FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE CORBELS STRENGTHENED WITH CARBON FIBER REINFORCED POLYMER BY USING ABAQUS

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ABSTRACT

This research is devoted to investigate the effect of Carbon Fiber Reinforced Polymer (CFRP) strips on the behavior and load carrying capacity of the strengthened concrete corbels. Numerical investigation was carried out. The experimental program variables include location, direction, amount of CFRP strips, and effect of shear span to effective depth (a/d) ratio on the behavior of strengthened corbels. All corbels had the same dimensions and flexural reinforcement and they were without horizontal shear steel (stirrup) reinforcement. In this paper, ABAQUS V.6.13-1 software was used to investigate the non-linear structural behavior of reinforced concrete corbel through considering total of thirty concrete corbels model for study variables of concrete and steel material nonlinearity, concrete grade, shear span to effective depth ratio, horizontal shear reinforcement, finite element mesh size and corbel geometry for simulation response of the structure. Finally finite element result was validated with the experimental result. In this work, Solid, Solid, wire and shell elements were used to model concrete, steel bearing plates, steel flexural reinforcing bars, and CFRP strips respectively. Full bond was assumed between CFRP sheets and concrete interface. The full Newton-Rap son method is used as a nonlinear solution algorithm. The displacement criteria are used for convergence. The adopted finite element analysis showed good agreement with experimental results throughout the load-deflection history the maximum difference in the ultimate load was less by 8%.However,the finite element models show a slightly stiffer response.

KEY WORDS: *Corbel, Carbon Fiber, Strengthened, Nonlinear Analysis, Finite Element Analysis, Abaqus*

1.INTRODUCTION

1.1 Background of the Study

Corbels or brackets are short-reinforced concrete (RC) cantilever members with shear-span depth ratio (a/d) less than 1.0. Such members are used to transfer vertical load and horizontal loads to wall or column element and they support primary beams and girders. However, horizontal force must be considered in the design to restrained shrinkage, creep and temperature change, unless special precaution is taken in the consideration. Corbels are structural element which supports the pre-cast structural members such as precast beam and prestressed beam. The corbel casting system is monolithic with the column element or wall element. Corbel cannot be adequately designed using beam theory concept due to discontinuity in load and geometry.

The principal failure modes for members without stirrups are: -

1. *Concrete crushing on the strut (flexural compression)*
2. *Shear failure*
3. *Yielding of the principal reinforcement (flexural tension)*
4. *Diagonal splitting*

Corbels are designed mainly to provide for the vertical reaction Vcv at the end of the supported beam and sometimes they must also resist a horizontal force Nc transmitted from the support beam due to restrained shrinkage, creep and temperature *change, Typically, the general cross-section, reinforcement and loading figure is as shown below.*

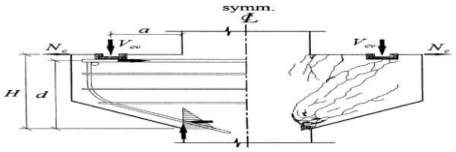

Figure 1. Corbel Cross-section, reinforcement and loading (Shyhh-Jiann et al, 2000)

Corbel is system of structure used to carry the shear and transfer it safely to column or wall during at industrial and at applicable structural member when properly analyzed and designed.

Externally strengthened with advanced composite material namely, carbon fiber reinforced polymer (CFRP) represents the state of the art in upgrading or rehabilitation techniques, carbon fiber reinforced polymer (CFRP) laminates is becoming widely used in upgrading and rehabilitation of reinforced concrete members. The utilization of carbon fiber reinforced polymers in the construction fields has received a special attention in the last two decades. This is attested by extensive research activities on CFRP and resulted in a significant advancement in state of the art of use CFRP in the construction fields.

In recent year many experimental and finite element method investigation of reinforced concrete corbel was performed to study the structural response or behavior under shear loading, Experimental and finite element method analysis were conducted to investigate structural behavior like capacity of corbel under loading, deflection of corbel mode of failure and other response by considering common parametric study like concrete strength, shear-span to depth ratio, percentage of reinforcement, The researcher considers geometry of model taken from experimental investigation of reinforced concrete corbel to validate the work and further study of the parameter under consideration, Use software was appropriate and important to simulate the model by considering the most common and identification of influential parameter, The aim of this study is investigating the behavior of reinforced concrete corbels externally strengthened or repair with carbon fiber reinforced polymer (CFRP) sheets with finite element analysis, The result of Abaqus software will be validated with experimental result.

1.2 Statement of the Problem

The rehabilitation, strengthening and repair of old building is more economical than rebuilding them. That is why the behavior of strengthening techniques should be understood to make the best decision for repair, strengthening and rehabilitation and helpful to save time and cost.

Reinforced concrete corbel is small projecting cantilever beam which project from column and prone under the action of shear force, Corbel when subjected to large shear forces shows the failure due to stress concentration, crushing of concrete, yielding of steel of the whole or parts of structure. The shear failure developed within the corbel at different location along corbel shear span may affect the response of structure due to brittle in nature which is not acceptable in design since the structure fails suddenly as brittle failure without warning. Shear capacity must be investigated in detail to identify the most influential parameter that helps the designer for design of structure. To do so it`s important to have spatial design and investigation on structural properties of structure as whole and its members in detail using finite element analysis.

Finite element analysis for corbel structural response like maximum load carrying capacity, mode of failure, principal stress, deformation and crack propagation will be area of research require simulation by updated software using Abaqus.

1. 3 Significance of the Study

Corbel or bracket cannot be adequately designed using beam theory concept due to discontinuity in load and geometry, That means reinforced concrete corbel response to loading like stress trajectory, mode of potential failure, shear capacity and nature crack propagation are not clearly identified at the ultimate load under experimental analysis due to concrete and steel non-linear material complexity,

Finite element analysis and simulation output by Abaqus among other design methods can provide sound structural behavior of reinforced concrete corbel ultimate shear capacity, failure mode, crack pattern, stress trajectory and maximum deformation, Finite element analysis provides the actual response to the structure under loading that helps designer to have the maximum capacity and location potential stress for design of structure for the loading and the designed structure safely provide service for client to the intended purpose, Finite element analysis also helps students to location of crack, nature of crack, stress contour and shear capacity for design and compare result of design section capacity of any structural element with other design method and further understanding,

1.4 Objective of the Study

1.4.1 General objective

The general objective of this research is investigate the behavior of reinforced concrete corbels externally strengthened or repaired with carbon fiber reinforced polymer sheets (CFRP) by finite element analysis method.

1.4.2 Specific objective

The specific objectives of this research are: -

- ✓ To investigate the shear behavior of reinforced concrete corbels strengthened with CFRP strips
- ✓ To compare the performance of reinforced concrete corbels strengthened or repaired with CFRP sheets in shear with control corbel,
- ✓ To study the effect of shear span to depth ratio on the behavior and load carrying capacity of strengthened corbels,
- ✓ To study the effect of the presence of CFRP strips on the width of shear cracks,
- ✓ To investigate the load displacement response for varied finite element mesh size

1.5 Research Question

1. To what extent the shear behaviors affect the reinforced concrete corbels strengthened with CFRP strips?
2. How geometric cross-sectional variations affect the RC corbels strengthened with CFRP sheets response?
3. What is the variation in response due to shear span to depth ratio parameter for strengthened corbel under loading?
4. What is the effect of the presence of CFRP strips on the width of shear cracks?
5. Which structural response of RC corbel strengthened with CFRP sheet is sensitive to finite element mesh size?

1.6 Scope and Limitation of the Study

The rational for conducting this study will be providing the bench marks(boundary) under which externally strengthened reinforced concrete corbel will be used for construction purpose.

Every study which have been studied numerically by using any software have to be verified and validated with experimental result, Abaqus will be used for finite element analysis and material properties are taken from experimental.

Reinforced concrete corbels strengthened with CFRP sheets with other than reinforced concrete is beyond the scope of this study and the effect of method of construction, and shape of cross-section will be not considered.

2.LITRATURE REVIEW

2.1 General

This chapter deals with the previous research works and theoretical views which related to the behaviors of reinforced concrete corbels strengthened with CFRP sheets, It deals with the experimental study and finite element modeling on the effect and behavior of CFRP strips on the reinforced concrete corbels, The primary response variables are: load versus deflection curve, shear crack pattern, concrete strain and the tensile strain of CFRP strips.

Corbels are short cantilevers with a shear-span to depth ratio lower than unity. Generally, corbel built monolithically with the column or wall, Corbels are principally designed to resist the ultimate shear force applied to them by the beam (Aziz, O.Q., 2001),Unless special precautions are taken to avoid horizontal loads caused by shrinkage, creep(in case of prestressed beam), or temperature changes, they must also be able to resist a horizontal force, Steel plates are usually provided at the top surface and distribute the reaction (M.A. Elgwady, M. Rabie, M.T. Mostafa, 2005).

Externally strengthening with advanced composite materials, namely carbon fiber reinforced polymers(CFRP) represents the state of the art in upgrading or rehabilitation techniques (ACI-318, 2011),Carbon fiber reinforced polymer(CFRP) laminates are becoming widely used in upgrading and rehabilitation of reinforced concrete members (A.M.A. Hafez, M.M. Ahmed, H. Diab, A.A.M. Drar, 2012).

2.2 Theoretical Reviews

2.2.1 Constituents of fiber reinforced polymers

Fiber reinforced polymer (FRP) is composite material made of a polymer matrix reinforced with fiber. The fibers are usually glass fibers, carbon fibers, or aramid fiber, although other fibers such as papers, wood or asbestos have been sometimes used. The polymer is usually an epoxy, vinyl-ester or polyester the rmoseting plastic, and phenol formaldehyde resins are still in use, FRPs are commonly used in aerospace, automotive, marine, and construction industries, Composite materials are Engineered or naturally occurring materials made from two or more constitute materials with significantly different physical or chemical properties which remain separate and distinct within the finished structure, The objective is usually to make a component which is strong and stiff often with low density (Martin, 2013).

2.2.2 Advantage and disadvantage of fiber reinforced polymers

FRP materials for use in concrete strengthening application have a number of key advantages over conventional reinforcement steel, Some of the most important advantages include (CSC.TRN55, 2010).

1. Do not corrode electrochemically, and have demonstrated excellent durability in a number of harsh environmental conditions,

2.Have extremely high strength to weight ratios (typically weigh less than one fifth the weight of steel, with tensile strength that can be as much as 8 to 10 times as high)

3. Their installation is easy and simple with no need for temporary support

4. Have low thermal conductivity

FRP material also have a number of potential disadvantages (ACI 440R-07, 2007);

1. The relatively high cost of the materials especially carbon fiber is expensive than Other fibers

2. The risk of fire, vandalish or accidental damage, unless the strengthening is Protected

3. The relatively low elastic modulus of FRPs as compared with steel

2.2.3 Types of FRP materials used in construction industry

There are three types of fibers dominating in construction industry,

These are: - 1. Glass fibers

2. Carbon fibers

3. Aramid fibers

2.2.3.1 Glass fibers

Glass fibers are a processed form of glass which is composed of a number of oxides (mostly silica oxide) with other raw materials (such as limestone, Fluor spar boric acid, clay), There are five forms of glass fiber used as the reinforcement of the matrix material: These are: - 1. Chopped fibers 2. Chopped strands 3. Chopped strand mats

4. Woven fabrics 5. Surface tissue

The glass strands and woven fabrics are the forms most commonly used in civil Engineering applications, For applications involving concrete a more alkaline resistant so called AR fiber(also called cemfil fiber) has been developed with increased zircon content (Potyrała, 2011)

Figure 2.Glass fiber fabrics **(Potyrala, 2011)**

2.2.3.2 Carbon fibers

Carbon fibers are a type of high performance fiber available for civil Engineering applications, Carbon fibers have high elastic modulus and fatigue strength than those of glass fibers, The advantage of carbon fiber is: have low density, high modulus of density, have high tensile strength, and have minimum elongation than the other fiber polymer, Their disadvantage include: inherent an isotropy (reduced radial strength), low impact resistance, comparatively high energy requirement in their production as well as relatively high costs (Amateau, 2003).

There are many types of continuous CFRP, however the most common are unidirectional and bidirectional, Because of directional of the fabrics, the material is considered anisotropic, (Potyrała, 2011).

Figure 3.Carbon fiber fabrics **(Potyrała, 2011)**

2.2.3.3 Aramid fibers

Aramid or aromatic polyamide fiber is one of the two high performance fibers used in civil Engineering application. Fiber left from evaporation are stretched and drawn to increase their strength and stiffness. Aramid fibers have high static, dynamic fatigue, and impact strengths. The advantage of aramid fibers are: superior resistance to damage, good in tension, moderate stiffness, low density, high strength and less expensive than carbon fibers. The disadvantage of aramid fibers are: low compressive strength, reduced long term strength as well as sensitivity to ultra violet radiation. Another drawback of aramid fibers is that they are difficult for cutting and matching (Potyrała, 2011).

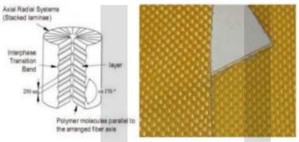

Figure 4.Single aramid and aramid fiber fabric **(Setunge, 2002)**

2.3 Properties of Fiber Materials

This section reviews the basic mechanical properties of FRP materials, Density, coefficient of thermal expansion, tension and compression behavior and durability of FRP materials are briefly summarized below.

Table 1.Tyipical density of FRP material (KN/m^3) **(Smith, 1996)**

steel	GFRP	CFRP	AFRP
79	12-21	15-16	12-15

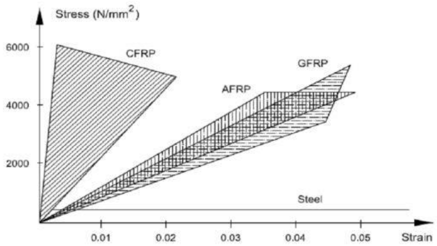

Figure 5.Different stress-strain diagrams of FRP to steel (courtesy of Sika Corporation)

2.4 Previous works on the RC Corbel strengthened with CFRP strips

(L.B. Kriz, C.H. Raths, 1965) carried out the first pioneering experimental and analytical work on the behavior of RC corbels using normal strength concrete[NSC].The following parameters have been taken in to consideration: reinforced ratio, shear-span to depth ratio, concrete strength and applied load(vertical load only or combined vertical and horizontal loads).The authors concluded that the tension reinforcement and horizontal stirrups have the same effect on corbels strength increase when subjected to vertical only, while the horizontal load reduce their strength significantly.

Depending on the same parameters taken by Kris and Raths (L.B. Kriz, C.H. Raths, 1965),mattock et al (A.H. Mattock, K.C. Chen, K. Soongswang, 1976) reported that minimum amount of horizontal stirrups should be provided to avoid diagonal tension failure and to permit the main reinforcement to reach the yield strength.

Series of researches reported to investigate the effect of adding different types of steel fibers reinforced (SFR) to concrete corbels, (B.P. Hughes, 1989) .Investigated that in addition to that SFR improved the capacity of tested corbels and the mode of failure changed from diagonal splitting to flexure when fibers with efficient bond characteristics were used.

(M.A. Elgwady, M. Rabie, M.T. Mostafa, 2005) reported experimentally that the load carrying capacity of the corbels was increased by using different strengthening configuration of CFRP fabrics. The failure were brittle and sudden without adequate warning due to increase the stiffness that the all corbels were failed due to debonding of CFRP strips and spalling of concrete cover.

Ozden and Atlay (S. Ozden, H.M. Atalay, 2011) investigate the strength and pos-peak performance of using GFRP in strengthening corbels subjected to vertical load only. The main parameters were shear span to effective depth ratio, ratio of main reinforcements, layers numbers and changing the orientation of GFRP. Findings concluded that GFRP wrapping with 45^0 fiber orientation was more active than lateral wrapping, The strength gain increased due to reinforcement ratio and number of GFRP layers increase.

Ivanova et.al (I. Ivanova, J. Assih, A. Li, D. Dontchev, Y. Delmas, 2015) present study on performance of externally strengthened short RC corbel by CFRP fabrics a horizontal form and in wrapping form. The result stated that the attached fabrics on the tensile face of the corbel have a greater effect.

3.MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter highlights methodological details appropriate to the study. It describes precisely what will be recorded, the proposed tools to be used in data collection and the methods of analyzing the data, It includes: study area, study design, variables of study, method of data analysis and limitation of the study is set in order to generate the appropriate result for the proposed objectives. The research methodology is based on finite element analysis of RC corbels strengthened with CFRP sheets by using Abaqus software and compare results with experimental result.

This chapter deals also with the overall process and method of modeling, analysis and non-linear finite element analysis using Abaqus/standard 6.13-1 software,

3,2 Description of the Study

This study is to carry out the behavior of RC corbel strengthened with CFRP sheets. The primary independent variables on this study are: width of CFRP fabrics, length of CFRP strips, number of CFRP strips, strengthening direction of CFRP strips and shear span to depth ratio. The response variables are: load carrying capacity, load versus deflection curve, shear crack pattern, concrete strain and tensile strain of CFRP strips.

Strengthened schemes are chosen carefully based on the practical needs and the field conditions; mainly crack pattern and practical applied in the actual and economic. In this research work, thirty corbels will be strengthened with externally bonded with CFRP sheets. Twenty-six of these specimens are tested with (a/d=0,7), two will be tested with (a/d=1,0), and two will be tested with (a/d=0,5), Corbels CONT1, CONT2, and CONT3 with shear span to effective ratio 1,0, 0,7, and 0,5 respectively. They are considered as control corbels for comparison.

3.3 Research Design

The research design is based on experimental research in terms of which a relevant factor, which are essential for the comparative study of RC corbel strengthened with CFRP by Abaqus software for finite element analysis. This research is a systematic investigation to find answer to the problem. On the other hand, it is a process of collecting, analyzing and interpreting information to provide a recommendation to the research findings.

After comprehensively organizing literature review of different previous published researches, designate the comparative study of RC corbel strengthened by CFRP with a previous experimental result for different parameters,

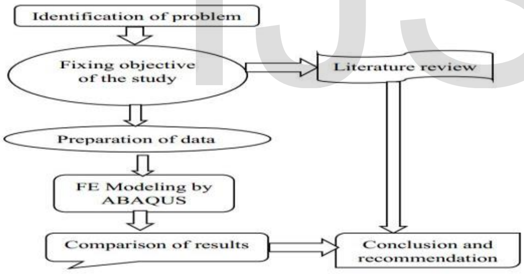

Figure 6. Flow Chart for Research design

3.4 Data Collection

The data collection for this research is both primary data which is from the result of Abaqus/CAE software finite element analysis and secondary data from different literature reviews.

3.5 Variables of the Study

In this study the parameters those considered for the investigation of structural behavior of reinforced concrete corbel was independent variable which are responsible for the response of structure under consideration.
Thus the independent variables are:-

- ✓ Applied load to the model
- ✓ Horizontal shear reinforcement
- ✓ Concrete compressive strength
- ✓ location of applied load
- ✓ width of CFRP strips
- ✓ Length of CFRP strips
- ✓ number of CFRP strips
- ✓ strengthening direction of CFRP strips
- ✓ shear span ratio

Therefore, the above study variables are used as input variable to investigate the response of reinforced concrete corbel. The dependent variables which have to be observed and measured to determine the effect of independent variables is behavior of RC corbel strengthened with CFRP.
Dependent variables of the research were: -

- ➢ Corbel load displacement
- ➢ Corbel shear failure
- ➢ Corbel flexural failure
- ➢ Crack pattern and other responses

3.6. Material Properties

In this research reinforced concrete corbels of heterogeneous material of concrete and steel are modeled to investigate the structural behavior under vertical shear loading. In general the material used in reinforced concrete corbel was concrete and reinforcement according to their elastic and actual inelastic properties. The structural behavior of RC structures is highly complex, because of the bond operation of concrete and steel. Concrete behavior is brittle, but, under stress reversal, tensile cracks might close, then broken parts being reassembled. Conversely, steel behavior is ductile, with extremely rare fractures, and broken parts cannot be reunited. Therefore, concrete behavior can be better described with damage models, whereas plasticity models better represent steel behavior. The property of reinforced concrete was the combined property contributed from concrete and reinforcement bar.

3.6.1 Modeling of Concrete

Reinforced concrete is one of the composite materials that have complex behavior, especially after cracking, Concrete behaves as linear-elastic before cracking. A new behavior occurs at the onset of cracking, the behavior in a plain parallel to the crack, is different from that in a plain perpendicular to the cracking surface. The orthotropic behavior of concrete in tension together with the nonlinear inelastic behavior in compression complicates the modeling of this material in connection with the finite element analysis (Bangash, 1989).

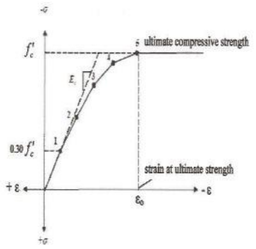

Figure 7. Idealized uniaxial stress-strain curve for concrete

The behavior of reinforced concrete structures under severe demands is highly complex; this is mainly due to bond operation of concrete and steel. In reinforced concrete structures, there are several coupled degradation and failure modes: cracking, crushing and spilling of concrete, yielding and pull-out of tensioned reinforcement, and yielding and buckling of compressed reinforcement. Therefore, in this simulation the elastic plastic property of concrete necessary used for and validity of the software output with the experimental and numerical comparison was performed (Hognestad, 1951).

Behavior of concrete was linear as low load but, if the load further increased it start to achieve yielding property until ultimate strength in compression then starts to crush for further load increment and finally fails by fracture. In similar manner, the concrete also possesses the tensile property under loading until the cracking stress and strain in the concrete reached and stress softening failure occurs. Quasi-brittle materials, as concrete, exhibit nonlinear stress strain response mainly because of micro-cracking, Cracks are oriented as the stress field and generate the failure modes. In tension, failure is localized in a narrow band; stress-strain behavior is characterized by sudden softening accompanied with reduction in the unloading stiffness. In compression, failure begins usually in the outside and is more complex, involving volumetric expansion, strain localization, crushing, and inclined slipping and spilling; stress-strain behavior involves ductile hardening followed by softening and reduction in the unloading stiffness. In mixed stress states, failure depends usually on the ratio between the principal stresses; in tension-compression, failure is generated by the compression of the material that is between the cracks. Noticeably, in tension the behavior is closer to damage than to plasticity; conversely, in compression the participation of plasticity is higher (Alfarah, et al, 2017).

In this research the concrete property as parameter of the consideration was nonlinear behavior through concrete damage plasticity was used in Abaqus software program algorithm for simulation of the structural behavior of the concrete corbel material input data. Tabular data for Abaqus input for concrete material property definition can developed from stress strain curve for compressive and tensile behavior and damage property of concrete was develop by considering compressive and tensile damage parameter (d_c and d_t) as compressive and tensile damage parameter.

In Abaqus concrete stress and strain required as tabular data was developed according to hongnestad approach: (based on strain interval)

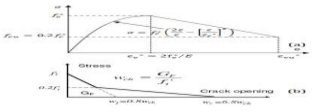

Figure 8,Concrete uniaxial stress-strain behaviors

a) Hognestad concrete compressive behavior b) Bilinear tensile behavior

$G_F=G_{fo}*(fc/10)^{0,7}$--(1)

In this equation G_F is a fracture energy related to the maximum aggregate size (d_{max}), Several values are given below.

Table 2.Relation between fracture energy and aggregate size

Maximum aggregate size d_{max}(mm)	Coefficient G_{fo}J/m^2
8	25
16	30
32	58

For low grade concrete the ES EN 1992:2015 material model works resemble with the Abaqus requirement (-1 -1 2004).

$$\frac{\sigma}{f_{cu}}=\frac{(k\eta-\eta 2)}{1+(k-2)\eta}\ ,\ where\quad k=\frac{1.05*\left(E_{cm}/\varepsilon_{c1}\right)}{f_{cm}}\quad and\quad \eta=\frac{\varepsilon_c}{\varepsilon_{c1}}\qquad (3.4)$$

It is assumed that the uniaxial stress-strain curves can be converted into stress versus plastic strain curves in Abaqus for concrete damage plasticity model, Compressive stress data are provided as a tabular function of inelastic or crushing strain.

3.6.2 Modeling of Steel

In developing a finite element model of reinforced concrete member, at least three alternative representations of the reinforcement have been used (Al-Shaarbaf, 1990).

Distributed representation: the steel is assumed to be distributed over the concrete element, with a particular orientation angle θ, A composite-reinforcement constitutive relation is used in this case. To derive such a relation, perfect bond must be assumed to occur between the concrete and the steel, Embedded representation: the reinforcing bar is considered as an axial member built into the concrete element such that its displacements are consistent with that of the element, Also, perfect bond must be assumed to occur between the concrete and the steel.

Discrete representation: one-dimensional bar element may be used in this approach to simulate the reinforcement, this element is connected to concrete mesh nodes at bar location. Therefore, the concrete and the reinforcement mesh share the same nodes and concrete occupies the same regions occupied by the reinforcement. This representation is adopted in the present study.

In ABAQUS computer program the behavior of a steel bar is described by a bilinear stress-strain curve starting at the origin with positive stress and strain values. The initial slope of the curve is taken as the elastic modulus of the material, At the specified yield stress (FY=C1), the curve continues along the second slope defined by the tangent modulus C2 (having the same units as the elastic modulus). The tangent modulus cannot be less than zero nor greater than the elastic modulus.

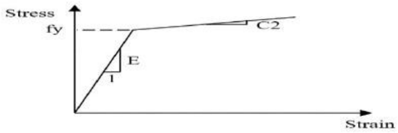

Figure 9.Typical stress-strain for steel bar

3.6.3 Modeling of CFRP Composites

FRP composites are materials that consist of two constituents. The constituents are combined at a macroscopic level and are not soluble in each other, One constituent is the reinforcement, which is embedded in the second constituent; a continuous polymer called the matrix. The reinforcing material is in the form of fibers, which are typically stiffer and stronger than the matrix. The FRP composites are anisotropic materials, that is, their properties are not the same in all directions.

Linear elastic orthotropic properties of the FRP composite are assumed thought out this study, as shown in Fig, 10. In addition, full bond between the concrete and CFRPs is assumed.

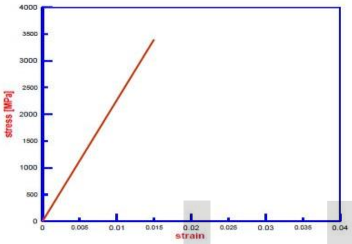

Figure 10.Stress-strain relationship for CFRP composite

3.7 Finite Element Analysis

3.7.1 Introduction

The general purpose of finite element program (Abaqus) will be used in this study to investigate the behavior of reinforced concrete corbels strengthened with CFRP.A three dimensional finite element models will be developed to account for geometric and material non-linear behavior of RC corbel. Finite element analysis is a powerful computer method of analysis that can be used to obtain solutions to wide range of structural problems involving the use of ordinary or partial differential equations. Finite element user cans either liner or non-linear analysis, (Bath, 2014).

In building a finite element model, it is necessary to define the element types, element real constants, material properties and the model geometry.

3.7.2 Element Types

The element types for this model are shown in Table 1. The Solid element was used to model the concrete, Wire element was used to represent the main reinforcement and Shell represents the CFRP strips.

Table 3.Element types for working model.

Material type	**Abaqus element**
Concrete	3D deformable Solid homogenous
Steel plate	3D deformable Solid homogeneous
Reinforcement	3D deformable wire homogenous
CFRP strips	3D deformable shell homogenous

Abaqus/CAE is the Complete Abaqus Environment that provides a simple, consistent interface for creating Abaqus models, interactively submitting and monitoring Abaqus jobs, and evaluating results from Abaqus simulations. A complete Abaqus analysis usually consists of three distinct stages:

- ➢ Preprocessing
- ➢ simulation, and
- ➢ Post processing

3.7.3 Preprocessing

In this stage models of the physical problem defined and create an Abaqus input file. The model is usually created graphically using Abaqus/CAE or another preprocessor, although the Abaqus input file for a simple analysis can be created directly using a text editor.

<u>FE preprocessing procedure of RC Corbel on Abaqus software</u>

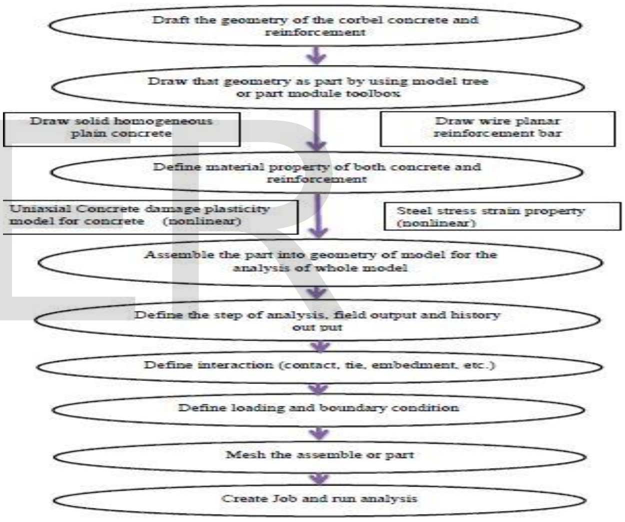

Figure 11.Preprocessing of finite element modeling flow chart

3.7.4 Modeling of the Structure

The dimensions and the reinforcement details for the corbels are presented in Fig. 12. By taking advantage of symmetry of the tested corbel, only one quarter of corbel was used for modeling as shown in Fig. The overall mesh (for example CONT1) of the concrete, plate, and support volumes is shown in Fig. For the other corbels, the same mesh of elements is used but the distribution of the elements in x and y-direction is modified to be more compatible with location of CFRP strips. The section below describes the mesh density, boundary condition and applying load techniques that adopted in the present study. A total of thirteen corbels were tested. The pertinent details are presented in Table below. The three a/d ratios considered are 1.0, 0.7, and 0.5.

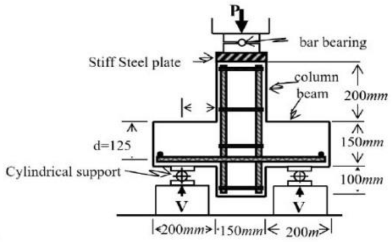

Figure 12.Dimensions and reinforcement details (Mohammad Ali and Attiya, 2012)

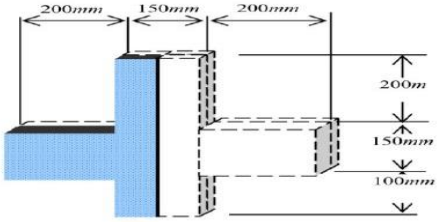

Figure 13.Sketch for a quarter of corbel model

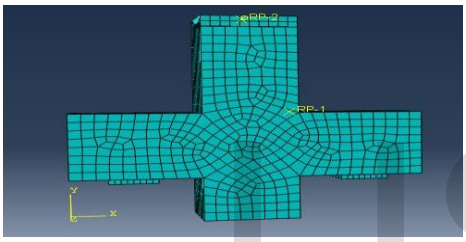

Figure 14.Mesh of concrete, steel plate and steel support of corbel(control specimen without CFRP strip),

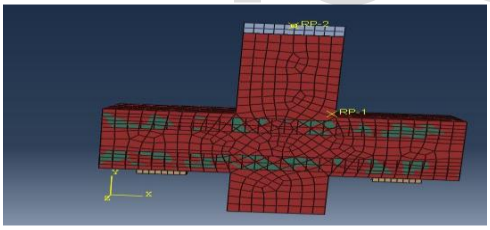

Figure 15.Mesh for the corbel with Horizontal strengthening (CHS2)

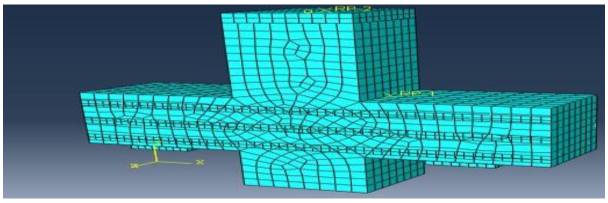

Figure 16.Mesh of corbel with horizontal strengthening (CHS3)

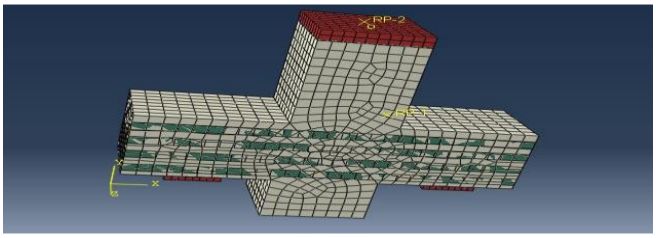

Figure 17.Mesh of corbel strengthening with horizontal CFRP (CHS4)

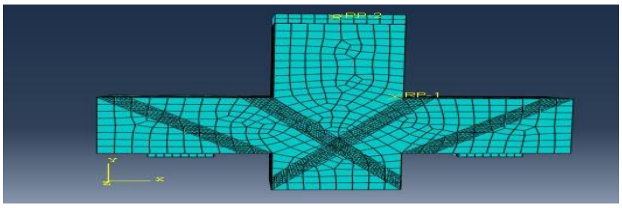

Figure 18.Mesh of corbel strengthening with inclined CFRP (CIS2)

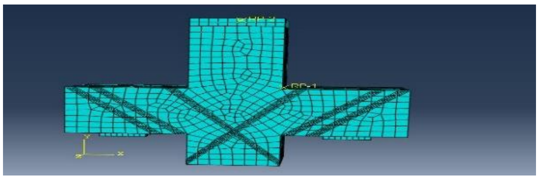

Figure 19. Mesh of corbel strengthening with inclined CFRP (CIS3)

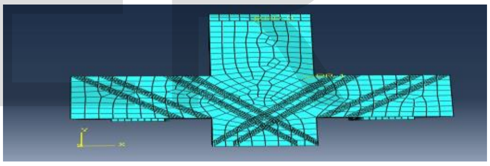

Figure 20.Mesh of corbel strengthening with inclined CFRP (CIS4)

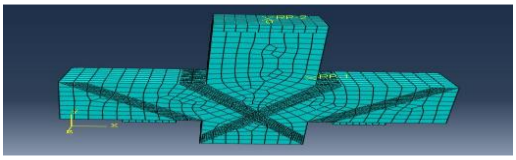

Figure 21.Mesh of corbel strengthening with inclined CFRP (CISR2)

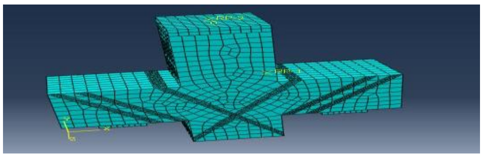

Figure 22.Mesh of corbel strengthening with inclined CFRP (CISR3)

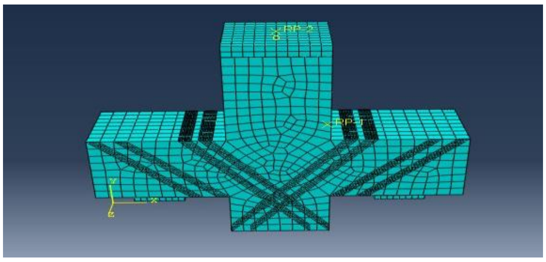

Figure 23.Mesh of corbel strengthening with inclined CFRP (CISR4)

Table 4.Details of the tested corbel,

Corbel designation	**Strips inclination (θ)**	**Strips Thickness (mm)**	**Width of Strips (mm)**	**No, of Strips**	**(a/d) Ratio**
CONT1	---	---	---	---	0,7
CIS2	45°	0,13	36,0	2	0,7
CIS3	45°	0,13	18,0	3	0,7
CIS4	45°	0,13	18,0	4	0,7
CISR2	45°	0,13	36,0	2	0,7
CISR3	45°	0,13	18,0	3	0,7
CISR4	45°	0,13	18,0	4	0,7
CISFR2	45°	0,13	36,0	2	0,7
CONT2	---	---	---	---	1,0
CISR2	45°	0,13	36,0	2	1,0
CONT3	---	---	---	---	0,5
CISR2	45°	0,13	36,0	2	0,5
CISR2	45°	0,13	36,0	2	0,7
CHS2	0°	0,13	36,0	2	0,7
CHS3	0°	0,13	18,0	3	0,7
CHS4	0°	0,13	18,0	4	0,7
CHSR1	0°	0,13	72,0	1	0,7
CHSR2	0°	0,13	36,0	2	0,7
CHSR3	0°	0,13	18,0	3	0,7
CHSR4	0°	0,13	18,0	4	0,7
CHSFR4	0°	0,13	18,0	4	0,7

3.7.5 Loading and Boundary Conditions

Displacement boundary conditions are needed to constrain the model to get unique representation for the actual corbel. Boundary condition need to apply at points of symmetry and where the supports and loads exist. The boundary conditions are set first. The model being used is about two planes. To model the symmetry, nodes on these planes must be constrained in the perpendicular directions. Therefore, the nodes in Ux and Uz have a degree of freedom equal to zero. The support (steel plate of 75x150x10) was modeled in such a way as a roller. A single line of nodes on the plate is given constraint in the UY direction. By doing this, the corbel will be allowed to rotate at the support, as shown in Figure. A steel plate of (75x150x10) and (150x150x25 mm) which is used at loading and reactions locations to avoid the situation of stress concentration. A line of load is applied to the center of steel plate at the location of the load, but due to symmetry the part of load which is lying on the symmetrical plane must be divided as illustrated in Figure.

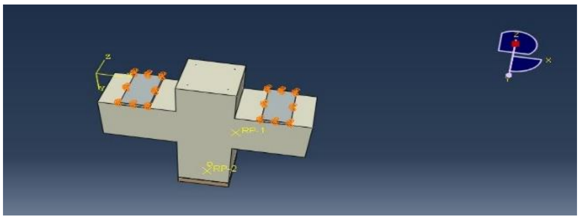

Figure 24.Boundary conditions of corbel support

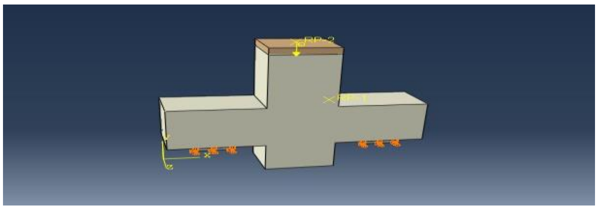

Figure 25.Boundary condition of corbel load

3.8 Ethical Consideration

I am ensuring that no harm occurs because of carefully evaluate the potential for harm to arise accordingly behave to appropriate ethical standards, consider harm my thesis might negatively affect participants and protect myself and advisors resulting in public criticism.

4.RESULT AND DISCUSSION

4.1. Post Processing Finite Element Analysis

In finite element analysis method by using any software one can look at the result in the software output storage in the visualization module once the analysis by monitor indicate the job completion. The result is displayed based on the parameter or variable incorporated in the step field output and history output. The variables are stresses, strain, deflection, reaction; failure or fracture and any other parameter can be considered based on the type of analysis performed, Hence these response variables are aimed to be considered under investigation in this research inside with parametric study.

To illustrate the validity of the proposed numerical method for the analysis of reinforced concrete corbels strengthened with CFRP strips, all tested corbels were analyzed by using ABAQUS computer program, as mentioned previously. The analysis follows the same procedure as that given in experimental work taking into account the variation in material properties, dimensions and other specifications.

4.2 Load Deflection Behavior

The experimental and numerical Load-deflection curves obtained for the tested corbels are shown in Figs. 26 – 37. In general, good agreement has been obtained by using the finite element model compared with the experimental results throughout the entire range of the behavior. A relatively stiffer numerical post-cracking response is noticed for all corbels as compared with the experimental results. Also, it can be seen that the axial ultimate load values obtained from the finite element analysis are slightly higher than the actual experimental ultimate loads.

The ratios of the predicted finite element ultimate loads to the corresponding experimental ultimate loads ranges between 0991 and 1.098 of the analyzed corbels are listed in Table 5.

Table 5.A comparison between experimental and numerical ultimate loads of the analyzed corbels.

Corbel designation	**a/d**	**Numerical ultimate load (KN)**	**Experimental ultimate load (KN) (Mohammad Ali and Attiya,2012)**	**P_{nu}/P_{ex}**
CONT1	0.7	311	292	1.065
CIS2	0.7	440	430	1.023
CIS3	0.7	440	422	1.042
CIS4	0.7	438	425	1.030
CISR2	0.7	509	467	1.089
CISR3	0.7	478	435	1.098
CISR4	0.7	488	447	1.091
CISFR4	0.7	473	454	1.041
CISR2 rep,	0.7	-	458	-
CONT2	1.0	233	235	0.991
CISR2	1.0	314	294	1.068
CONT3	0.5	389	358	1.086
CISR3	0.5	544	504	1.079
CHS2	0.7	350	335	1.044
CHS3	0.7	390	370	1.054
CHS4	0.7	360	347	1.037
CHSR1	0.7	358	348	1.028
CHSR2	0.7	355	340	1.044
CHSR3	0.7	402	383	1.049
CHSR4	0.7	365	353	1.033
CHSFR4	0.7	372	356	1.045

4.2.1 Test Results of Unstrengthen Corbels (Control Corbels)

During loading of Specimen CONT1, the first major crack appeared at 70 KN as depicted the first crack was a vertical crack appearing approximately at the corbel face close to the column side. The other crack was a diagonal crack almost at an angel of 45 degrees (i.e. shear crack), this was at a load level 43% of the ultimate failure load (i.e. there was a high level of ductility) diagonal shear cracks formed at a load level of 130 KN. As the load increased, this crack started to widen and propagated leading to failure at a load level of 311 KN. Increasing the load led to new diagonal cracks and the diagonal cracks propagated rapidly until failure.

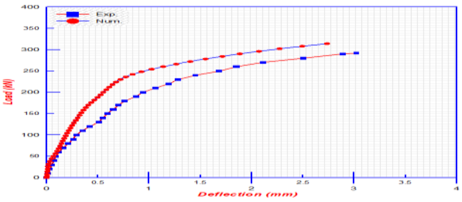

Figure 26. Comparison between numerical and experimental load deflection curve (CONT-1)

4.2.2 Strengthening Effect of Using CFRP Strips

To study the effect of strengthening reinforced concrete corbels with horizontal externally bonded carbon fiber reinforced polymer strips, series corbel specimens CHS were strengthened with two (CHS2), three (CHS3) and four (CHS4) layers of CFRP strips and with layer width 36mm for corbel specimen CHS2, 18,0mm for both corbel specimens CHS3 and CHS4.

For specimens CHS2, The first crack to appear during the loading sequence was a flexural crack similar to that of a cantilevered beam, While a second crack started at the bearing plate, and propagated towards the junction of the column and face of the corbel. This crack caused failure of the corbel. The corbel failed at an ultimate load of (335 KN) with an increase in strength of about (14.7 %) compared to Unstrengthened corbel specimen CONT1 (control corbel).

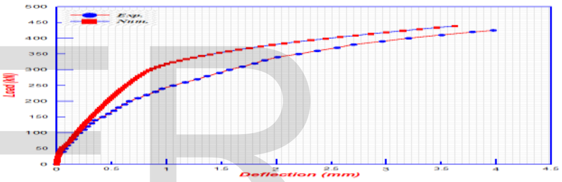

Figure 27.Comparation between numerical and experimental load -deflection curve (CHS2)

To study the effect of strengthening reinforced concrete corbels with ***inclined*** externally bonded carbon fibre reinforced polymer strips, three corbel specimens CIS2, CIS3 and CIS4 were strengthened with two, three and four layers of CFRP strips having 36,0,18,0 and 18,0mm width respectively. The major differences between series CHS, and CIS were the area of secondary cracks and the spalling of the concrete between the cracks.

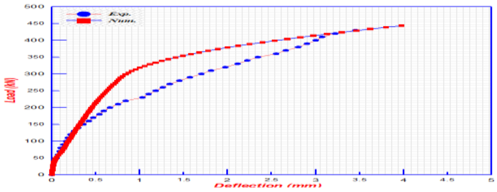

Figure 28,Comparison between numerical and experimental load-deflection curve (CIS2)

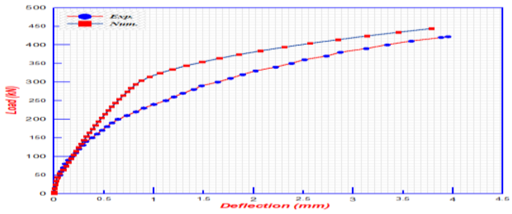

Figure 29.Comparsion between numerical and experimental load-deflection curve (CIS3)

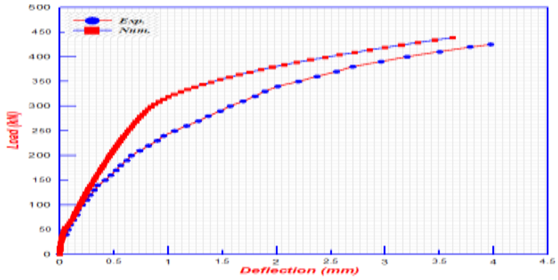

Figure 30.Comparison between numerical and experimental load-deflection curve (CIS4)

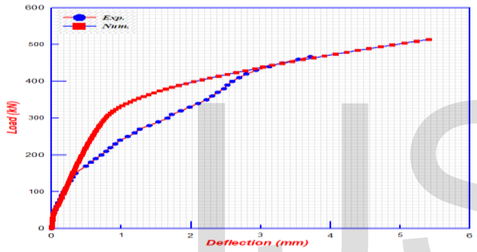

Figure 31.Comparison between numerical and experimental load-deflection curve (CISR2)

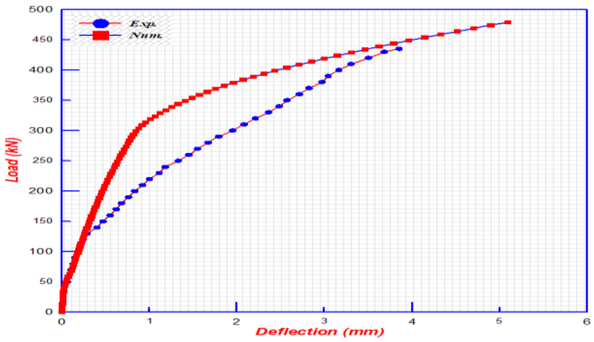

Figure 32.Comparison between numerical and experimental load -deflection curve (CISR3)

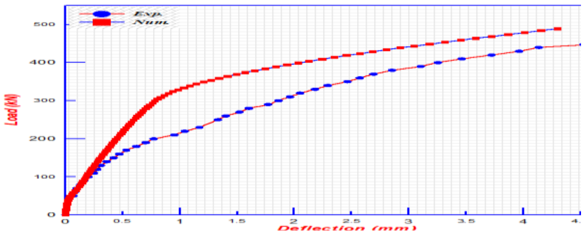

Figure 33.Comparison between numerical and experimental load-deflection curve (CISR4)

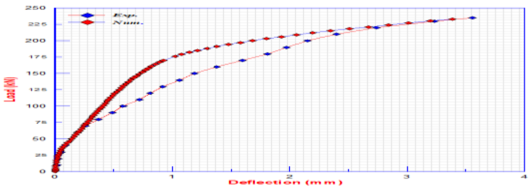

Figure 34.Comparison between numerical and experimental load - deflection curve (CONT-2)

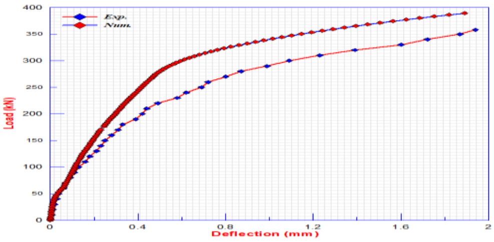

Figure 35.Comparison between numerical and experimental load-deflection curve (CONT-3)

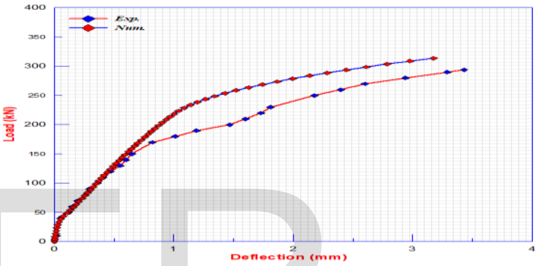

Figure 36.Comparison between numerical and experimental load-deflection curve (a/d=1.0)

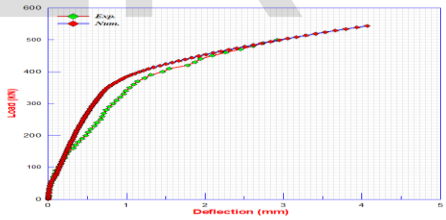

Figure 37.Comparison between numerical and experimental load-deflection curve (a/d=0.5)

4.3 Stress, Strain and Deflection Distribution

Specimen corbel CONT1, CHS2 and CIS2 were taken for example to verify the application of the proposed numerical solution by using ABAQUS computer program V6,13-1 software. The deflected shape of corbel CONT1, and CIS2 due to external applied loads and variation of stress in the longitudinal x, y, and x-y-direction, and variation of strain in x and y-direction is shown in Figs, 38 – 47. In these figures, it is obvious that the maximum stress is at upper of column face.

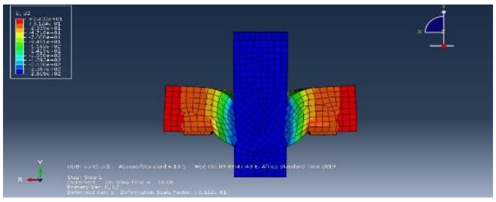

Figure 38.Variation of deflection U2 of corbel CONT-1 at ultimate load,

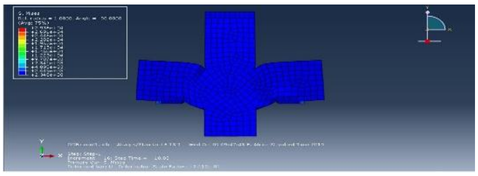

Figure 39.Variation of stress in x-direction of concrete corbel cont-1 at ultimate load,

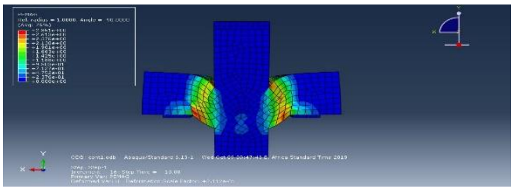

Figure 40.Variation of strain in x-direction of concrete corbel CONT-1 at ultimate load

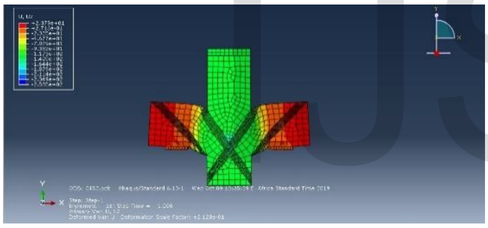

Figure 41.Variation of deflection U2 of corbel CIS2 at ultimate load,

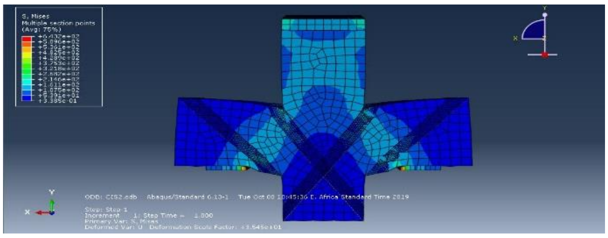

Figure 42.Variation of stress in X-direction of concrete corbel CIS2 at ultimate load,

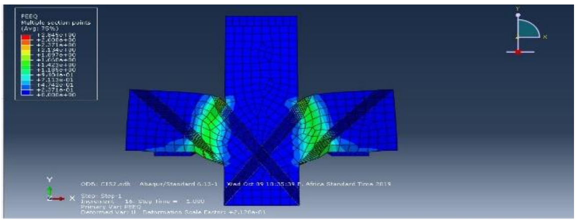

Figure 43.Variation of strain in X-direction of concrete Corbel CIS2 at Ultimate load,

4.4. Strain in Concrete

The numerical concrete strains are obtained at the same positions where the corresponding experimental strains are recorded. A comparison between experimental and numerical concrete strain distribution shows good agreement within the elastic of behavior or before cracking.

Table 6 shows the numerical and experimental compressive strains of concrete located at 20 mm from top and bottom face, and at column face of analyzed corbels. It may also be noted that the numerical tensile strains of concrete are in good agreement with experimental data of corbels CONT1 and CIS2 at early stages of loading, while some difference between numerical and experimental strain occurred at final stages of loading, This difference is because that the presence of wide cracks at the tensile zone of mid span section.

Figs. 44 and 45 show a comparison between experimental and numerical concrete strain distribution for corbels CONT1 and CIS2 respectively.

Table 6.Experimental and numerical extreme fiber concrete compressive and tensile strains of corbels CONT-1 and CIS2.

		Load	**50 KN**	**100 KN**	**180 KN**	**270 KN**
CONT1	Numerical		0,0008	0,0012	0,0018	0,0025
			-0,0005	-0,0006	-0,0009	-0,00157
	Exp.		0,0006	0,0009	0,0016	0,00204
			-0,00035	-0,0008	-0,0013	-0,00192
		Load	**130 KN**	**220 KN**	**300 KN**	**380 KN**
CIS2	Numerical		0,001	0,0014	0,0018	0,0023
			-0,0009	-0,00153	-0,00173	-0,00214
	Exp.		0,0008	0,0009	0,0013	0,0015
			-0,0009	-0,00145	-0,0016	-0,00199

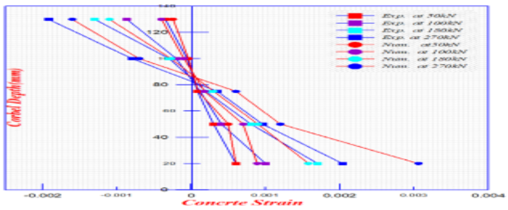

Figure 44.Comparison between numerical and experimental for concrete strain distribution of corbel control-1,

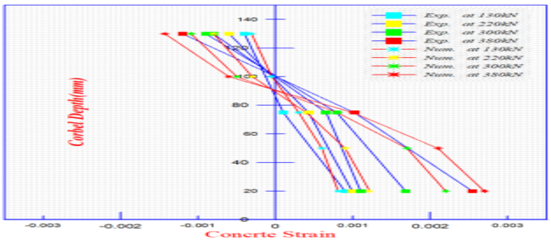

Figure 45.Comparison between numerical and experimental for concrete strain distribution for corbel CIS2.

Fig. 46. Shows a comparison between numerical and experimental tensile strain developed in 1st and 2nd inclined strips of corbel CIS2, the development of tensile strains gives good agreement between numerical and experimental results.

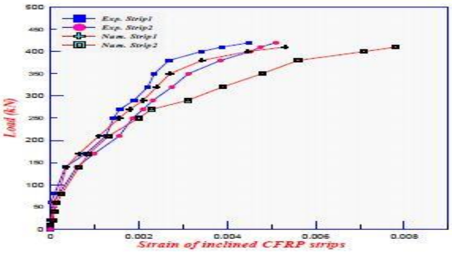

Figure 46.Development of tensile strain in inclined CFRP strips of corbel CIS2.

4.5. Tensile Stress in CFRP

The finite element solutions reveal that the maximum stress developed in each CFRP strips is smaller than ultimate stress of CFRP strips which was 3500 MPa. Failure of the corbels occurred due to presence of diagonal shear cracks. These cracks occur at integration points of the solid brick elements. At ultimate load level, the CFRP strips ruptured at regions where the major diagonal shear cracks. Figs. 47 - 55 shows variation of tensile stresses developed in CFRP inclined strips at different loading stages for corbel specimens of series CIS and CISR.

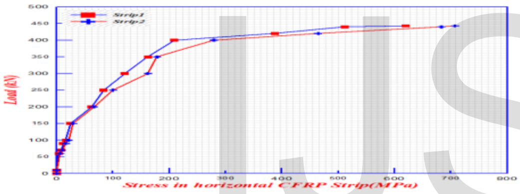

Figure 47.Development of tensile stress in inclined CFRP strips of corbel CIS2.

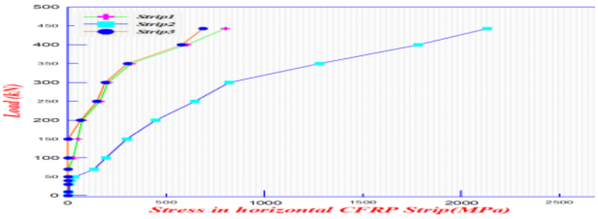

Figure 48.Devlopment of tensile stress in inclined CFRP strips of corbel CIS3

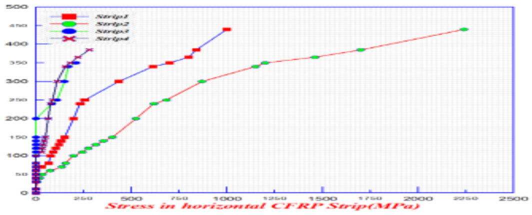

Figure 49.Development of tensile stress in inclined CFRP Strips of corbel CIS4.

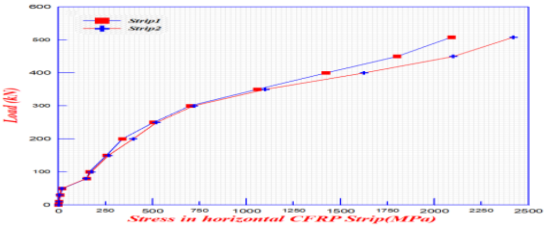

Figure 50.Development of tensile stress in inclined CFRP strips of corbel CISR2

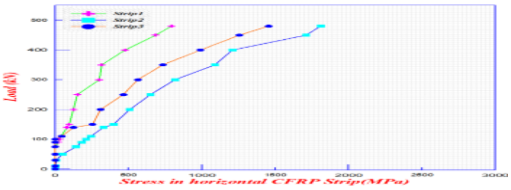

Figure 51.Development of tensile stress in inclined CFRP strips of corbel CISR3.

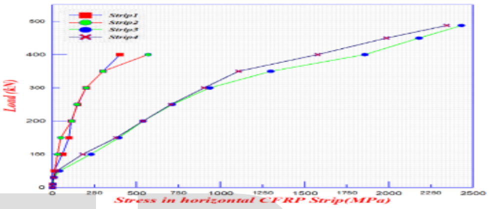

Figure 52.Development of tensile stress in inclined CFRP Strips of corbel CISR4.

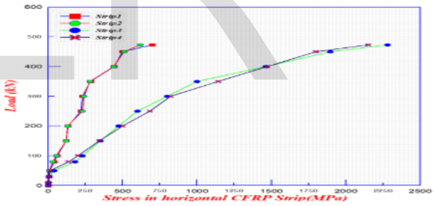

Figure 53.Development of tensile stress in inclined CFRP strips of corbel CISFR4.

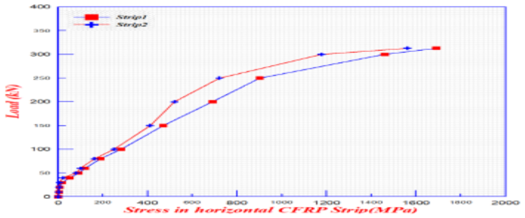

Figure 54.Development of tensile stress in inclined CFRP Strips of corbel CISR2 (a/d=1.0).

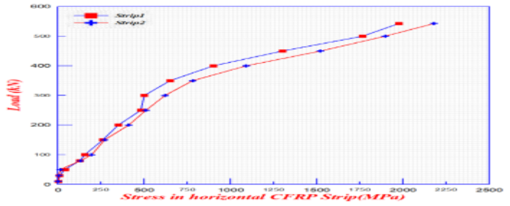

Figure 55.Development of tensile stress in inclined CFRP strips of corbel CISR2 (a/d=0.5).

5.CONCLUSION AND RECOMMENDATION

5.1 General

Nonlinear 3D finite element models have been developed using ABAQUS finite element software to investigate the behavior of reinforced concrete corbel externally strengthened with CFRP strips. A static solution strategy was implemented in the analytical model to trace stable post peak response in the load-deformation curve. The concrete material in the reinforced concrete corbel was modeled using the damage plasticity model available in ABAQUS and CFRP material was modeled using default type of Damage available in ABAQUS. The surface contact of steel and concrete was modeled as embedded constraint and the surface contact of CFRP and concrete as well as surface contact between CFRP was modeled as Tie constraints. To investigate the performance of this FEM model, simulations were conducted for reinforced concrete corbel strengthened with CFRP test, reported in the literature. The loading condition was limited to only concentric loading, The effects of the selected parameters on the behavior of CFRP strengthened concrete corbel were studied with respect to axial load versus displacement curve. The conclusions of parametric study and performance of FE model are listed below.

5.2 Conclusion

Based on the overall results obtained from the finite element analysis for the externally strengthened reinforced concrete corbels by CFRP strips, the following conclusions can be drawn:

1. The three-dimensional nonlinear finite element model adopted in the present research work is suitable for predicting the behavior of the strengthened reinforced concrete corbel with CFRP sheets, The numerical results are in good agreement with experimental load-deflection results throughout the entire range of the behavior, The maximum difference in the ultimate load was less than 8%,
2. The cracking patterns obtained from the finite element models are similar to the crack patterns observed in the experimental work, where all the analyzed corbels failed with a mode of failure similar to that which occurred in the experimental test,
3. The tensile strain in CFRP obtained from finite element analysis is in good agreement with those obtained from experimental work, especially at the early load stages,
4. The concrete strain at different stages of loading observed from the finite element model is in good agreement with those obtained from experimental work,
5. The finite element analysis reveals that the maximum tensile stresses developed in CFRP strips at failure ranged between (522) and (2430) MPa for inclined CFRP strips respectively,

5.3 Recommendation

- Further investigation is needed to study the effect of hybridized concrete and steel fiber by using finite element method,
- Further investigation is needed to study the concrete corbel under cyclic loading for well-defined and setup cyclic loading protocol experimental literature,
- Further investigation is needed to study the effect of retrofitting corbel by carbon fiber on the structural behavior of RC corbel like load displacement, nature of cracking and other parameters,
- In this study the developed FE model was verified for concentric loading only, Therefore, in future research eccentric loading should be incorporated in the FE model,
- In this study, the external strengthening of RC corbel with CFRP was investigated, Strengthening with other available fiber reinforced polymer (FRP) materials like glass fiber reinforced polymer (GFRP) can be studied to investigate the efficiency of the strengthening technique using different materials with different properties,
- In this study, the bond between concrete and CFRP as well as the bond between CFRP and CFRP was assumed to be perfect, Although this assumption did not cause a significant error in the obtained results comparing with experimental investigations, The behavior of the bond and de-bonding issue can be studied analytically to get more precise results especially regarding failure modes,

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