.B)	Deflection (mm) of Repaired beam by			
		UHPC	UHPFRC	OPC	SRM
4.5	1.6	1.2	0.83	1.5	1
9	2.4	1.8	1.25	2.3	1.5
13.5	3.1	2.325	1.6	2.9	2
18	3.7	2.775	1.9	3.5	2.3
22.5	4.2	3.15	2.2	4	2.6
27	4.7	3.525	2.5	4.5	3
31.5	5.1	3.825	2.6	4.8	3.2
36	5.6	4.2	3	5.3	3.5
40.5	6	4.5	3.1	5.7	3.8
45	6.5	4.875	3.4	6.2	4.1
49.5	7	5.25	3.6	6.6	4.4
54	7.4	5.55	3.8	7	4.6
58.5	7.9	5.925	4.1	7.5	5
63	8.6	6.45	4.5	8.2	5.4
67.5	---	6.90	5.05	---	5.95
72	---	---	5.5	---	---
75	---	---	6.15	---	---

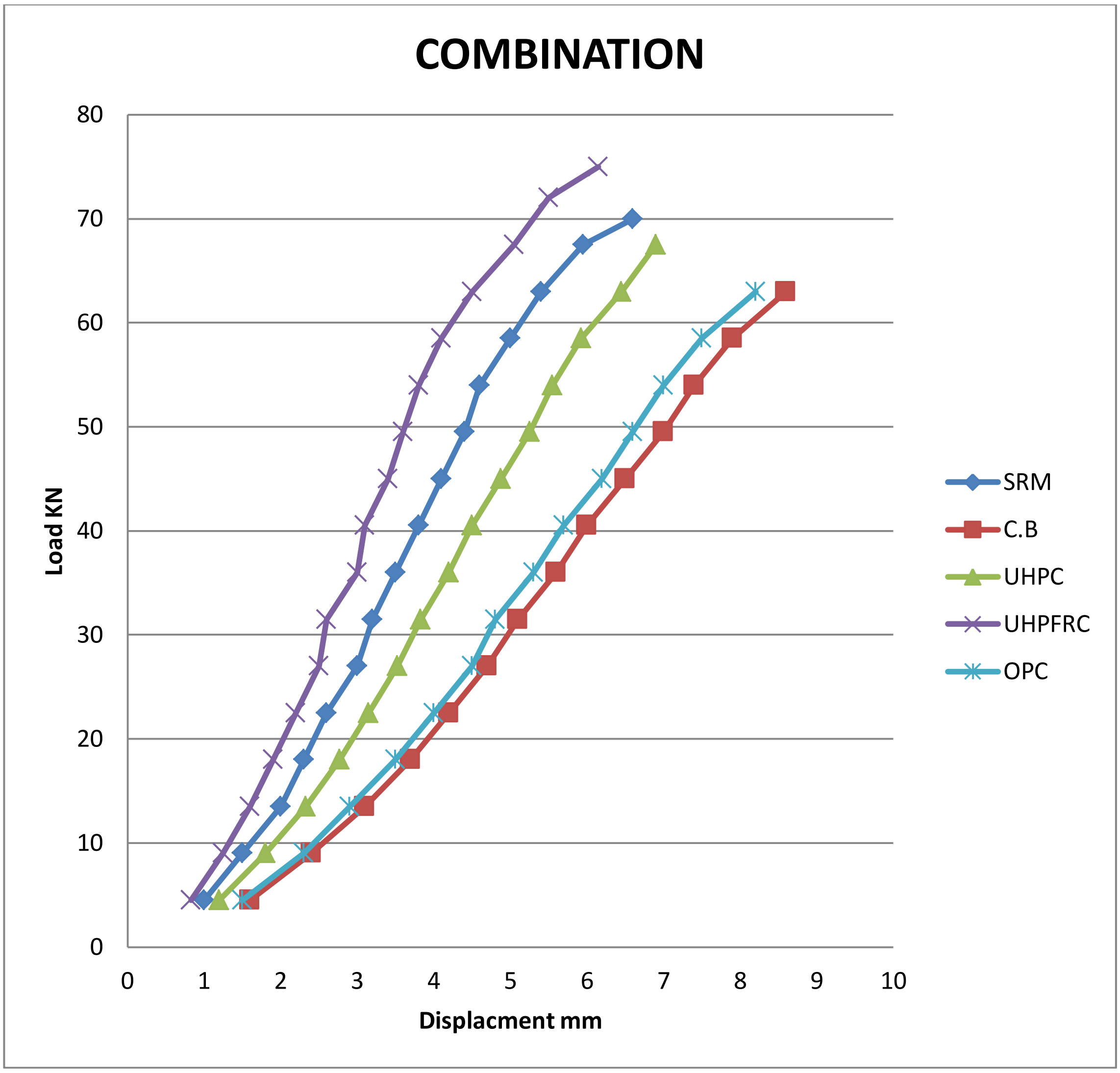


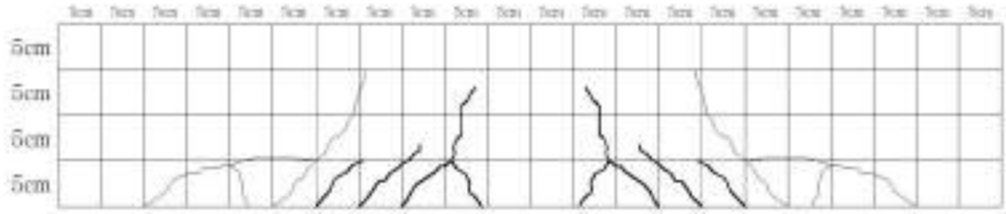
Figure 4-18: Load - Deflection Relationship

4.4.3. Crack patterns:

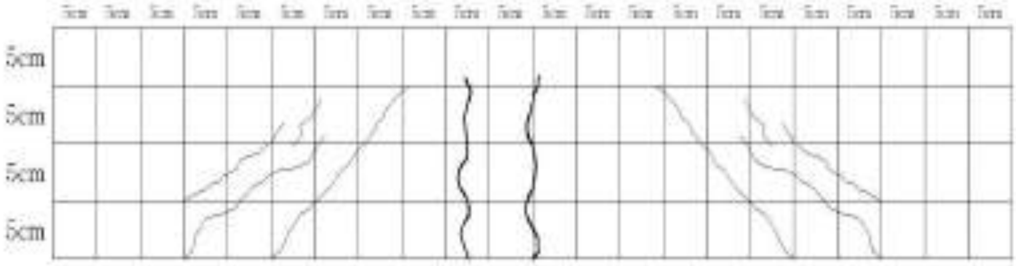
The control beams displayed a crack pattern as shown in Figure 4-19. At low loads, flexural cracks appeared and propagated at the bottom of the beam within the middle third of the span. As the load was increased, shear cracks also began to develop between the loading points. The increased shear force pushed down on the longitudinal steel and links, and causes the destruction of the bond between concrete and steel. The hooks at the end caused the beams to behave as a two-hinged arch until the internal stresses destroyed the surrounding concrete. However, the presence of laps within the test beams prevented this stage developing fully as the bars, once stripped of their bond, deflect downward restrained only by the links and, ultimately, break off the surrounding concrete. Thus, cracks are clearly visible on the underside of the beam, following the position of the steel.

The repaired beams followed a semi similar cracking pattern, although within the repair material only nominal cracks were observed. The main cracks were concentrated within the concrete at areas of high bending moment either side of the repair. Failure was again due to the breakdown of the bond between the steel and concrete on compression zone. The reduced cracking in the repaired zone implies that this section suffered less straining than the adjacent concrete may be due to lack of perfect bond between the repair material and host concrete.

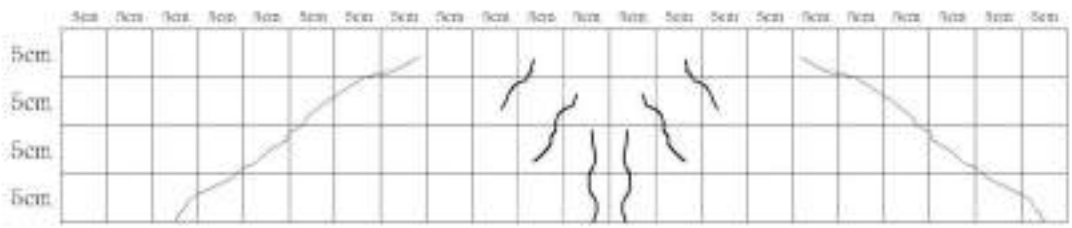
Improvement of crack pattern for beams repaired by UHPFRC and SRM that refer to good bonding between the repair materials and old concrete. The crack pattern of beams repaired by OPC and UHPC are similar cracking pattern of control beam that refers to less bonding between these materials and old concrete.



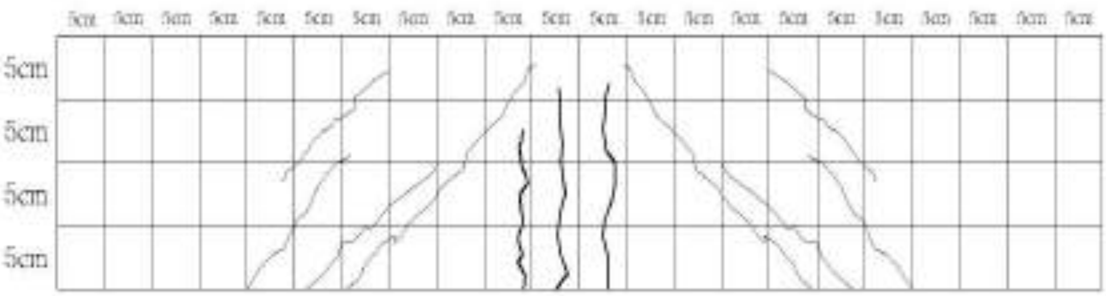
Crack pattern of control beams



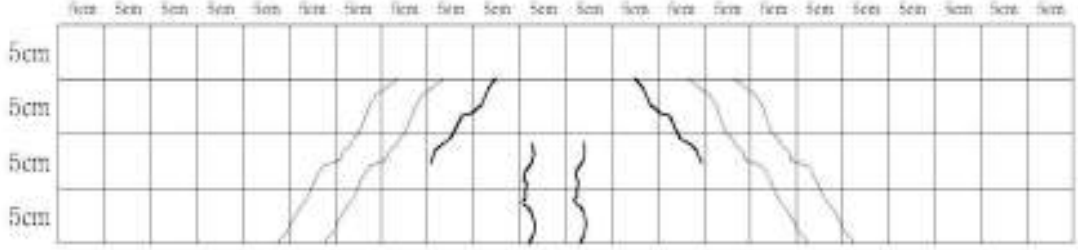
Crack pattern of UHPC beams



Crack pattern of UHPFRC beams



Crack pattern of OPC beams



Crack pattern of SRM beams

Figure 4-19: Crack pattern comparisons

CHAPTER 5 REPAIR OF HONEYCOMBED BEAMS

5.1. Introduction:

Reinforced concrete is a combination of concrete (cement and aggregates) and reinforcing steel. The cement mortar portion of this composite material (approx 25% of the concrete) acts as a paste or glue that binds aggregates together. When properly designed and placed these three materials create a unique composite that can be cast into thousands of different infrastructure applications. In order to have a reinforced concrete beam, column, slab or wall function properly, the concrete must be properly consolidated in the forms, i.e. it must completely encapsulate the reinforcement and be free of voids or "honeycombs". Voids are completely empty or hollow spaces in the form in which no concrete exists. Honeycombs based on a Portland Cement Association definition, are voids left in concrete due to failure of the cement mortar to effectively fill all the spaces between the coarse aggregate particles. Severe honeycombs (sometimes known as rock pockets) occur when an excessive amount of aggregate is found without the presence of cement paste. (See Figure 5-1).

Figure 5-1: Honeycomb in a column due to excessive lift depth

5.2. Causes of honeycomb:

Primary causes of voids or honeycombs in reinforced concrete:

- Rebar Congestion: if rebar is placed too close together or too close to formwork it will trap the larger pieces of aggregate while the mortar in the mixture may or may not pass through. Other causes related to rebar congestion include excessive reinforcement splices that prevent the concrete from properly filling the forms.

- Mix Design: Improper mix design can lead to low workability, early stiffening or an aggregate that is too large to properly consolidate the concrete for a given application. A good mix design should take in consideration the issues noted for rebar congestion and lift depth.

- Lift Depth: When single concrete placements or "lifts" are too deep, proper vibration can become very difficult or impossible. Excessive lift depths can also allow too much free-fall of the concrete that can create a separation of the cement mortar and aggregate as the aggregate impacts the reinforcing steel when falling through the forms.

- Inadequate Vibration: When the concrete is properly vibrated it acts more like a liquid allowing it to better settle in the form, consolidate around the reinforcement and completely fill the forms. It also helps in releasing any of the air voids in the mix to the surface. Improper vibration can be related to:
  - Too small or large a vibrator for the size of the pour and mix design.
  - Too low a frequency or amplitude of the vibrator for the size of the pour and mix design.
  - Too short or long an insertion time of the vibrator in the concrete in a single location.
  - Too wide of a spacing between each insertion of the vibrator.
  - Lift depths too deep to actually vibrate the concrete.
  - Congested reinforcing that will not allow a standard vibrator to reach all areas required.

- Form Leaks: Leaks in the formwork can allow the cement paste to escape out of the form leaving behind only unbounded aggregate and rock pockets.

5.3. Prevention of honeycomb:

Preventing honeycomb and voids start with attention to concrete mix proportions. Proper techniques for forming, rebar placement, and concrete placement are important.

5.3.1. Concrete preparation:

- Provide enough paste: Concrete not containing enough cementitious material and fine sand will be prone to segregation and won't flow well. Consider adding a blend sand or additional Portland cement or fly ash to increase the amount of fines. Increasing the ratio of fine-to-coarse aggregate will increase workability only if 5% to 10% of the sand passes the No. 100 sieve.

- Increase slump: Even with the correct amount of paste, a mix can lack workability and will not flow into place. To improve flow, increase slump to 15 to 20 cm by adding a water reducer or super plasticizer.

- Reduce aggregate size: If closely spaced reinforcement or other obstacles hinder concrete flow, consider reducing coarse aggregate size below the maximum allowed by ACI 318-08, "Building Code Requirements for Structural Concrete." Such a change requires an overall review of mix proportions.

- Control setting rate: Slow placement rates and high ambient and concrete temperatures can cause concrete to stiffen, reducing its flow ability. Adding a retarder may help, but retarders do not necessarily prevent slump loss.

5.3.2. Forming and rebar placement:

- Review reinforcement details: Closely spaced rebar, insufficient clearance between the rebar and forms, and closely spaced lap splices all interfere with concrete flow and vibration. Work with the steel detailer to minimize these problems.

- Provide access to forms: Narrow or tall forms prevent observation and access during concrete placement. Consider reducing lift heights or using flexible tremiehose. You may have to cut placing ports into forms containing heavily reinforced sections.

- Build tight form joints: Mortar loss through form joints may cause honeycomb, particularly with wetter mixes. Tighten or tape form joints as necessary.

5.3.3. Concrete placement:

- Vibrate properly: Workers must be trained to vibrate concrete correctly to ensure that it flows around reinforcing steel, embedments, and blockouts.

- Ensure flow under blockouts: Build up a head of concrete on one side of small blockouts, and vibrate the concrete until it appears on the other side. Large blockouts require concrete to flow many feet laterally, so may need to use pour pockets beneath these blockouts. Drill holes in the bottom of a blockout to allow displaced air to escape.

- Avoid delays: If the placement is not going as fast as planned, ready mix trucks may have to wait before discharging material and the concrete will start to stiffen. You can reduce stiffening by using retarding admixtures, but a better approach is to alert the concrete producer when unavoidable placing delays occur.

5.4. Repair Process:

There are several factors to consider when repairing honeycombs and voids:

- Honeycomb size and depth.
- Access to the repair area.
- Rebar details and congestion within the repair area.
- Quality assurance (how do you determine actual honeycomb size and prove the problem is fixed).
- Costs from a "repair or replace?" perspective ... which is more cost effective?

These critical items will clearly define the following key steps and sequential order of repairing the honeycomb, which are:

1. Define the size of the repairs.
2. Define the depth of the repairs.
3. Is shoring required?
4. Select the type of removal.
5. Select the material for repairs.
6. Select the proper placement technique of this material to ensure filling of the honeycomb and create a composite bond with the substrate.

5.4.1. Defining the size and depth:

The actual repair process starts with defining the removal geometry - i.e. size and depth of the area requiring repair. Methods used can include chipping, sounding and Non Destructive Testing (NDT) such as Impulse Response or Pulse Echo testing. These tests measure response times or frequency of a wave or impulse though a concrete section. If a void exists, the wave or travel time is of course greatly affected. In many cases the area of repair is going to be larger than what is noticeable to the eye from the surface of the concrete. This difference is based on several items:

- The presence of unseen honeycomb.
- The concrete materials around the honeycomb may not be sound and typically must be removed deep enough to reach a sound substrate.
- The final repair shape is normally larger than the rough shape of the actual honeycomb. Per ACI repair specifications the final surface shape should be rectilinear in shape vs the rough, multi-shaped honeycomb left after removal of unsound concrete. Rectilinear can be defined as a combined series of rectangular and/or square shapes.
- Additional removal requirements, in relation the depth of the repair, must be considered. Typical repair specifications call for a uniform depth throughout the repair area and where there is any exposed reinforcing steel (50% of the bar exposed), the concrete should be removed at a minimum of 2 cm behind the bar.

Careful thought must be given to the size, depth and location of the honeycomb as removal may affect the structural capacity of the element being repaired. If enough material is missing or is being removed from critical sections of a beam or slab, shoring should be installed when the honeycomb is detected or prior to removal. This is especially true with gravity elements such as columns. For example, any chipping or removal on a column inside the structural core (any section inside the horizontal rebar ties) will dramatically affect the load carrying capacity. As a rule of thumb, it is better to err on the side of safety and shore the element.

5.4.2. Removal Techniques:

Removal of the unsound material can be accomplished using hydro demolition techniques, or typically with 15# chipping hammers. Why use such a small hammer? When using anything greater than a 30# chipping hammer, the impact forces of the bit will micro fracture the substrate and damage it. Also in may cases due to the concentration of rebar in the void, a smaller hammer is easier to accomplish the "dental" like removal without breaking the bond of the concrete around the rebar outside the repair area. Chipping is done until a uniform depth and shape is achieved and a "Fractured Aggregate Profile" is present in the substrate. This chipping profile is achieved when the aggregate in the concrete is sound and so well bonded that it will shear in half while being chipped with a 15# hammer. At this point it is clear that the substrate is sound as the cement paste is well bonded to the aggregate. This is a typical gauge to determine when sound substrate has been reached.

Hydro demolition on the other hand utilizes water pressure up to 50,000 psi to literally explode the cement in order to remove it. This is advantageous in situations where the concentration of rebar is so high that it is impossible to remove the concrete with a chipping gun. It also requires a water collection process due to the volumes of water required which can be difficult in some environments.

The last step of surface preparation requires that the concrete substrate has an "open pore structure". During chipping or Hydro demolition, the pores of the concrete have been impacted and filled with concrete dust and slurry. Removing this is imperative as the bond between the repair material and substrate can only be achieved by forcing the repair material into these pores. The concrete can be properly prepared by abrasive blasting or high pressure water after demolition.

5.4.3. Repair Materials and placement techniques:

Now that the size and depth of the repairs are known, the next step is to determine the optimum repair material and the best technique for placing it into the honeycomb. For most honeycomb and voids repairs, the Form and Pump Technique is the best choice to fill the repair area and ensure a good bond to the existing concrete. Form & Pump, as the name suggests, pumps the repair material into a closed form. This guarantees two key requirements noted above. One is making certain that the repair material has entirely filled the formwork and is consolidated around all rebar. The second relates to the fact that once the form is full and all air voids removed, it is pressurized. This assures that the repair material has been literally driven into the open pores of the existing prepared concrete. This will achieve a bond sufficient to make the two materials act as one. Use of vent tubes and bleed locations in a Form & Pump repair operation are important in order to make sure that material is reaching all the sections of the repair area. Selection of repair material must consider the required flow ability and aggregate size for void size, shape and rebar clearances. For smaller, more minor honeycombs or voids, a Form and Cast in Place placement technique and vibration may be an option for a repair method.

5.5. Control beam testing:

Control beam samples are tested under 4-point load and increasing the load slowly until failure to get the flexural capacity of section, crack pattern, and deflection. The average load obtained from the three tested samples is 6.30 ton. This value is very close to the theoretical value of the section is 6.24 ton. The experimental results, together with the specimen geometries, are reported in Figure 5-3 and Table 5-1.

Crack pattern were taken and drawn to make a comparison with those of the repaired beams (see Figure 5-2).

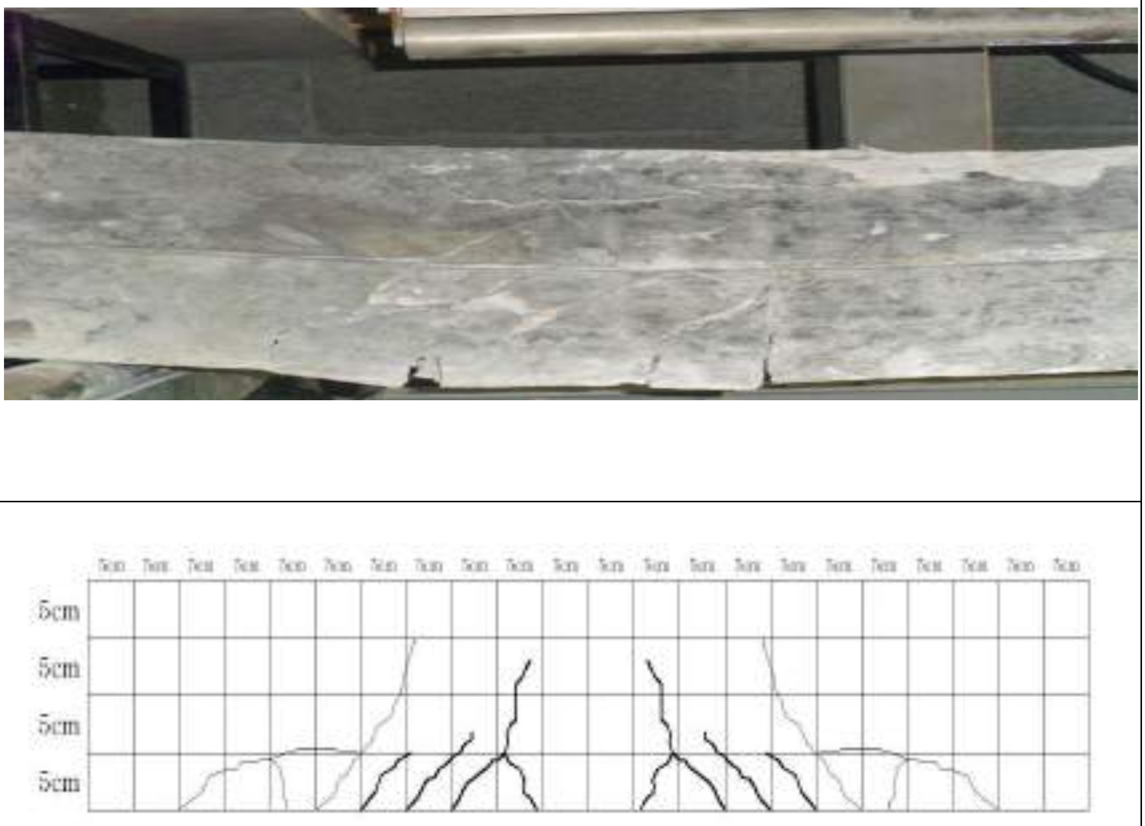


Figure 5-2: Crack pattern of control beams

Table 5-1: Control Beam Deflections

load (KN)	Deflection (mm)
4.5	1.6
9	2.4
13.5	3.1
18	3.7
22.5	4.2
27	4.7
31.5	5.1
36	5.6
40.5	6
45	6.5
49.5	7
54	7.4
58.5	7.9
63	8.6

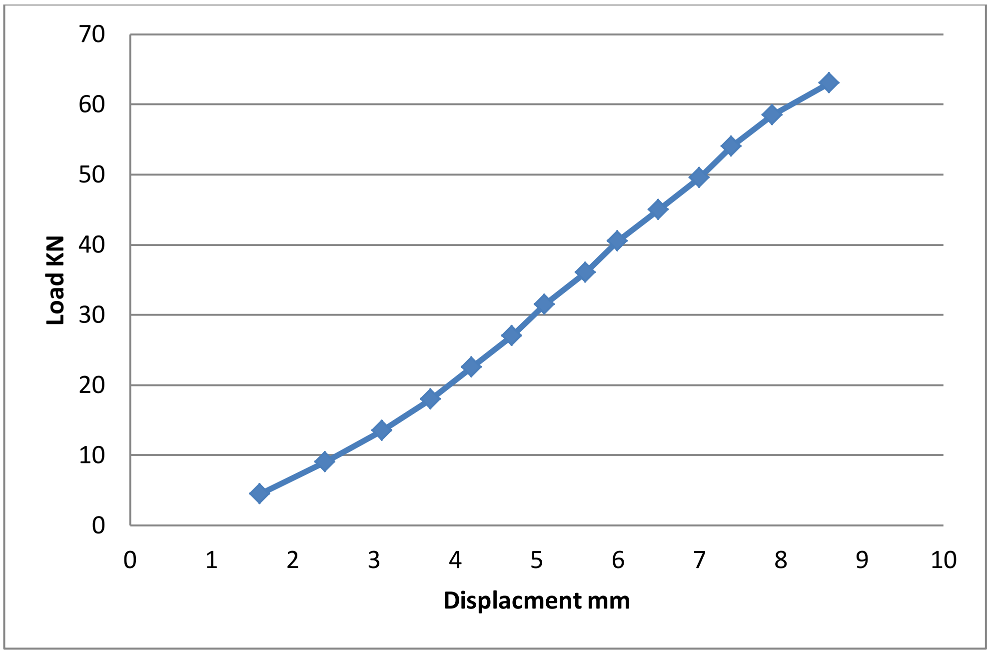


Figure 5-3: Mid-span Displacement

5.6. Testing of Repaired Honeycombed Beams:

Before start the repairing technique on RC beams, we prepare and cast samples with missing part of concrete at the middle of the span on the tension side of the beam, to simulate the honeycomb. They steps are summarized below:

1st Cast the samples and cure them for 28 days.

2nd Clean the samples after curing time to be ready for applying a cementiouion material, as shown in Figure 5-4:

Figure 5-4: Cleaning the honeycomb hamples

3rd Chip the honeycomb area to make a good bond with the repair material. This step appears in Figure 5-5:

Figure 5-5: Hand Blasting Honeycomb Area

4th Wash the samples after chipping process to clean the sample from any loose aggregate see Figure 5-6.

Figure 5-6: chipping the sample by water

5th Prepare the samples to receive the four cementious repair materials.

5.6.1. Repair of Honeycombed beams using UHPC:

6th Prepare the required amount of UHPC, see Figure 5-7.

Figure 5-7: Applying UHPC matrix on Honeycombed beams

7th Cure the samples after applying the UHPC matrix for 7 days.

8th Test the samples and record the results including, flexural capacity, crack pattern, and deflection. See Figure 5-8:

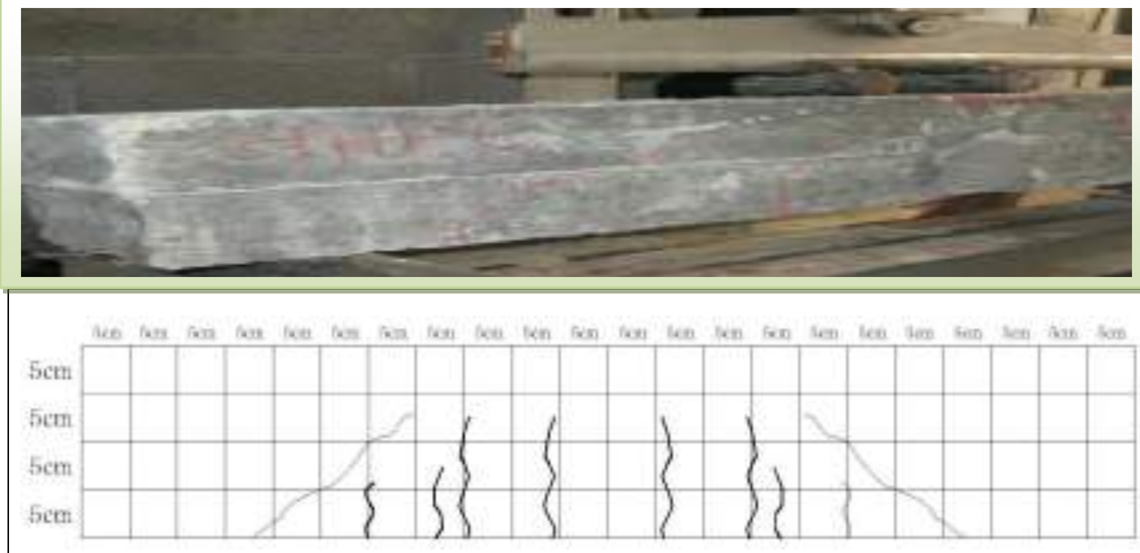


Figure 5-8: Honeycombed beam repaired, and its crack pattern

Beams repaired by UHPC were tested under 4-point load and increasing the load slowly until failure to get the maximum capacity of the section, crack pattern, and deflection. The average value obtained from three tested samples is 7.50 ton, and the deflection values are recorded in Table 5-2 and Figure 5-9.

Table 5-2: deflection of repaired beams by UHPC

Load (KN)	Deflection (mm)
4.5	1.35
9	2.4
13.5	2.6
18	3.2
22.5	3.6
27	4
31.5	4.4
36	4.8
40.5	5.2
45	5.6
49.5	6
54	6.4
58.5	6.8
63	7.4
67.5	7.9
72	8.4
76.5	8.8

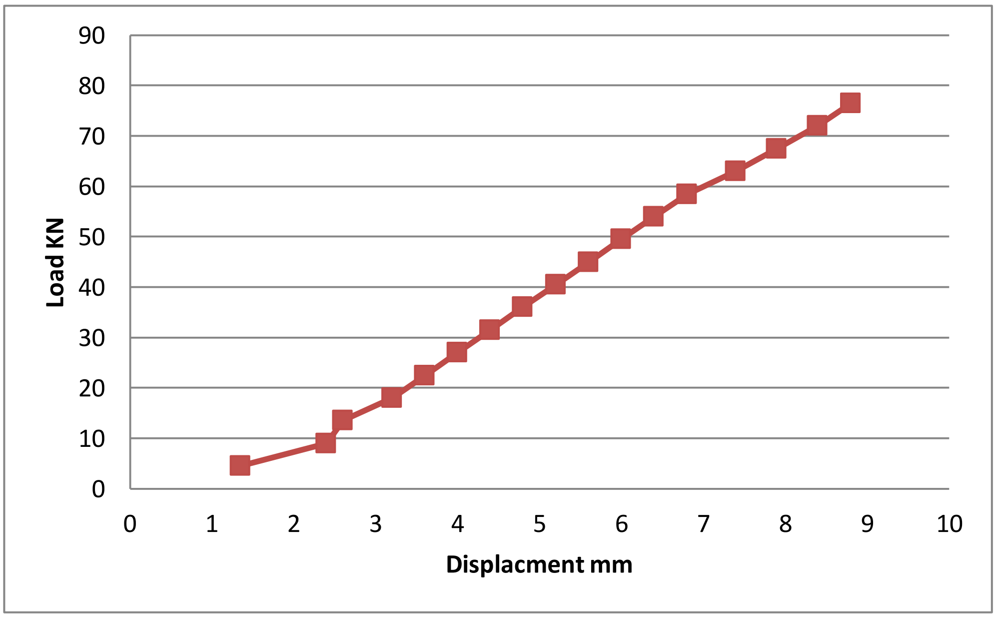


Figure 5-9: Displacement – load curve for honeycombed beams repaired by UHPC

5.6.2. Repair a Honeycombed beams using UHPFRC:

6th Prepare the required amount of UHPFRC, See Figure 5-10.

Figure 5-10: Applying UHPFRC matrix to Honeycombed beams

7th Cure the samples after applying the UHPFRC matrix for 7 days.

8th Test the sample repaired and record the results including, flexural capacity, crack pattern, and deflection. See Figure 5-11.

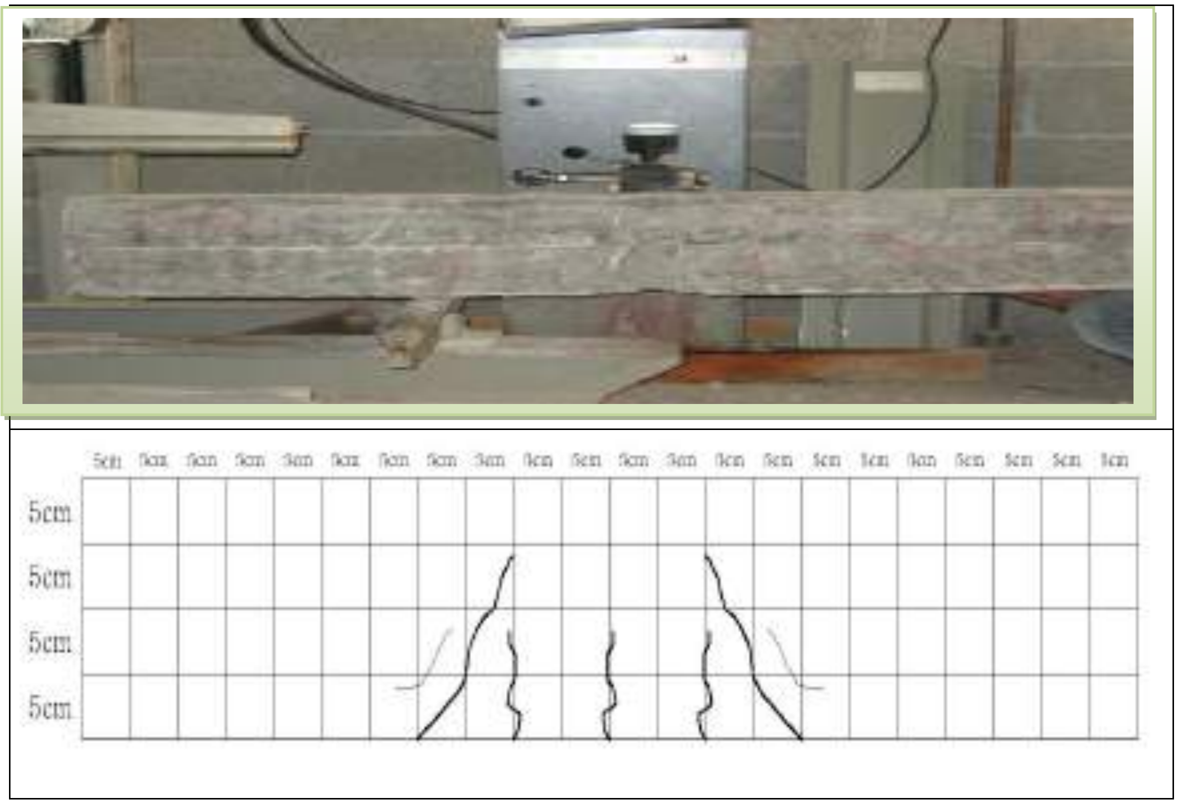


Figure 5-11: Honeycombed beams repaired, and its crack pattern

Honeycombed beam repaired using UHPFRC were tested under 4-point load by increasing the load slowly until failure to get the maximum capacity of section, crack pattern, and deflection. The average load of testing three samples is 8.20 ton, and the deflection values are recorded in Table 5-3 and Figure 5-12.

Table 5-3: UHPFRC Deflection

Load (KN)	Deflection (mm)
4.5	1.05
9	1.5
13.5	2
18	2.5
22.5	2.7
27	3
31.5	3.3
36	3.6
40.5	4
45	4.2
49.5	4.6
54	4.9
58.5	5.2
63	6.1
67.5	6.7
72	7.2
76.5	7.9
81	8.4

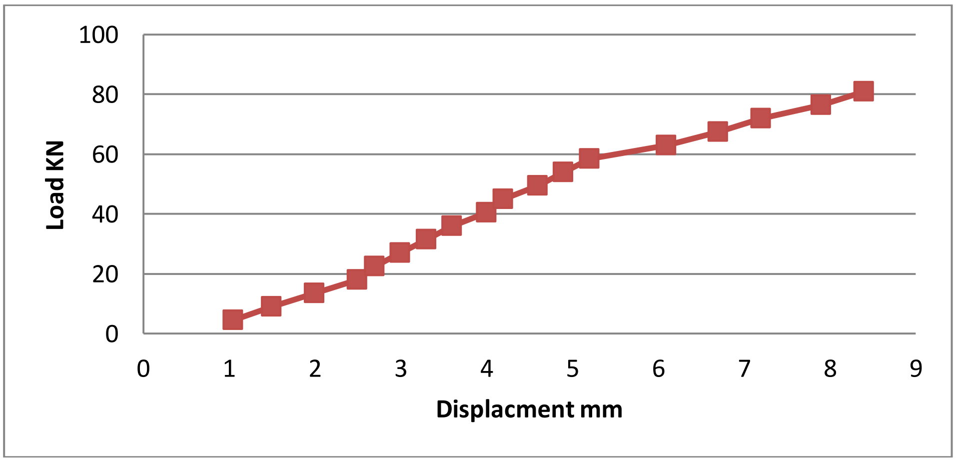


Figure 5-12: Displacement – load curve for honeycombed beams repaired by UHPFRC

5.6.3. Repair of Honeycombed beams using OPC:

6th Prepare the required amount of OPC, See Figure 5-13.

Figure 5-13: Applying OPC matrix on honeycombed beams

7th Cure the samples after applying the OPC matrix for 7 days.

8th Test the samples repaired and record the results including, flexural capacity, crack pattern, and deflection. See Figure 5-14.

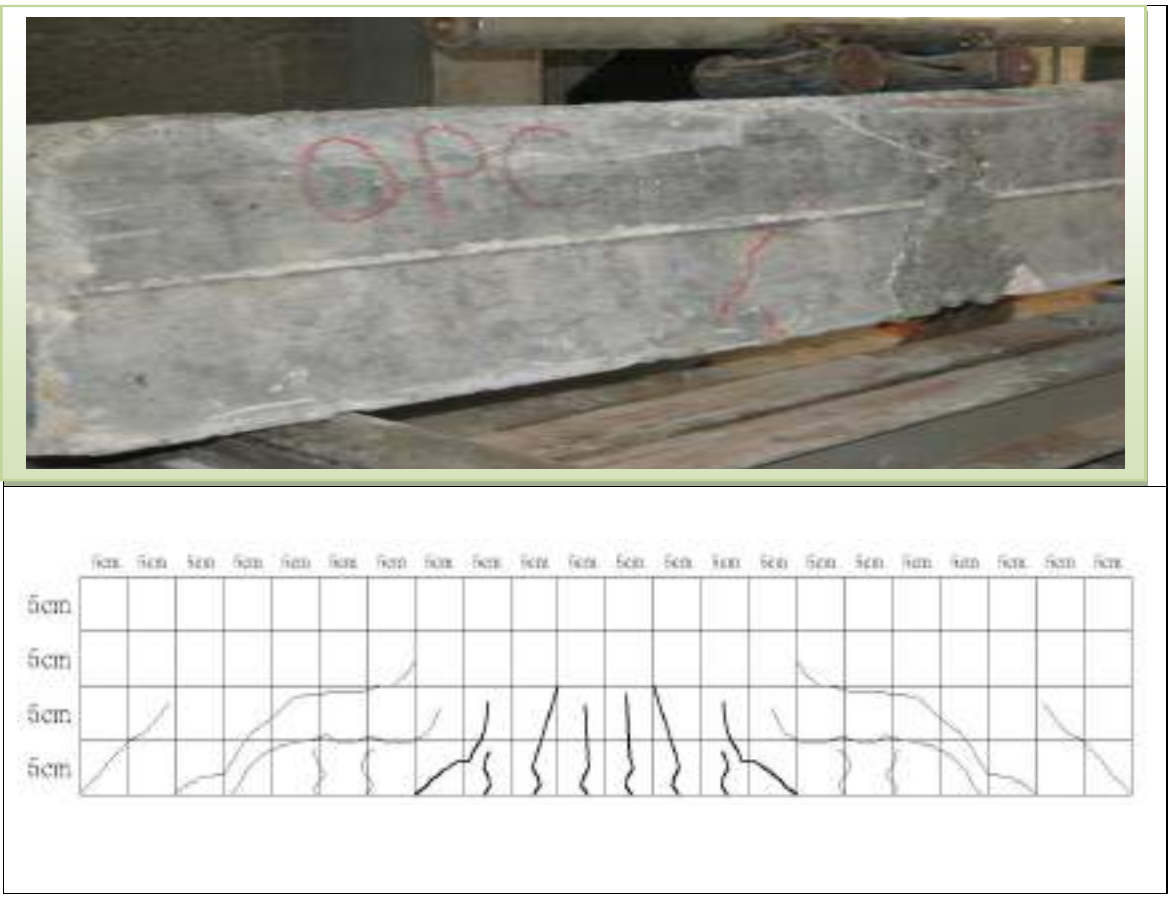


Figure 5-14: Honeycomb beam repaired by OPC tested, and its crack pattern

Honeycomb beams repaired using OPC were tested under 4-point load by increasing the load slowly until failure to get the maximum capacity of section, crack pattern, and deflection. The average load of testing three samples is 6.45 ton, and the deflection values are recorded in Table 5-4 and Figure 5-15.

Table 5-4: OPC Deflection

Load (KN)	Deflection (mm)
4.5	1.65
9	2.5
13.5	3.2
18	3.85
22.5	4.35
27	4.85
31.5	5.3
36	5.8
40.5	6.2
45	6.7
49.5	7.2
54	7.65
58.5	8.15
63	8.9

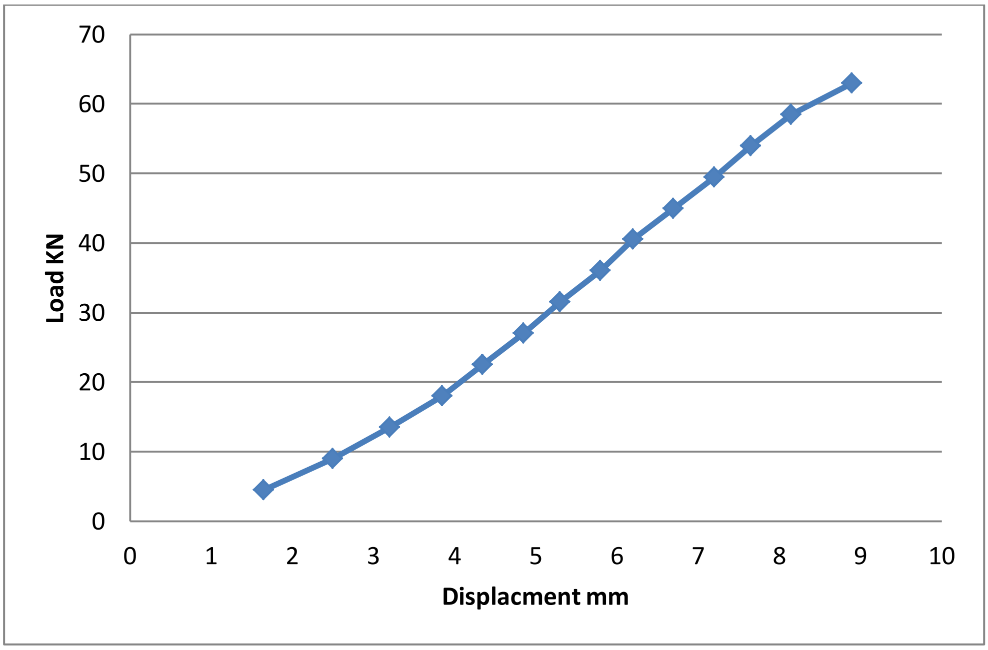


Figure 5-15: Displacement – load curve for Honeycombed beam repaired by OPC

5.6.4. Repair of Honeycombed beams using Special Repair Material:

6th Prepare the required amount of SRM, See Figure 5-16.

Figure 5-16: Applying RM matrix on Honeycombed beam

7th Cure the samples after applying the RM matrix for 7 days.

8th Test the samples repaired using RM and record the results, bearing capacity, crack pattern, and deflection. See Figure 5-17.

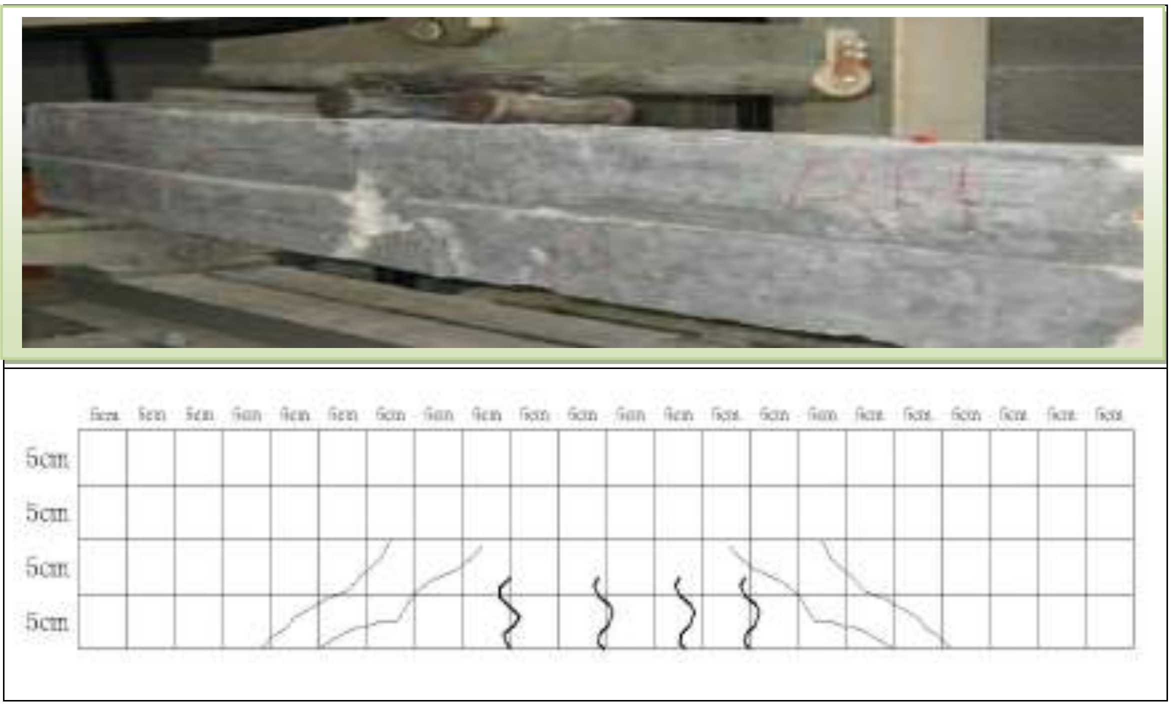


Figure 5-17: Honeycomb beams repaired by SRM tested, and its crack pattern

Honeycomb beams repaired using SRM were tested under 4-point load by increasing the load slowly until failure to get the maximum capacity of section, crack pattern, and deflection. The average load of testing three samples is 8.00 ton, and the deflection values are recorded in Table 5-5 and Figure 5-18.

Table 5-5: RM Deflection

Load (KN)	Deflection (mm)
4.5	0.95
9	1.45
13.5	1.9
18	2.25
22.5	2.55
27	2.85
31.5	3.1
36	3.4
40.5	3.65
45	3.95
49.5	4.3
54	4.8
58.5	5.45
63	5.25
67.5	5.55
72	5.9
76.5	6.90
81	8.3

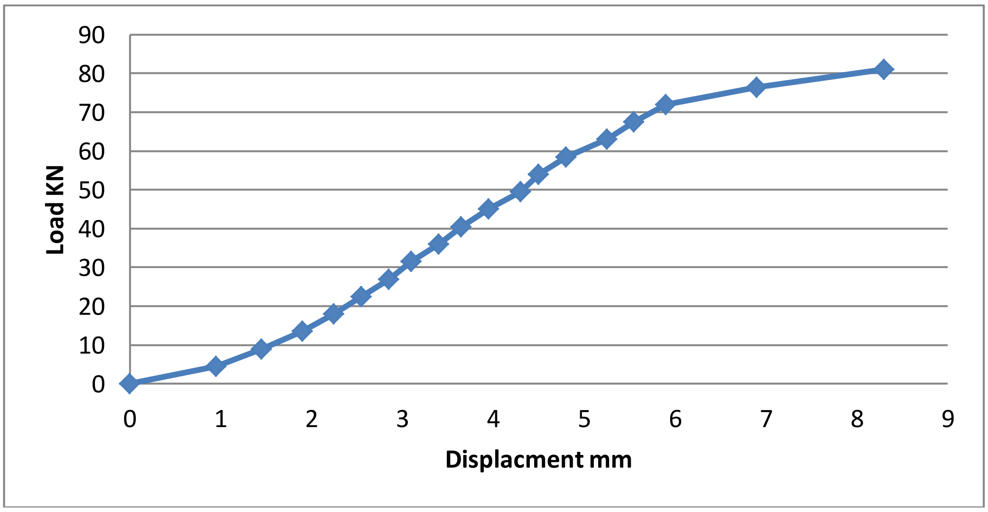


Figure 5-18: Displacement – load curve for Honeycombed beams repaired by SRM

5.7. Results and Discussion:

In the following subsections the results are elaborately discussed.

5.7.1. Flexural capacity:

Table 5-6 shows that there is a significant difference between the repaired beams and the control beams. This demonstrates that repair process has a significant impact on the results of the section and load bearing capacity. It also shows that the repaired cemetituous materials thus formed a good material for repair beam honeycomb.

Comparing the repaired beams with the control ones, it is clear that the repair process developed the flexural capacity of the section when tested 1 week after the application of the repair material, except for the beams repaired by OPC, the outcome very close to the control beam.

This shows that there is difference between the outcome results of used repair materials. The beams which were repaired by UHPC developed the flexure capacity of the section about 19%, beams was repaired by UHPFRC develop the bearing capacity about 30%, beams was repaired by OPC its results is closed to control beam with improvement about 1.5%, and beams was repaired by SRM develop the bearing capacity about 27% as shown in Table 5-6. Noted that the outcome results of beams repaired by UHPFRC and SRM, are almost closed together.

The significant improvement in flexural capacity of the section that occur, due to good bonding between the repair materials was used and steel reinforcement of it.

The failure of all beams did not occur in the repair zone but was a sudden explosive collapse in the compression zone of the beam with no apparent sign of reduced bond.

Table 5-6: Flexural capacity comparisons

Beam code	No. of beam	Bearing of Capacity (KN)	Average Bearing (KN)	Percentage of Improvement over the control beam
Control beam (C.B)	C.B 1	62		
	C.B 2	63	63	1
	C.B 3	65		
Honeycomb beam repaired by (UHPC)	UHPC 1	76		
	UHPC 2	77	75	1.19
	UHPC 3	73		
Honeycomb beam repaired by (UHPFRC)	UHPFRC 1	80		
	UHPFRC 2	81	82	1.30
	UHPFRC 3	85		
Honeycomb beam repaired by (OPC)	OPC 1	63		
	OPC 2	64	64	1.015
	OPC 3	65		
Honeycomb beam repaired by (RM)	RM 1	79		
	RM 2	81	80	1.27
	RM 3	80		

5.7.2. Mid Span Deflections:

The actual deflection at mid-span was measured and plotted against the actual load, see Figure 5-19. Given that deflections are related to stiffness, it can be said that the process of repair has a major effect on stiffness. But it can be noticed that lower deflections are recorded for the repaired beams when compared with the control ones. The repair material was applied at the area of highest bending moment, which has got the bending reinforcement overlapped. Given that the honeycombed concrete was defined prior to repair, the decrease in deflection of repaired beams shows that the repair process developed full anchorage with the reinforcement bars.

The repaired beams on the other hand show four broad categories. The first is beams repaired by UHPC which exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with decrease in the deflection values of about 82.5% from the control beam see *Table* 5-7. The second is beams repaired by UHPFRC, which exhibited stiff behavior with low total deflection, and approximately linear load-deflection plots, with decrees deflection about 64% from the control beam see. The third is Beams repaired by OPC, which exhibited stiff behavior with low total deflection, and approximately linear load-deflection plots, with semi deflection of the control beam. The fourth is beams repaired by SRM, which exhibited stiff behavior with low total deflection, and approximately linear load-deflection plots, with decrees deflection about 61% from the control beam. Note that the deflection of beams repaired by UHPFRC and SRM, is very close in behavior.

The curves in *Figure* 5-19 can easily establish the four stages including the plastic one. This more flexible behavior may be due to the lower modulus of elasticity of the repair material used.

Table 5-7: Deflection Comparisons

Load (KN)	Deflection (mm) of control beam (C.B)	Deflection (mm) of beams repaired by			
		UHPC	UHPFRC	OPC	SRM
4.5	1.6	1.35	1.05	1.65	0.95
9	2.4	2.4	1.5	2.5	1.45
13.5	3.1	2.6	2	3.2	1.9
18	3.7	3.2	2.5	3.85	2.25
22.5	4.2	3.6	2.7	4.35	2.55
27	4.7	4	3	4.85	2.85
31.5	5.1	4.4	3.3	5.3	3.1
36	5.6	4.8	3.6	5.8	3.4
40.5	6	5.2	4	6.2	3.65
45	6.5	5.6	4.2	6.7	3.95
49.5	7	6	4.6	7.2	4.3
54	7.4	6.4	4.9	7.65	4.5
58.5	7.9	6.8	5.2	8.15	4.8
63	8.6	7.4	6.1	8.9	5.25
67.5	---	7.9	6.7	---	5.55
72	---	---	7.2	---	5.9
75	---	---	7.9	---	6.9
81	---	---	8.4	---	8.3

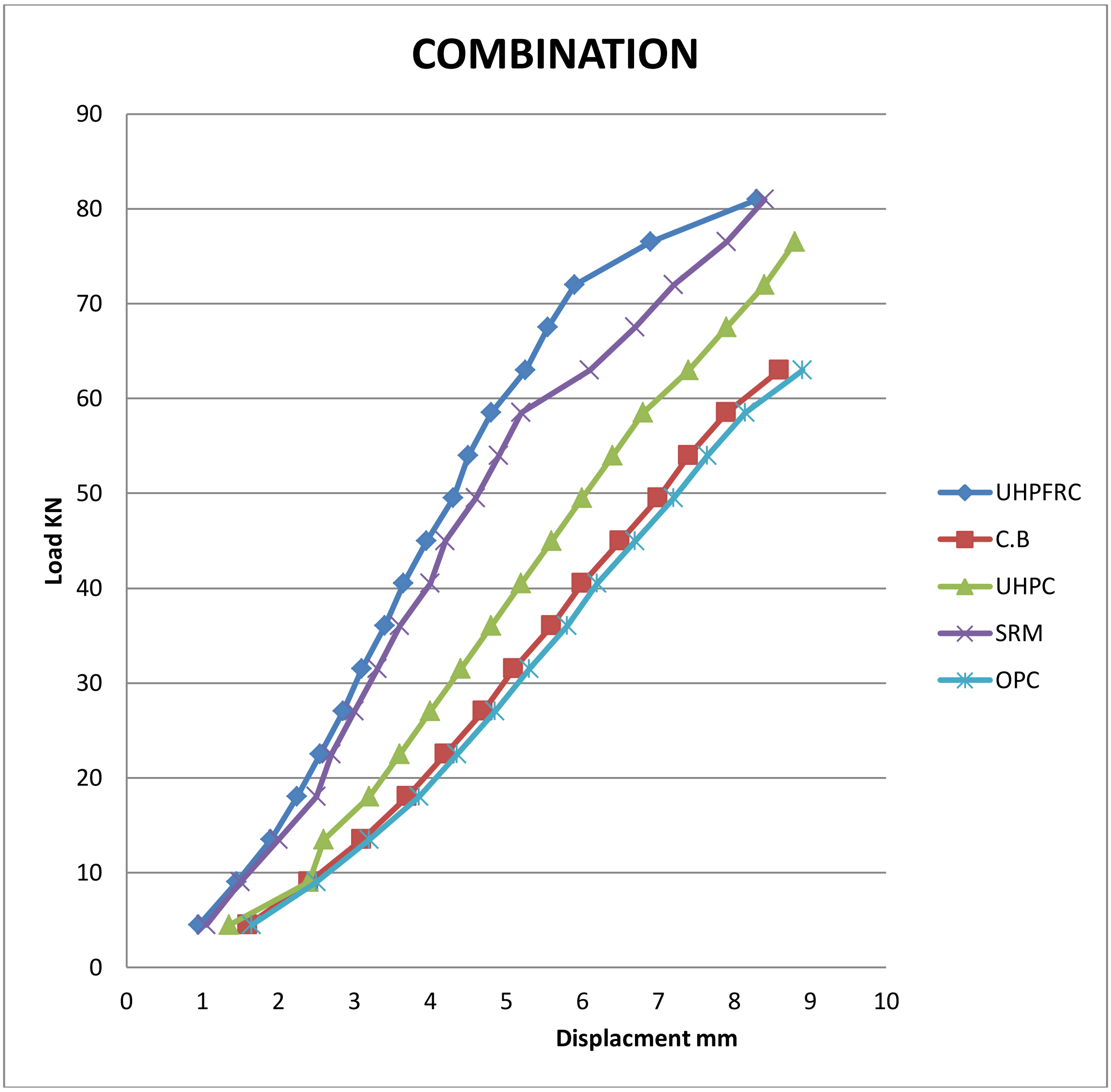


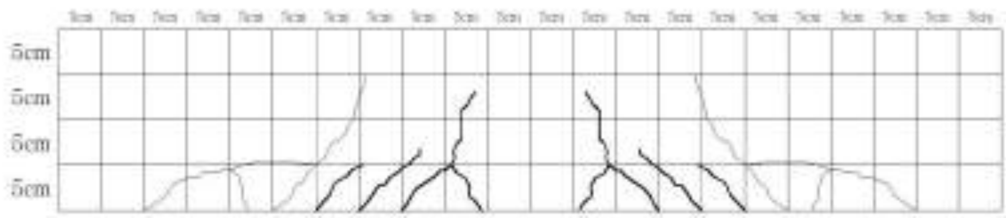
Figure 5-19: Load - deflection relationship

5.7.3. Crack patterns:

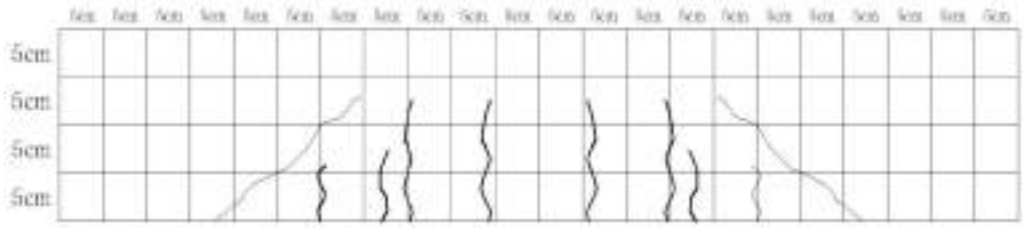
The control beams displayed the crack pattern as shown in Figure 5-20. At low loads, flexural cracks appeared and propagated at the bottom of the beam within the middle third area of the greatest moment. As the load was increased shear cracks also began to develop between the loading points. The increased shear force pushes down on the longitudinal steel and links, and causes the destruction of the bond between concrete and steel. The hooks at the end cause the beam to behave as a two hinged arch until the internal stresses destroy the surrounding concrete. However, the presence of laps within the test beams prevented this stage developing fully as the bars, once stripped of their bond, deflect downward restrained only by the links and, ultimately, break off the surrounding concrete. Thus, cracks are clearly visible on the underside of the beam, following the position of the steel.

The repaired beams followed a semi similar cracking pattern as shown in Figure 5-20 , although within the repair material only nominal cracks were observed. The main cracks were concentrated within the concrete at areas of high bending moment either side of the repair. Failure was again due to the breakdown of the bond between the steel and concrete on compression zone. The reduced cracking in the repaired zone implies that this section suffered less straining than the adjacent concrete may be due to lack of perfect bond between the repair material and host concrete.

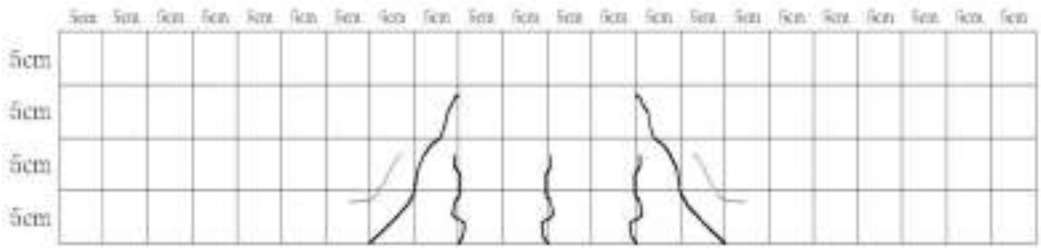
There is a significant improvement in crack patterns for beam repaired by UHPFRC and SRM which good bonding between the repair materials and the old concrete see Figure 5-20, while the crack patterns of beams repaired by OPC and UHPC are similar to cracking pattern of the control beam which shows less bonding between these materials and the old concrete.



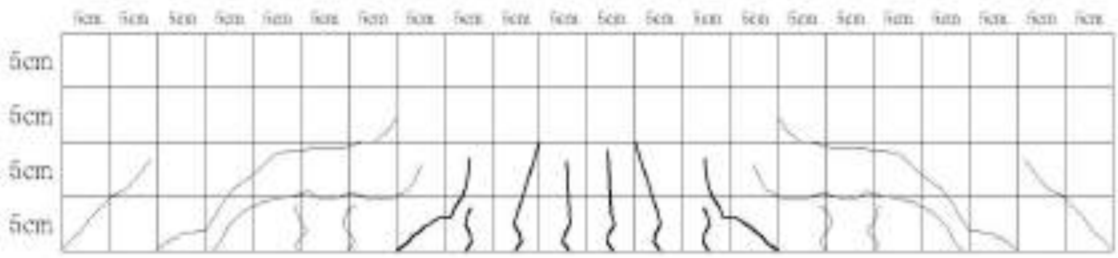
Crack pattern of control beams



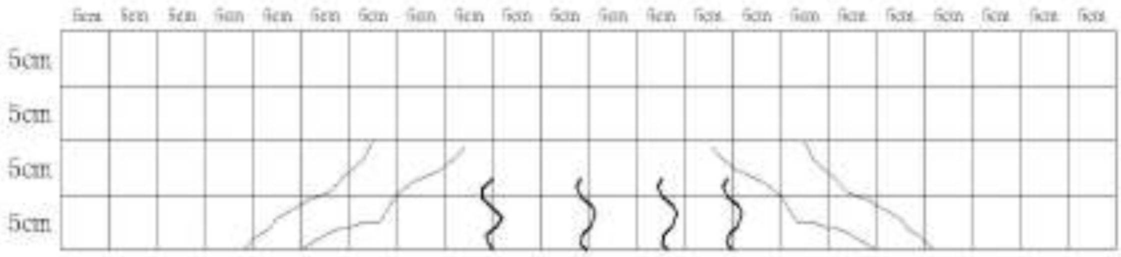
Crack pattern of UHPC beams



Crack pattern of UHPFRC beams



Crack pattern of OPC beams



Crack pattern of SRM beams

Figure 5-20: Crack pattern comparisons

CHAPTER 6 REPAIRED OF HEATED BEAMS

6.1. Introduction:

Concrete spalling is usually caused by corrosion of the steel reinforcement bars embedded in the concrete matrix, but can be caused by other ferrous elements either fully or partially embedded in the structure. Steel frame window systems, handrails, structural I-beams, metal pipes and conduits are among the most common of the damage causing building components. Corrosion of the reinforcement steel however, is by far the most common cause of spalling and splitting in older concrete structures.

Explosive spalling occurs when concrete is exposed to fire. It results in loss of section and reduction in the load bearing capacity. Although spalling has occurred frequently in buildings, it is the recent examples in tunnel fires that have highlighted the problem in the public's mind. Solving of the spalling problem is now a primary requirement in any new tunnel design. Generally explosive spalling is more likely the higher the rate of heating, the stronger the concrete, the higher the moisture level and the larger the imposed compressive load. It occurs during the first 7-20 minutes of a fire when the concrete temperatures are only in the region of 150-300C^{o}. In this case, the heating rate is a prime influence.

The most recent theories of the causes of explosive spalling indicate that two factors play a crucial role, namely, the buildup of (a) pore pressure and (b) thermal stresses in the concrete when exposed to a rapidly increasing temperature.

In this study the fire problem was simulate by exposing the beam samples for elevated temperature in an electric oven at 250 C^{o} for four hours.

6.2. Definition of Spalling:

Spallin, is defined as the violent or non-violent breaking off layers or pieces of concrete from the surface of a structural element when it is exposed to high and rapidly rising temperatures as experienced in fires. There are four types of spalling: explosive, surface, aggregate and corner spalling. The most important of these is explosive spalling, which occurs violently and results in serious loss of material.

6.3. Effect and consequence of explosive saplling:

Explosive spalling can take place as a single explosion or a series of explosions, each removing a thin layer of concrete ranging from 100 mm to 300 mm in length and 15mm to 20mm in depth, capable of causing physical damage on impact. In many cases, explosive spalling is restricted to the unreinforced part of the section and usually does not proceed beyond a reinforcing layer (e.g. mesh reinforcement in a slab, or a cage of bars and links in a beam or a column).

Explosive spalling may, however, result in a sudden and complete failure of the concrete member to sustain its load-bearing function because of significant loss of section. Explosive spalling can also blow holes in concrete partitions thus facilitating the spread of fire and undermining the partition's "integrity".

6.4. Factors Influencing Saplling:

BS 8110:Part 2:1985 states that "rapid rates of heating, large compressive stresses or high moisture contents (over 5% by volume or 2% to 3% by mass of dense concrete) can lead to spalling of concrete cover at elevated temperatures, particularly for thicknesses exceeding 40 mm to 50 mm."

In fact, a large number of factors influence explosive spalling of concrete. These are described as follows:

1. Heating rate.
2. Temperature level during the explosion.
3. Heating profile.
4. Section size.
5. Section shape.
6. Moisture content.
7. Water curing.
8. Pore pressures.
9. Permeability of the concrete and mean pore radius.
10. Concrete age.
11. Concrete strength, mix and quality.
12. Compressive stress and restraint.
13. Type of aggregate.
14. Aggregate size.
15. Thermal expansion.
16. Cracking.
17. Reinforcement.
18. Cover to reinforcement.
19. Supplementary reinforcement.
20. Steel fibres.
21. Polypropylene fibres.
22. Air-entrainment.

6.5. Control beam testing:

Control beam samples are tested under 4-point load and increasing the load slowly until failure to get the flexural capacity of section, crack pattern, and deflection. The average load obtained from the three tested samples after heating is 13.50 ton. This value is about 72% of the theoretical value of the section, which is 18.76 ton. The experimental results, together with the sample geometry, are reported in Table 6-1 and Figure 6-2. Crack patterns were taken and drawn to make a comparison with the repaired beams and shown in Figure 6-1.

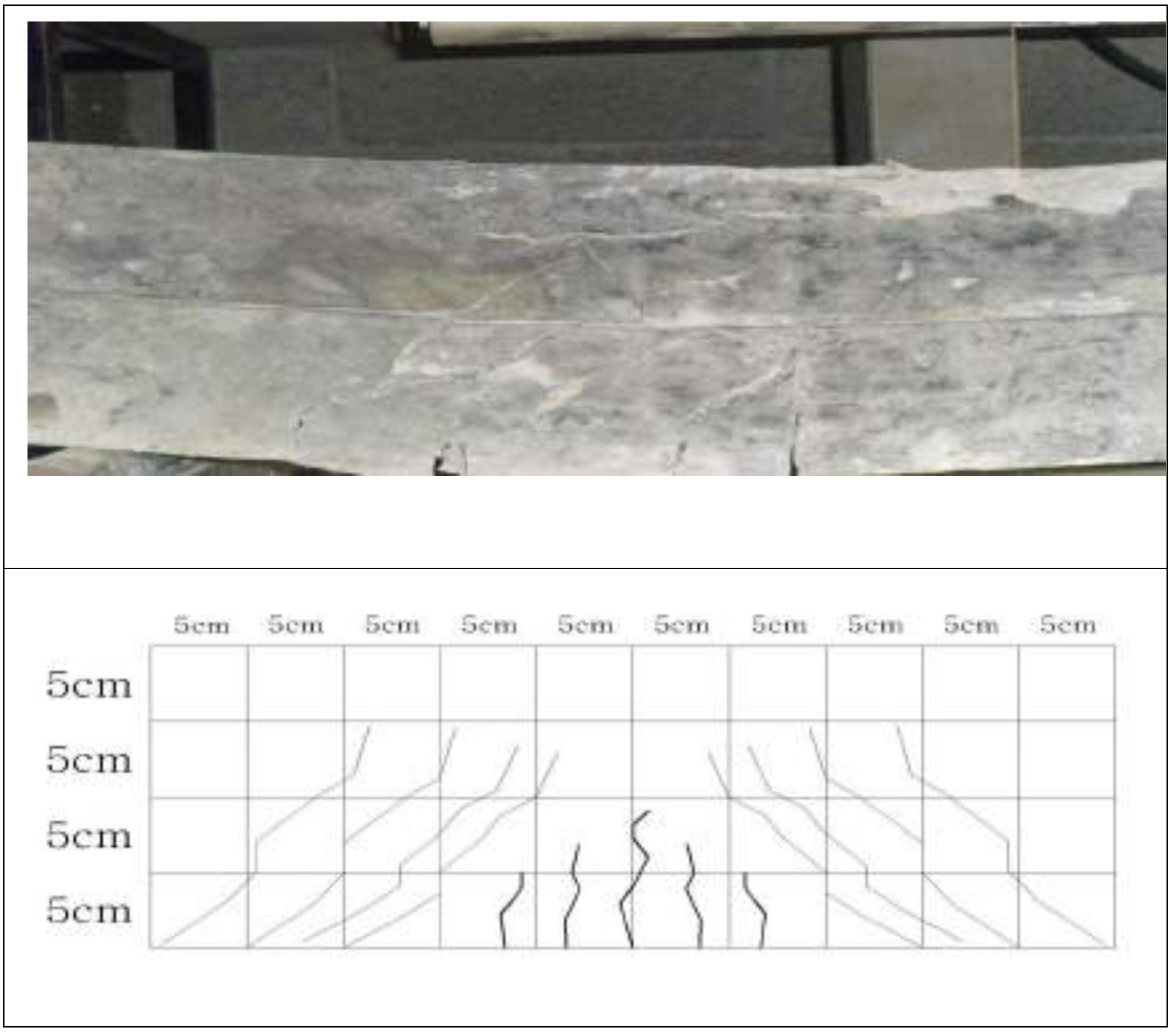


Figure 6-1: Crack Pattern of Control Beams

Table 6-1: control beam deflections

Load (KN)	Deflection (mm)
9	0.65
18	0.95
27	1.3
36	1.55
45	1.75
54	1.95
63	2.15
72	2.35
81	2.5
90	2.75
99	2.9
108	3.05
117	3.25
126	3.6
135	4

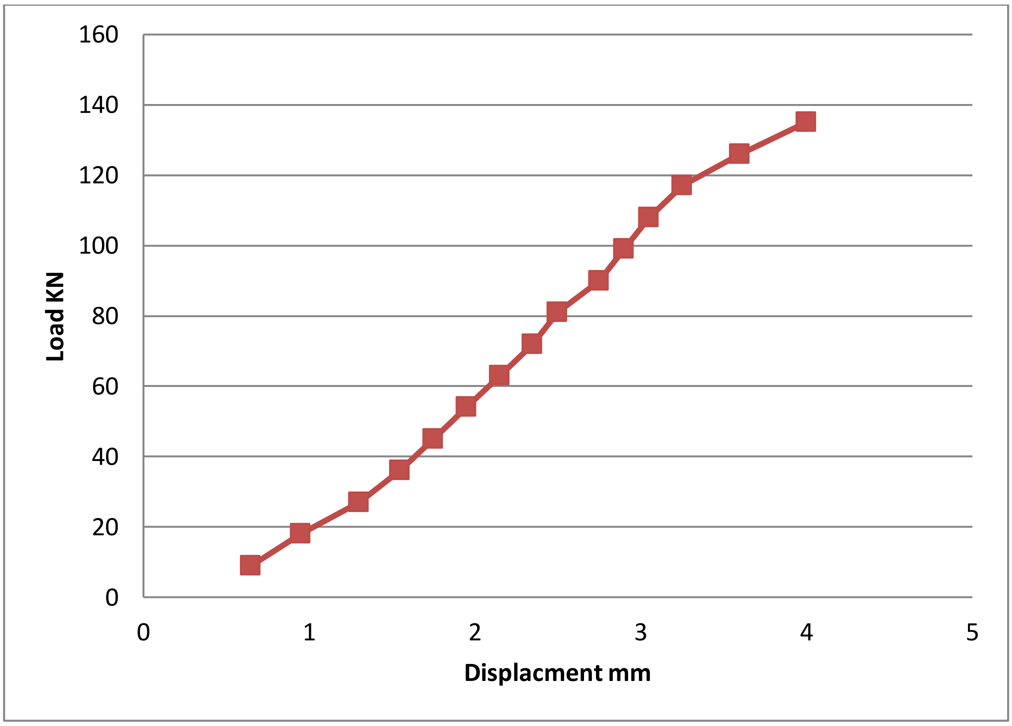


Figure 6-2: : Mid Span Displacement

6.6. Heated beams after repair:

Before stating the presses of repairing techniques on RC beam, sample was casted in suitable dimensions to suit the furnace dimensions. The steps are summarized here:

1^{st} Cast the samples and cure it for 28 days.

2^{nd} Heat the samples in a furnace with at 250 C^{o} for four hours, as shown in Figure 6-3.

Figure 6-3: Beam Samples Heated

3^{rd} Remove the samples form the furnace and cool it in normal conditions without spreading water on it, as shown in Figure 6-4:

Figure 6-4: Heated beam get cooled

4th Chip the concrete cover of the samples and roughen the surface to ensure a good bond with the repair materials, as shown in Figure 6-5.

Figure 6-5: chip the concrete cover of the heated samples

5th Wash the samples, as shown in Figure 6-6.

Figure 6-6: Cleaning the samples by Water

6th Prepare the samples to receive the four cementious repair materials.

6.6.1. Repairing the heated beams using UHPC:

The procedure is summarized in the following section:

7th Prepare the required material quantity of UHPC for application, see Figure 6-7:

Figure 6-7: Applying UHPC matrix to the heated beams

8th Cure the samples after applying the UHPC matrix for 7 days.

9th Test the samples by UHPC and record the results, flexural capacity, crack pattern, and deflection. (See Figure 6-8):

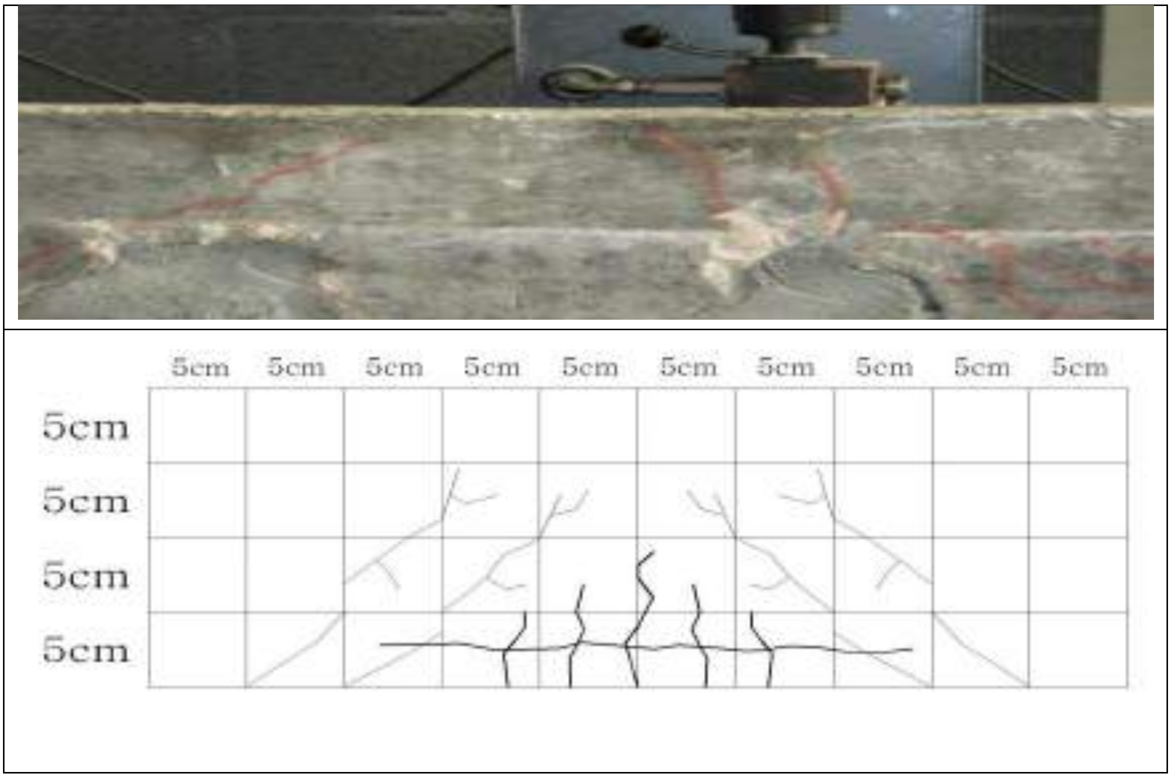


Figure 6-8: Heated beams repaired by UHPC tested , and its crack pattern

Beams repaired using UHPC were tested under 4-point load and increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average value obtained from three tested samples is 13.70 ton, and the deflection values are recorded on Table 6-2 and Figure 6-9.

Table 6-2: Deflection of UHPC Repaired Samples

Load (KN)	Deflection (mm)
9	0.7
18	1
27	1.35
36	1.65
45	1.85
54	2.05
63	2.25
72	2.45
81	2.65
90	2.9
99	3.05
108	3.2
117	3.4
126	3.8
135	4.2
137	4.5

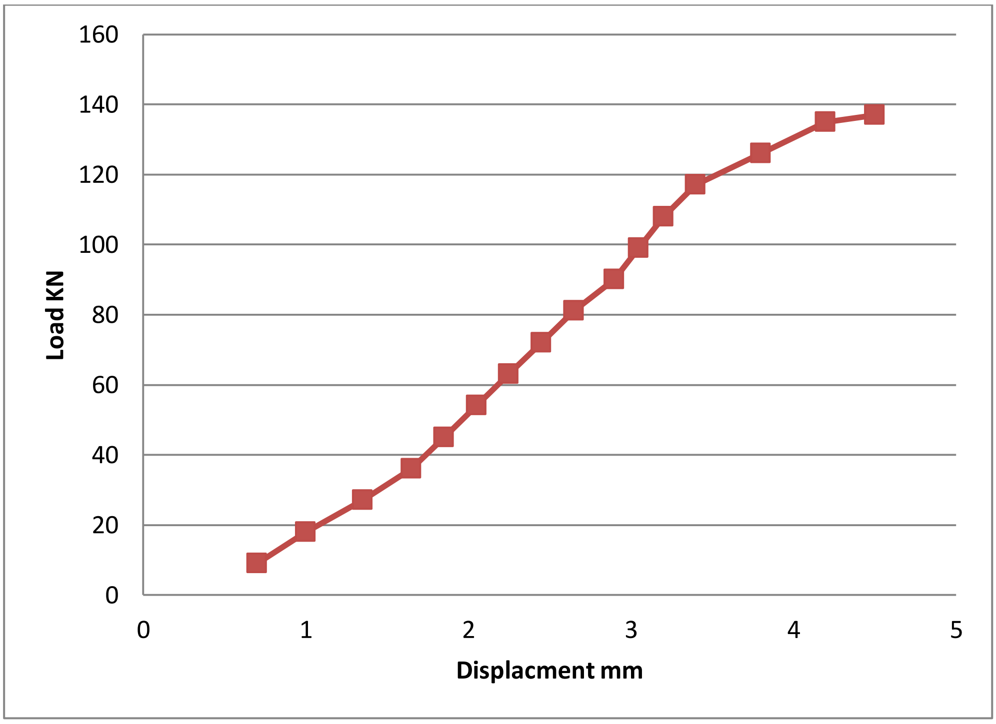


Figure 6-9: Displacement – load curve for heated beams repaired using UHPC

6.6.2. Repair of Heated beams using UHPFRC:

The procedure is summarized in the following section:

7th Prepare the required material quantity of UHPFRC for application, see Figure 6-10:

Figure 6-10: Applying UHPC matrix to the heated beams

8th Cure the samples after applying the UHPC matrix for 7 days.

9th Test the samples by UHPFRC and record the results, flexural capacity, crack pattern, and deflection. (See Figure 6-11):

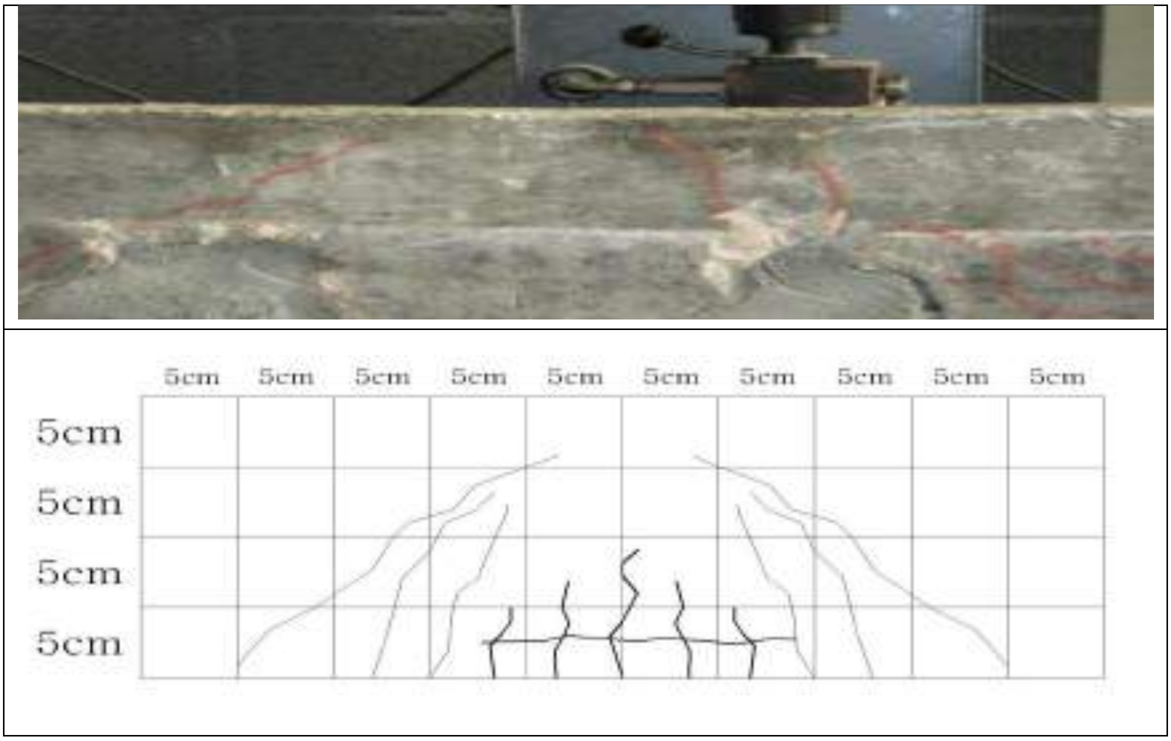


Figure 6-11: Heated beam repaired by UHPFRC tested , and its Crack Pattern

Beams repaired using UHPC were tested under 4-point load and increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average value obtained from three tested samples is 14.40 ton, and the deflection values are recorded in Table 6-3 and Figure 6-12.

Table 6-3: UHPFRC sample Deflections

load (KN)	Deflection (mm)
9	0.7
18	1.05
27	1.45
36	1.7
45	1.9
54	2.15
63	2.35
72	2.6
81	2.75
90	3.05
99	3.2
108	3.35
117	3.6
126	3.95
135	4.4
144	4.95

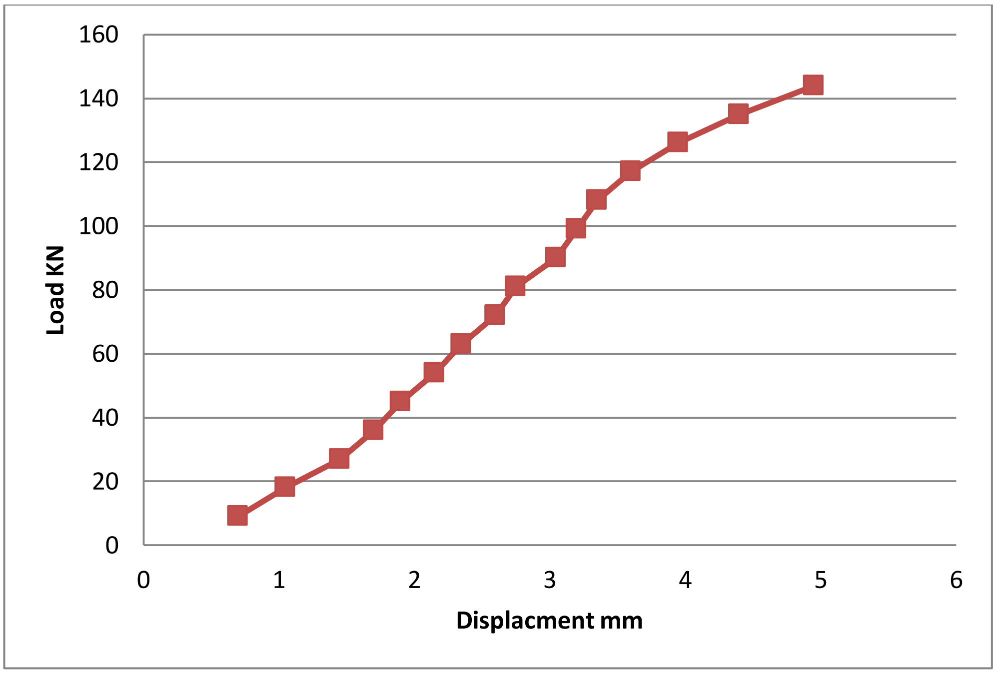


Figure 6-12: Displacement – load curve for heated beam repaired by UHPFRC

6.6.3. Repairing Heated beams using OPC:

The procedure is summarized in the following section:

7th Prepare the required material quantity of OPC for application, see Figure 6-13:

Figure 6-13: Applying OPC matrix to Heated beams

8th Cure the samples after applying the UHPC matrix for 7 days.

9th Test the samples by OPC and record the results, flexural capacity, crack pattern, and deflection. (See Figure 6-14):

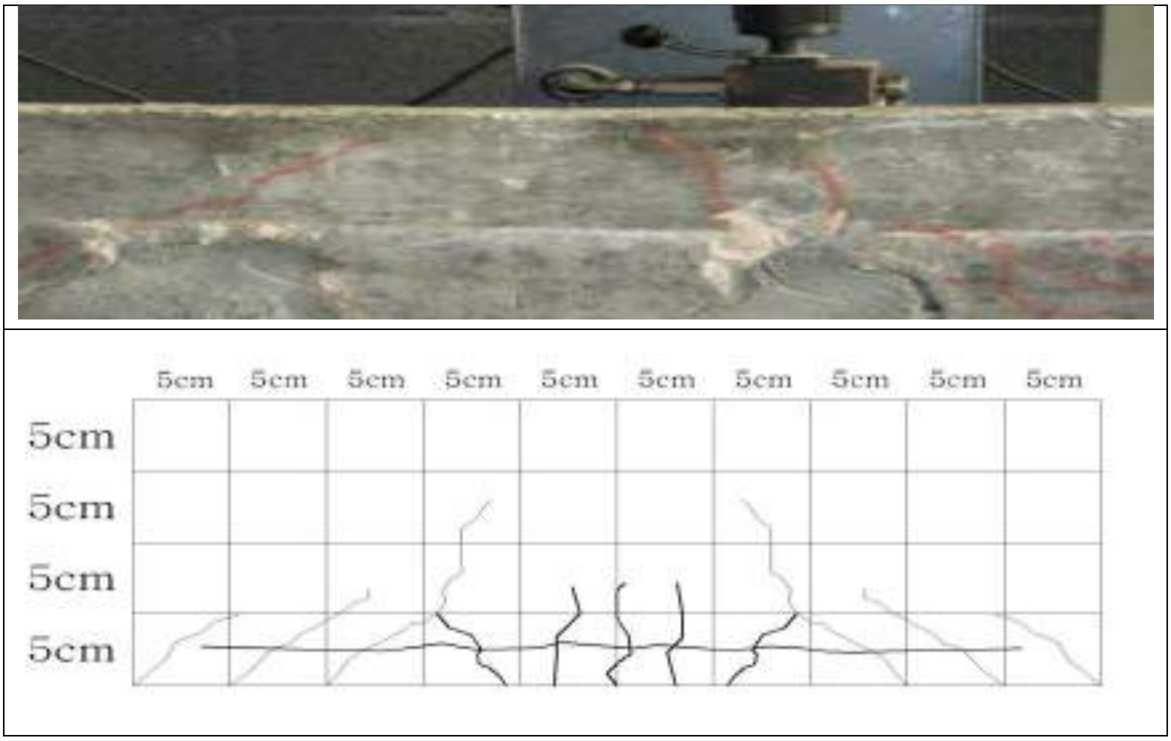


Figure 6-14: Heated beam repaired by OPC tested , and its Crack Pattern

Beams repaired using OPC were tested under 4-point load and increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average value obtained from three tested samples is 13.50 ton, and the deflection values are recorded in Table 6-4 and Figure 6-15.

Table 6-4: OPC Deflection

Load (KN)	Deflection (mm)
9	0.65
18	0.95
27	1.3
36	1.55
45	1.75
54	1.95
63	2.15
72	2.35
81	2.5
90	2.75
99	2.9
108	3.05
117	3.25
126	3.6
135	4

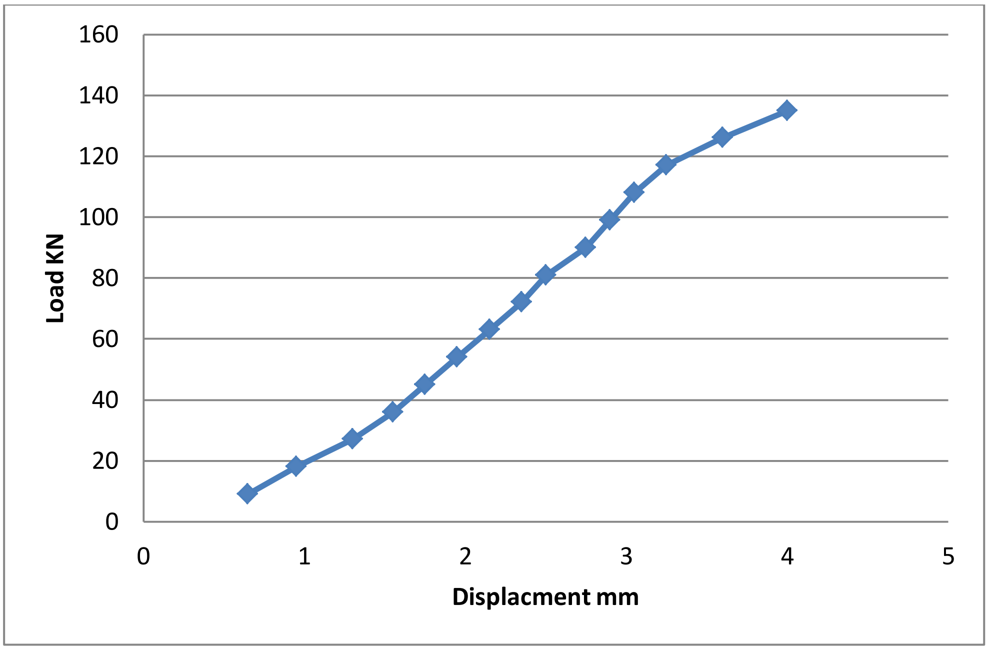


Figure 6-15: Displacement – load curve for cracked beam repaired by OPC

6.6.4. Repairing Heated beams using SRM:

The procedure is summarized in the following section:

7th Prepare the required material quantity of SRM for application, see Figure 6-16:

Figure 6-16: Applying RM matrix to Heated beams

8th Cure the samples after applying the RM matrix for 7 days.

9th Test the samples by SRM and record the results, flexural capacity, crack pattern, and deflection. (See Figure 6-17):

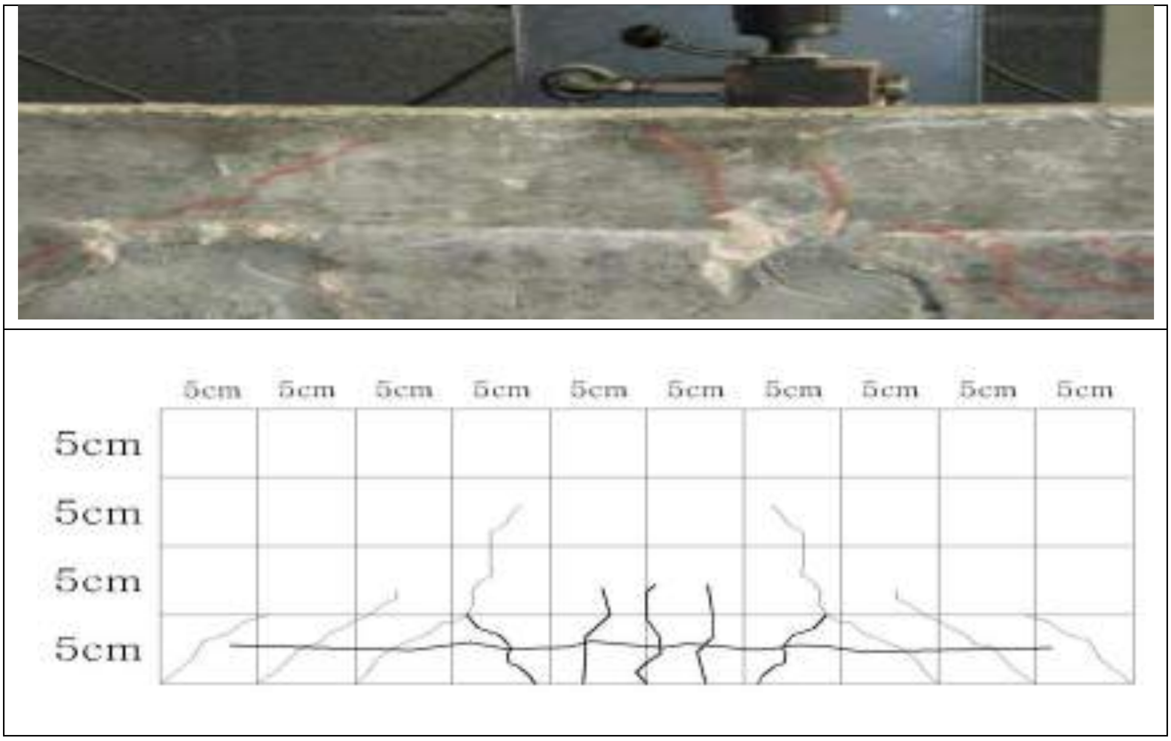


Figure 6-17: Heated beam repaired by SRM tested , and its Crack Pattern

Beams repaired using SRM were tested under 4-point load and increasing the load slowly to be failure to get the maximum capacity of section, crack pattern, and deflection. The average value obtained from three tested samples is 14.00 ton, and the deflection values are recorded in Table 6-5 and Figure 6-18.

Table 6-5: SRM Deflection

Load (KN)	Deflection (mm)
9	0.7
18	1
27	1.4
36	1.65
45	1.85
54	2.05
63	2.3
72	2.5
81	2.65
90	2.9
99	3.1
108	3.25
117	3.45
126	3.85
135	4.25
140	4.45

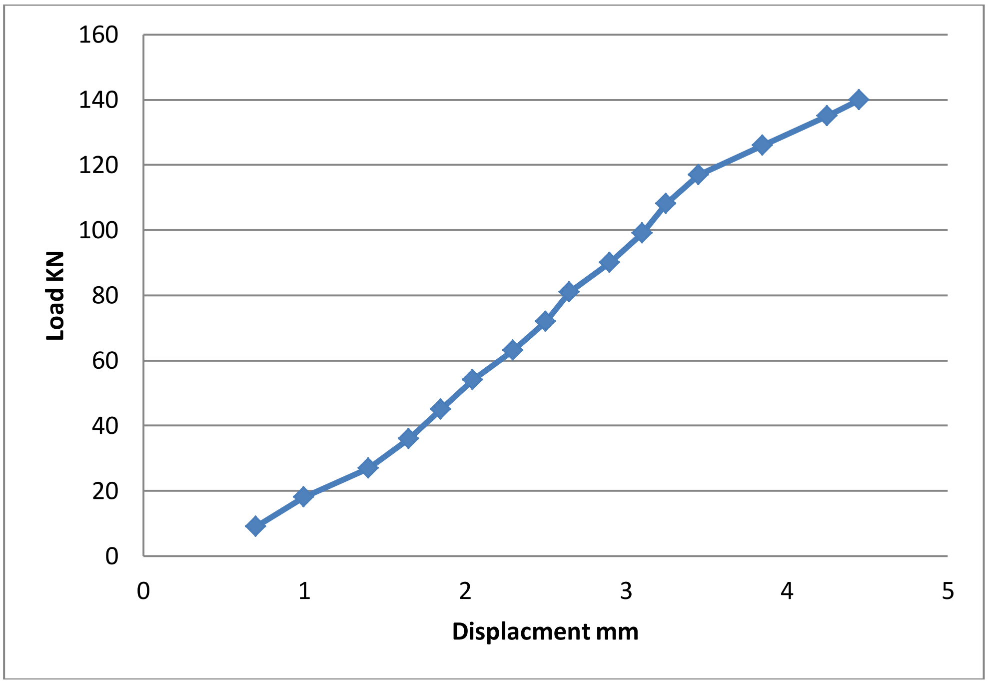


Figure 6-18: Displacement – load curve for cracked beam repaired by SRM

6.7. Result and Discussion:

6.7.1. Flexural capacity:

Table 6-6 shows that there are slight improvements between the capacities of the repaired beams and the control ones. This demonstrates that the repair process has little effect on the flexural capacity of the section. It also shows that the repaired cemetituous materials have little effect for repair of the heated beams.

Comparing the repaired beams with the control ones, it is clear that the repair process did not improve the bearing capacity of the section when tested 1 week after the application of the repair material, except for the beams repaired by UHPFRC and SRM which have a slight improvement over the control beam.

The beams, which were repaired by UHPC have achieved flexural strength 1.50 % higher than those of control beams. In addition, beams that were repaired by UHPFRC have developed flexural strength 6.66 % higher than those of control beams. Beams repaired by OPC have no improvement over the control beams. Beams that were repaired by SRM developed flexural strength 3.70 % higher than those of the control beams.

Table 6-6: Flexural Capacity Comparison

Beam code	No. of beam	Load capacity (KN)	Average load (KN)	Percentage of Improvement
Control beams C.B	C.B 1	13.35		
	C.B 2	13.65	13.50	-
	C.B 3	13.40		
Cracked beams repaired by UHPC	UHPC 1	13.60		
	UHPC 2	13.80	13.70	1.50 %
	UHPC 3	13.70		
Cracked beams repaired by UHPFRC	UHPFRC 1	14.30		
	UHPFRC 2	14.40	14.40	6.66 %
	UHPFRC 3	14.50		
Cracked beams repaired by OPC	OPC 1	13.35		
	OPC 2	13.65	13.50	0.00 %
	OPC 3	13.40		
Cracked beams repaired by RM	RM 1	13.90		
	RM 2	14.10	14.00	3.70 %
	RM 3	14.00		

6.7.2. Mid Span Deflection:

The deflections at mid-span were measured and plotted against the load as shown in Figure 6-19. Given that deflection is related to stiffness, it can be stated that the process of repair has a major effect on stiffness But it can be noticed that almost the same case deflections were recorded for the repaired beams when compared with the control ones. The repair material was applied at the bottom zone to compensate the concrete cover, which has got the bending reinforcement overlapped.

The repaired beams on the other hand showed four closed categories. The first is beams repaired by UHPC which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, with decrease in deflection of about 5% from the control beam (See Table 6-7). The second is beams repaired by UHPFRC that exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with decrees in the deflection of about 10% from control beam. The third is beams repaired by OPC which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, while semi deflection value of control beam). The fourth is beams repaired by SRM, which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, with decrees in the deflection of about 7% from control beam.

The curves in (Figure 6-19) on the other hand one can easily establish the four stages including the plastic one. This more flexible behavior may be due to the lower modulus of elasticity of the repair material used.

Table 6-7: Deflection Comparison

Load (KN)	Deflection (mm) of control beam (C.B)	Deflection (mm) of Repaired beam by			
		UHPC	UHPFRC	OPC	RM
9	0.65	0.7	0.7	0.65	0.7
18	0.95	1	1.05	0.95	1
27	1.3	1.35	1.45	1.3	1.4
36	1.55	1.65	1.7	1.55	1.65
45	1.75	1.85	1.9	1.75	1.85
54	1.95	2.05	2.15	1.95	2.05
63	2.15	2.25	2.35	2.15	2.3
72	2.35	2.45	2.6	2.35	2.5
81	2.5	2.65	2.75	2.5	2.65
90	2.75	2.9	3.05	2.75	2.9
99	2.9	3.05	3.2	2.9	3.1
108	3.05	3.2	3.35	3.05	3.25
117	3.25	3.4	3.6	3.25	3.45
126	3.6	3.8	3.95	3.6	3.85
135	4	4.2	4.4	4	4.25
144	-----	4.5	4.95	-----	4.45
153	-----	-----	-----	----	-----

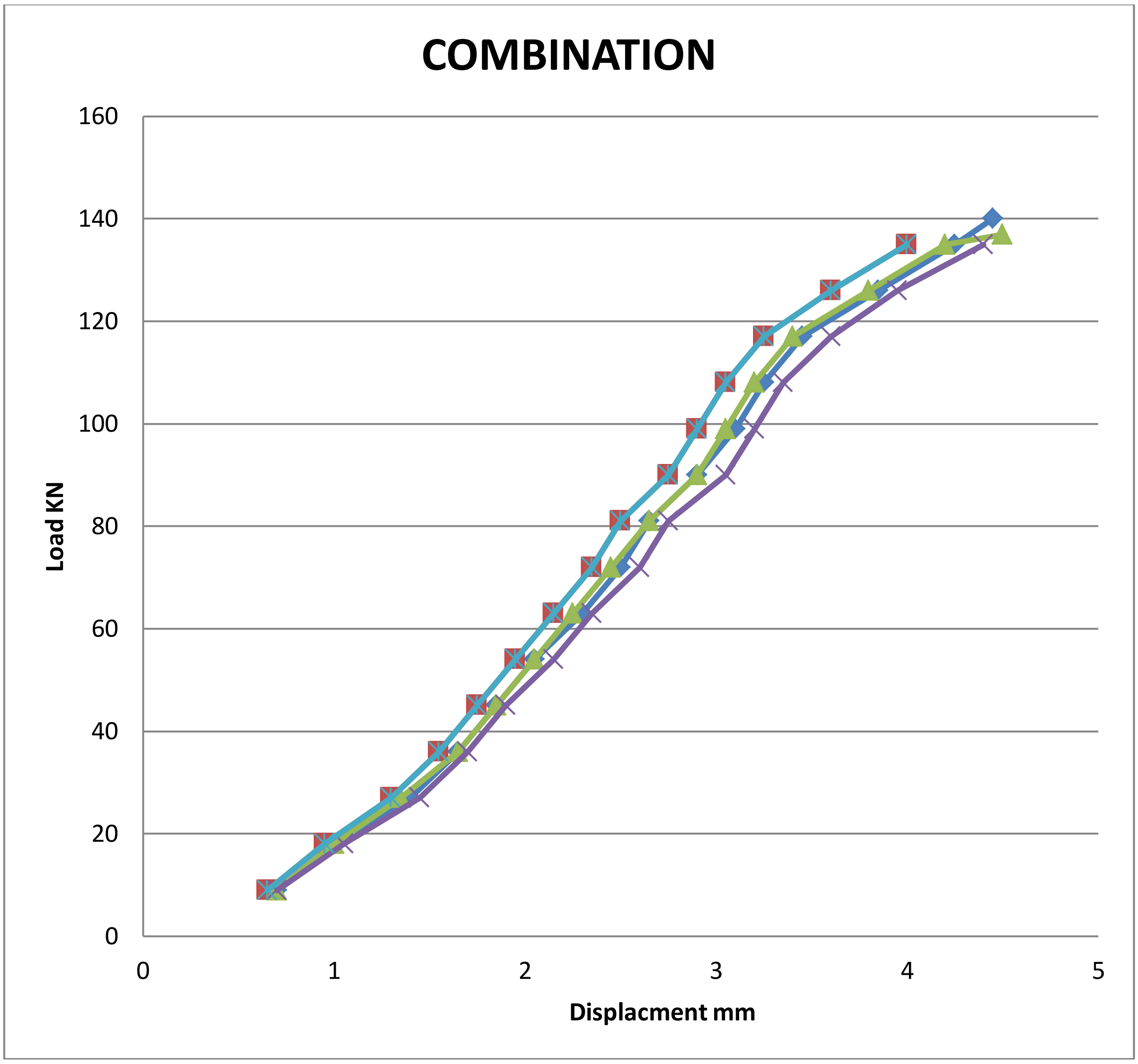


Figure 6-19: Load - Deflection Relationship

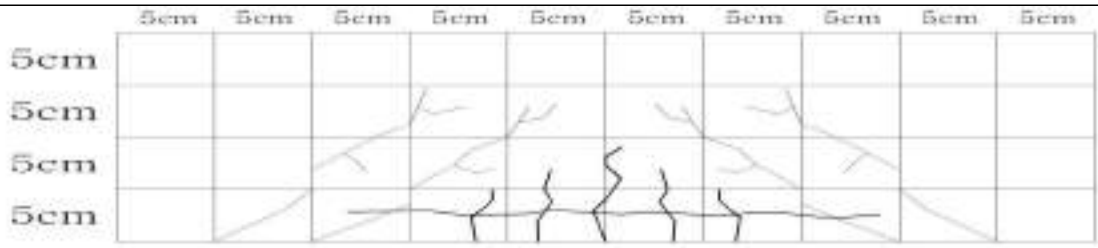
6.7.3. Crack patterns:

The control beams displayed a crack pattern as shown in Figure 6-20. At low loads, flexural cracks appeared and propagated at the bottom of the beam within the middle third of the span. As the load was increased, shear cracks also began to develop between the loading points. The increased shear force pushed down on the longitudinal steel and links, and cased the destruction of the bond between concrete and steel. The hooks at the end caused the beams to behave as a two-hinged arch until the internal stresses destroyed the surrounding concrete. However, the presence of laps within the test beams prevented this stage developing fully as the bars, once stripped of their bond, deflect downward restrained only by the links and, ultimately, break off the surrounding concrete. Thus, cracks are clearly visible on the underside of the beam, following the position of the steel.

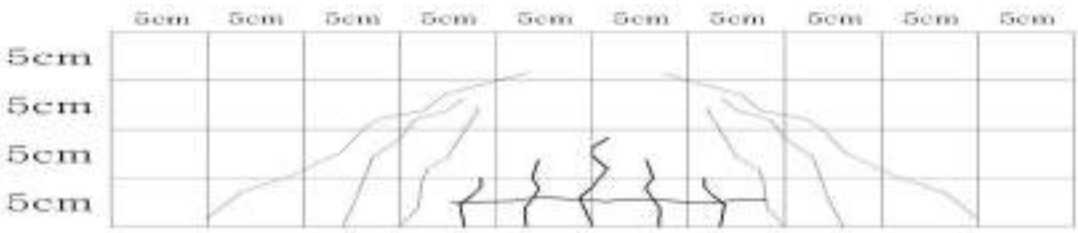
The repaired beams followed a semi similar cracking pattern, although within the repair material only nominal cracks were observed. The main cracks were concentrated within the concrete at areas of high bending moment either side of the repair. Failure was again due to the breakdown of the bond between the steel and concrete in the compression zone. In addition that appears longitudinal cracks through the boundary between the old concrete and repaired layer (concrete cover), but its length varies in each case of the repaired samples.

On case of samples repaired by UHPC and UHPFRC the longitudinal cracks are appear on the mid third of the span at the maximum flexural zone, but the samples were repaired by OPC and SRM the longitudinal cracks are appear through the all length of boundary line. This means that the layer that was added did not achieve satisfactory results, in terms of happened to her separation from the repaired samples and less bonding with old concrete.

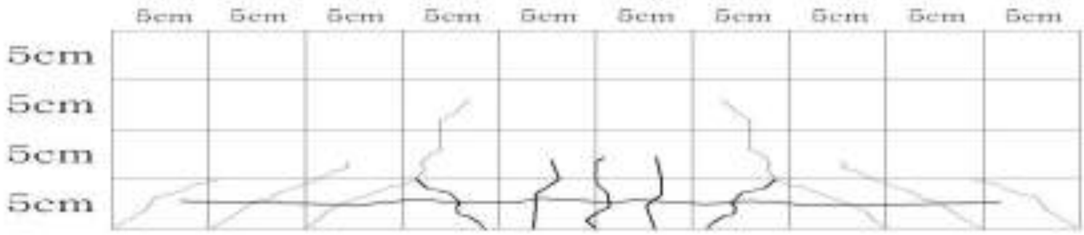
Crack pattern of control beams



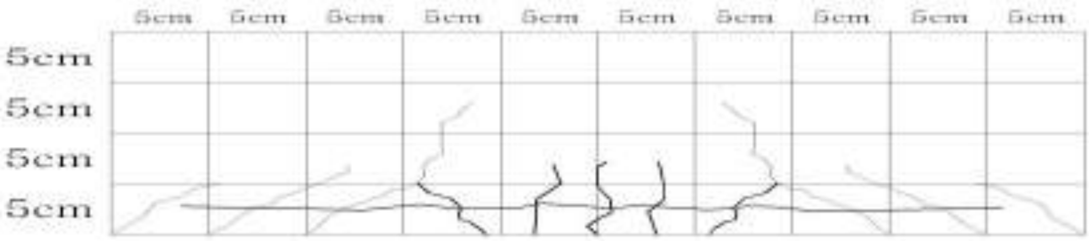
Crack pattern of UHPC beams



Crack pattern of UHPFRC beams



Crack pattern of OPC beams



Crack pattern of SRM beams

Figure 6-20: Crack PatternS Comparisons

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions:

The load capacity, deflection and crack patterns of RC beams retrofitted with UHPC, UHPFRC, OPC and SRM were studied experimentally. The study intended to assess the feasibility of using UHPC, UHPFRC, OPC, and SRM for repair and strengthening of damaged RC beams. A series of four-point bending tests were carried out on both damaged and undamaged RC beams in order to evaluate the performance of damaged RC beams after application of repaired materials and to select the best repair technique for each of the caused damage.

The tests yielded complete load–deflection curves from which the increase in load capacity was evaluated. The findings of the experimental study can be summarized as follows:

1. Comparing the repaired cracked beams with the control ones. It is clear that the repair process restored the flexural capacities of the sections when tested 1 week after the application of the repair material, except for the beams which were repaired using OPC where the outcome is much closer to the control beams.

2. The cracked beams, repaired using UHPC achieved flexural strengths 8 % higher than control beams. In addition, beams that were repaired using UHPFRC developed flexural strength 19 % higher than those for the control beams. Beams repaired using OPC had flexural strengths 3.17 % smaller than those for the control beams. In addition, beams that were repaired using RM developed flexural strengths 11 % higher than those for the control beams.

3. The cracked beams repaired using the four repair materials showed improvement in ductility of compared with the control beams, expect for the beams which were repaired using OPC, which showed results close to those obtained from the control beams.

4. The honeycombed beams repaired using UHPC developed flexural capacities 19%, higher than those repaired using UHPFRC developed the bearing capacities 30%, higher than those repaired using OPC its results is close to the control beam with improvement of about 1.5%, and beams which were repaired by SRM developed the bearing capacity about 27%.

5. A significant improvement in flexural capacity may be attributed good bonding between the repair materials and the old concrete. In addition to the higher performance of the repair materials.

6. The heated were repaired using UHPC have achieved flexural strength 1.50 % higher than those of the control beams. In addition, beams that were repaired using UHPFRC developed flexural strengths 6.66 % higher than those of the control beams. Furthermore, beams repaired using OPC has no improvement over the control beams. While beams repaired using SRM developed flexural strengths 3.70 % higher than those of the control beams.

7. The repaired cracked beams on the other hand showed four categories. The first is beams repaired using UHPC which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, with 73% decrease in deflection compared to control beam. The second is beams repaired using UHPFRC which exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with 51% decrees in the deflection of about compared with the control beams. The third is beams repaired using OPC, showed deflection close to those obtained from the control beams. The fourth is beams repaired using SRM, which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, with about 63% reduction in deflection compared to the control beams.

8. The repaired honeycombed beams on the other hand showed four categories. The first is beams repaired by UHPC which exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with 82.5% decrease in deflection compared control beam. The second is Beams repaired using UHPFRC, which exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with 64% decrees in the deflection value about from control beam. The third is beams repaired using OPC which exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, while semi deflection value of control beam. The fourth is beams repaired using SRM which exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with about 61% reduction in deflection compared to the control beams.

9. The repaired heated beams on the other hand showed four closed categories. The first is beams repaired using UHPC that exhibited stiff behavior with low deflections and approximately linear load-deflection plots, with 5% decrease deflection of about from control beam. The second is beams repaired using UHPFRC that exhibited stiff behavior with low total deflection and approximately linear load-deflection plots, with 10% decrees in the deflection of about from control beam. The third is beams repaired using OPC, which

exhibited stiff behavior with low deflections, and approximately linear load-deflection plots, while semi deflection value of control beam. The fourth is beams repaired using SRM, which exhibited stiff behavior with low deflections and approximately linear load-deflection plots, with 7% reduction in deflection compared with the control beams.

10. Improvement of crack pattern for the cracked beams repaired by UHPFRC and RM that refer to good bonding between the repair materials and the old concrete. The crack pattern of beams repaired by OPC and UHPC are similar to those of the control beams, which indicates to less bonding between these materials and old concrete.

11. Significant improvement in crack pattern for honeycombed beam repaired by UHPFRC and RM that refer to good bonding between repair materials and host concrete, while the crack pattern of beams repaired by OPC and UHPC are similar to those of the control beams that indicates to less bonding between these materials and host concrete.

12. For the case of the heated beams repaired using UHPC and UHPFRC the longitudinal cracks appeared within the mid third of the span at maximum flexural zone, but the samples which were repaired using OPC and SRM showed the longitudinal cracks are appear through the all length of boundary line. This means that the layer that was added did not achieve satisfactory results, due to less bonding with the old concrete.

7.2. Recommendation:

Based on the executed experimental programs and the obtained results, the following recommendation may be stated.

The recommendations can be summarized as follows:

1. Its encouraged to try using suitable bonding agents to bond old concrete with the repair materials. In this research only surface roughness in adhesion.

2. To prevent separation between the old concrete and the repair material for the heating case, shear studs may be used to prevent it and improving cracks pattern.

3. Adding additional concrete layers or increase beam dimensions to study the influence on the results. In this research, the original dimension are maintained after repair.

REFERENCES

[1] Shamim A. Sheikh, David DeRose, and JamilMardukhi, "Retrofitting of Concrete Structures for Shear and Flexure with Fiber-Reinforced Polymers" ACI Structural Journal99-S47.

[2] H.K. Lee ,L.R. Hausmann, "Structural repair and strengthening of damaged RC beams with sprayed FRP" Composite Structures 63 (2004) 201–209.

[3] Omrane Benjeddou ,Mongi Ben Ouezdou , AouichaBedday, "Damaged RC beams repaired by bonding of CFRP laminates" Construction and Building Materials 21 (2007) 1301–1310.

[4] Anugeetha B., Sheela S., "Study on the Performance of Reinforced Concrete Beams Retrofitted Using Ferrocement and GFRP" 10th National Conference on Technological Trends (NCTT09) 6-7 Nov 2009.

[5] F.A. Farhat, D. Nicolaides, A. Kanellopoulos, B.L. Karihaloo, "High performance fibre-reinforced cementitious composite (CARDIFRC) – Performance and application to retrofitting"Engineering Fracture Mechanics 74 (2007) 151–167.

[6] Yining Ding ,Ceclia Azevedo , J.B. Aguiar , Said Jalali ," Study on residual behaviour and flexural toughness of fibre cocktail reinforced self compacting high performance concrete after exposure to high temperature"Construction and Building Materials 26 (2012) 21–31.

[7] Luciano Ombres, "Flexural analysis of reinforced concrete beams strengthened with a cementbased high strength composite material", Composite Structures 94 (2011) 143–155.

[8] S. Granger , A. Loukili , G. Pijaudier-Cabot , G. Chanvillard, "Experimental characterization of the self-healing of cracks in an ultra high performance cementitious material: Mechanical tests and acoustic emission analysis" Cement and Concrete Research 37 (2007) 519–527.

[9] Su-Tae Kang , Jin-Keun Kim, "Investigation on the flexural behavior of UHPCC considering the effect of fiber orientation distribution" Construction and Building Materials 28 (2011) 57–65.

[10] Y. G.Diab, "Strengthening of RC beams by using sprayed concrete: experimental approach" Plh SO i 41-0296(97)00044-8.

[11] P. M. V. Udaya Kumar1, M. Potha Raju1 and K. Srinivasa Rao "Performance of repaired fire affected RC beams" CURRENT SCIENCE, VOL. 96, NO. 3, 10 FEBRUARY 2009

[12] S. Ahmad , A. Elahi , S.A. Barbhuiya , Y. Farid, "Use of polymer modified mortar in controlling cracks in reinforced concrete beams" Construction and Building Materials xxx (2011) xxx–xxx.

[13] S. Hashemi , R. Al-Mahaidi , " Experimental and finite element analysis of flexural behavior of FRP-strengthened RC beams using cement-based adhesives" Construction and Building Materials 26 (2012) 268–273.

[14] Zachary B. Haber , Kevin R. Mackie , Lei Zhao, " Mechanical and environmental loading of concrete beams strengthened with epoxy and polyurethane matrix carbon fiber laminates" Construction and Building Materials 26 (2012) 604–612.

[15] Sun-Woo Kim, Hyun-Do Yun, "Crack-damage mitigation and flexural behavior of flexure-dominant reinforced concrete beams repaired with strain-hardening cement-based composite" Composites: Part B 42 (2011) 645–656.

[16] Bo Gao ,ChristopherK.Y. Leung ,Jang-Kyo Kim, "Prediction of concrete cover separation failure for RC beams strengthened with CFRP strips" Engineering Structures 27 (2005) 177–189.

[17] L.A. Bisby, J.F. Chen, S.Q. Li, T.J. Stratford, N. Cueva, K. Crossling, " Strengthening fire-damaged concrete by confinement with fibre-reinforced polymer wraps" Engineering Structures 33 (2011) 3381–3391

[18] Mohd.Zamin Bin Jumaat, Md. Humayun Kabir, M. Obaydullah, "Structural Performance of Reinforced Concrete Beams Repairing from Spalling" European Journal of Scientific Research ISSN 1450-216X Vol.45 No.1 (2010), pp.089-102.