Palestine Polytechnic University

Deanship of Graduate Studies and Scientific Research

Master of Civil Engineering

Strengthening of Reinforced Concrete RC Beams using SWM SCC jacketing

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Thesis submitted in partial fulfillment of requirements of the degree
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ABSTRACT

Strengthening of reinforced concrete (RC) beams with Self-compacting concrete (SCC) jacketing reinforced with galvanized welded steel wire mesh (SWM) has been an important area of study so far. Increasing the mechanical characteristics of (RC) beams and structures to maintain the required service life and load capacity of any (RC) structure, is considered as an interesting area of study. In this research, a Finite Element (FE) investigation is conducted on series of (RC) beams which were previously strengthened experimentally with Self-compacting concrete (SCC) jacketing reinforced with galvanized welded steel wire mesh (SWM). A (FE) model will be conducted to predict the load-deflection behaviour and crack/failure pattern of the strengthened beams. Based on both experimental and numerical model achieved results, the FE model results will give some important conclusions and recommendations regarding the experimental strengthening of RC beams using this technique. Another strengthening technique using an external steel plate will be also used and checked to be compared with the SCC SWM strengthening technique. Finally parametric study will be conducted.

تقوية الجسور الخرسانية المسلحة باستخدام الخرسانة ذاتية الدمك

(مراجعة تجريبية ودراسة باستخدام النمذجة العددية)

اسم الطالب: يونس العثامين

الملخص

تقوية الجسور الخرسانية المسلحة بقميص خرساني مضغوط ذاتيًا , معززة بشبكة سلكية فولاذية ملحومة مجلفنة يعتبر مجالًا مهمًا للدراسة حتى الآن. تعتبر زيادة الخصائص الميكانيكية للجسور والهياكل الخرسانية من أجل الحفاظ على العمر التشغيلي المطلوب وسعة التحميل لأي مبنى خرساني مجال دراسة مثير للاهتمام. في هذا البحث ، تم إجراء دراسة باستخدام طريقة العناصر المحددة على سلسلة من الجسور الخرسانية المسلحة التي سبق تقويتها تجريبيًا باستخدام قميص خرساني مضغوط ذاتيًا مقوى بشبكة سلكية ملحومة من الصلب المجلفن . سيتم إجراء نموذج باستخدام برنامج اباكوس للتنبؤ بسلوك وقيمة الحمل القصوى ونمط التشققات / الفشل للجسور المقواة. بناءً على النتائج التي تم تحقيقها من خلال النموذجين التجريبي والرقمي ، سيقوم النموذج بعرض بعض الاستنتاجات والتوصيات المهمة المتعلقة بعملية تقوية الجسور الخرسانية المسلحة باستخدام هذه التقنية بالاضافة الى أنه سيتم أيضًا استخدام تقنية تقوية أخرى باستخدام لوح فولاذي خارجي وسيتم في نهاية الرسالة عمل دراسة على أهم العوامل المتحكمة في هذه التقنية الهجينة التي تستخدم أكثر من تقنية تقوية للجسور الخرسانية المسلحة في أن واحد.

DECLARATION

I declare that the Master Thesis entitled" **Strengthening of Reinforced Concrete RC Beams using SWM SCC jacketing**" is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name: **Yones Al Atamin**

Signature:——————————— Date:———————

DEDICATION

I want to thank my **family** and my **wife** for helping me to pursue my higher education in civil engineering. I'm incredibly thankful to my supervisor **Dr. Belal Almassri**, for his support and help. I also want to thank my **friends** and family who have been there for me during this process. I will always be grateful for everything they have done; I dedicate this work to all family members who helped me.

To everyone works in this field,

To the **soul of my father**,

I dedicate this humble work.

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I would like to express my sincere gratitude to my advisor, **Dr. Belal Almassri**, the head of civil engineering department for his invaluable guidance and support throughout my master's program. His expertise and encouragement helped me to complete this research and write this thesis.

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List of Abbreviations

SCC: Self Compacting Concrete

SWM: Steel Wire Mesh

CDP: Concrete Damage Plasticity

WWM: Welded Wire Mesh

FRP: Fibre Reinforced Polymer

RC: Reinforced Concrete

FE: Finite Element

EBR: Externally Bonded Reinforcement

NSM: Near Surface Mounted

CFRP: Carbon Fibre Reinforced Polymer

SFRC: Steel fibre reinforced concrete

UHPFRC: ultra-high performance fibre reinforced concrete

BFRP: Basalt Fiber Reinforced Polymer

ECC: Engineered Cementitious Composite

ACI: American Concrete Institute

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Chapter 1: Introduction

1.1 Research Background

Structural retrofitting and repair of existent RC structures is considered to be one of the major challenges that modern civil engineers are currently facing. To this effect, self-compacting concrete (SCC) mixes can be used efficiently as a material for retrofitting of various structural members. In this master thesis, the efficacy and applicability of SCC mixtures as retrofitting material for beam specimens using jacketing techniques was investigated, the SCC concrete will be discussed based on previous experimental data which used galvanized welded steel wire mesh (SWM). From the literature review, It was found that retrofitting of damaged beams samples making use of SCC jacket and reinforced with welded wire mesh SWM restores and enhances the ultimate load carrying capacity of primary beams specimen, no finite element FE research modelling approach was employed before in the literature to study this topic.

1.2 Research Problem

The literature review which was made based on related experimental, analytical and FE numerical modelling data showed that there was a research gab in the following points:

- FEM study need to be validated to study some beams repaired with SCC SWM Layers.
- There is a lack in the literature in the parametric study of the RC beams strengthened with SCC SWM.
- The literature did not employ this technique as repair technique for old and deteriorated RC beams.
- There is a need to investigate new and hybrid (more than one strengthening technique at the same time) using the FE modelling approach.

1.3 Research Objectives

Base on the research gap found in the literature review. The following points are the main objectives of this master thesis:

- Conduct a FE model in order to validate the experimental data which was performed on RC beams repaired with SCC SWM technique using the commercial software ABAQUS.
- Investigate the possibility of adding more than one strengthening technique to the RC beam at the same time, one of the proposed techniques is adding external steel plate to increase the flexural resistance of the RC beams which were previously repaired with SCC.
- Perform a parametric study in order to check the compressive strength of the concrete, the steel plate thickness and ductility index of repaired specimens.

1.4 Research Outline

The thesis consisted of five chapters; each chapter contains the following parts:

Chapter 1: Introduction, Research Problem and Research Methodology

Chapter 2: Experimental Investigation in the Literature review

Chapter 3: FE Modelling Parameters, Material Properties and Test set up

Chapter 4: Results and Discussion of verification of model, load-displacement curves, crack patterns and results of parametric study

Chapter 5: Some important Conclusions and Recommendations

1.5 Research Methodology

The main steps and the tools will be used in this study are shown below:

- A review for the experimental results for RC beams strengthened with SWM SCC jacketing will be presented.
- The validity of FE numerical analysis using the commercial software ABAQUS will be illustrated in anticipating the flexural performance of RC beams with SCC jacketing reinforced with SWM layers. Numerically obtained results are validated to those experimental counterparts in terms of crack patterns and the load-carrying capacity versus the mid-span deflection.
- The validated FE model will then widen to analyze the influence of adding external steel plates to the lower surface of the jacketed specimens on both the ultimate capacity and stiffness.
- The significance of the study arises from the fact that if an approach of FE can be validated, designers can predict the structural performance of various hybrid strengthening techniques on RC/SWM/SCC beams without the need for long and expensive experimental testing programs.
- Parametric Study will be done, it will give some important research conclusions on the important factors that affect the strengthening technique.

Chapter 2: Literature Review

2.1 General Theoretical Background

There are many different strengthening techniques are available in practice for reinforced concrete (RC) structures. The strengthening or repair technique is necessary for RC structures during their service life if the structures don't meet the code of practice requirements due to different types of deterioration and damages. A large number of structures constructed in the past using the older design codes are structurally unsafe according to the new design codes and hence need strengthening.

The main causes of deterioration depending on its cause can be classified into two categories. The first one is sudden damages which include natural disasters, wars and accidental damages, the other one is progressive damages which attributed to abuse use, neglect particularly the historical building and harmful environmental factors(Ziara et al., 1997), one of the environmental results of those damages is the corrosion of steel reinforcement which leads to several major defects. Firstly, a reduction in the cross-sectional area of the reinforcement and in its ductility results in premature bar failure. Secondly, the expansion of the corrosion products causes concrete cracking and steel–concrete bond deterioration and also affects the bending stiffness of the reinforced concrete members, causing a reduction in the overall load-bearing capacity of the reinforced concrete beams.

Beams are considered to be main and important structural members for affording loads, so finding the efficient strengthening/repair techniques are necessary in terms of maintaining the safety of the structures. The application of steel welded wire mesh (WWM) to the surface of RC members as external reinforcement is a promising and recent new technique for strengthening and rehabilitating damaged concrete elements (Xing et al., 2010).

These days, it is important to find a suitable strengthening technique in terms of cost and time. In this research, the focus has been placed on the investigation of structural behavior of rectangular RC beams strengthened with galvanized steel WWM embedded in Self-Compacting Concrete (SCC) jacketing, which is recently considered a new technique for strengthening damaged concrete elements.

2.2 Damage assessment and types of concrete structures damages

Concrete structures need to be strengthened for any of the following reasons:

- Load increases due to higher live loads, increased wheel loads, installations of heavy machinery, or vibrations.
- Damage to structural parts due to aging of construction materials or fire damage, corrosion of steel reinforcement, and/or impact of vehicles.
- Improvements in suitability for use due to limitation of deflections, reduction of stress in steel reinforcement and/or reduction of crack widths.
- Modification of structural system due to elimination of walls/columns and/or openings cut through slabs.
- Errors in planning or construction due to insufficient design dimensions and/or insufficient reinforcing steel.

The following figure shows the hierarchic structure of damage assessment for RC buildings which separated into five categories (main criteria). (Hamdia et al., 2018)

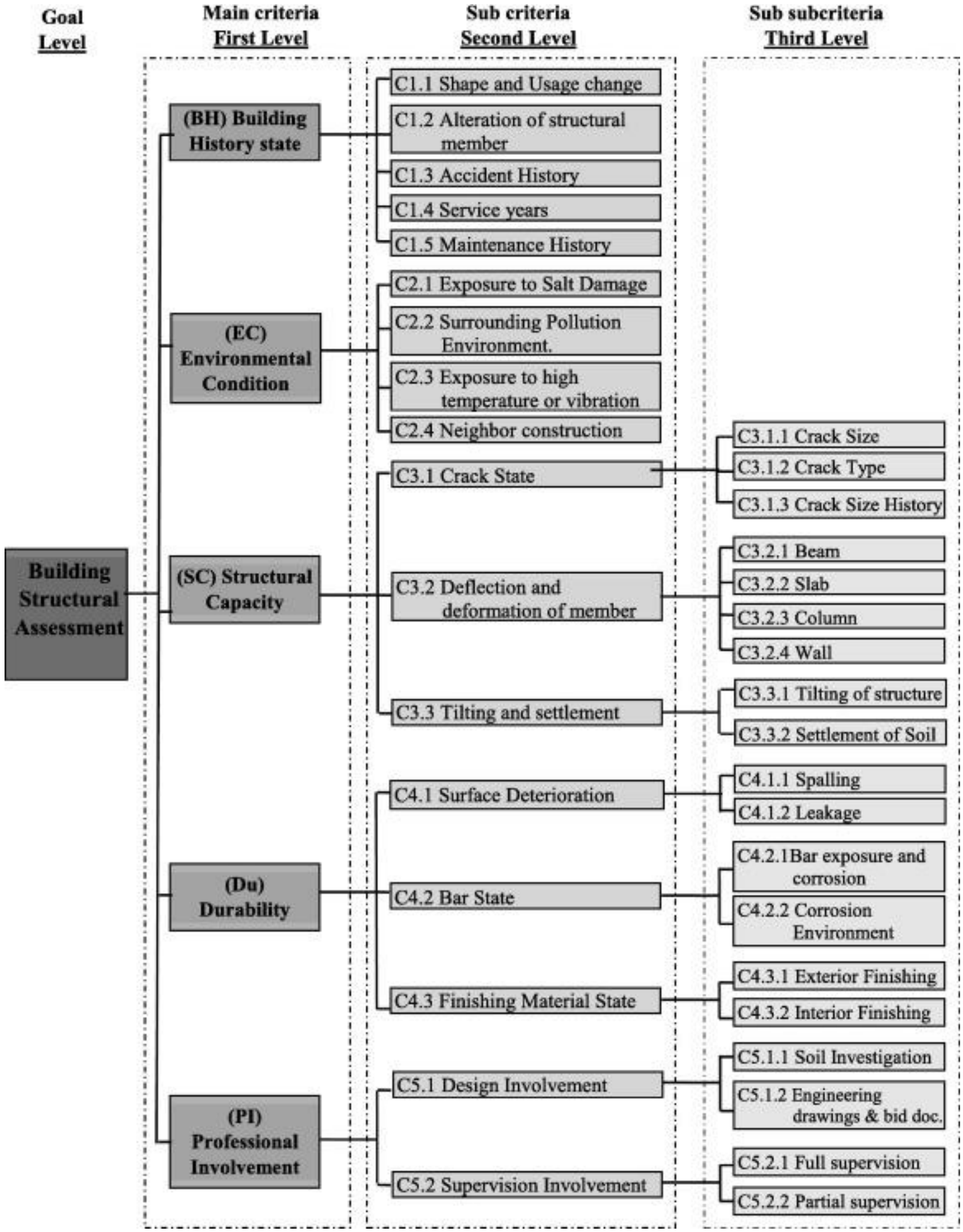


Figure 1 Damage assessment of structural buildings (Hamdia et al., 2018)

2.3 Damages in RC beams in Israel

Israel is costal country which has more than 270 Km coastline length on the Mediterranean Sea. This geographic location with the associated environmental conditions may have a considerable effect on the deterioration of existing concrete structures built in Israel, from the literature it was found the following causes are behind the majority of the structural defects in the buildings:

1. Many of the exposed concrete facades of buildings along Israel's seashore show the typical cracking and spalling caused by **corrosion of reinforcing steel** near the concrete surface, even after a few years of service. Field observations and tests confirm that high chloride concentrations in the vicinity of the reinforcing steel near the concrete surface are the main cause for the early onset of corrosion (Jaegermann, 1990).

Figure 2 Reinforced Concrete Building with severe damage due to Corrosion

2. **Vertical Flexural cracks due to excess of loadings**, a previous study by (Gluck et al., 2015) studied the existent structures in Israel and provided an assessment of the structural ability to stand the increased loads of the actual demand, the study found that the temperature changes can lead to crack development, FRP sheets as well as steel profiles can be used to strengthen the RC walls studied.
3. **Diagonal Shear cracks** due to inappropriate sections.
4. **Fire, and any other accidental damages** to the structures.

Figure 3 Structural Cracks and fire damages of RC buildings

2.4 Strengthening and repair Techniques of RC beams

Before choosing the right and suitable strengthening technique of different RC elements, it is important to consider the additional loads during repair process, the new loads after the repair finished and finally ensure a good bond resistance between old and new interfaces of materials or techniques used.

2.4.1 Compression Concrete Overlay

This technique can be conducted by roughening the original concrete surface then adding a new concrete overlay reinforced with light shrinkage reinforcement as shown in Figure 4, to ensure full interaction between new and old materials one of the following methods must be done:

1. Using of shear connectors to prevent inter laminar shear.
2. Making concrete keys for the original concrete surface and painting it with bonding agent.
3. Bonding of stirrups with original concrete through drilling holes and installing the ends of stirrups into these holes using epoxy resin, the fixation length must be sufficient to transfer the shear stresses.

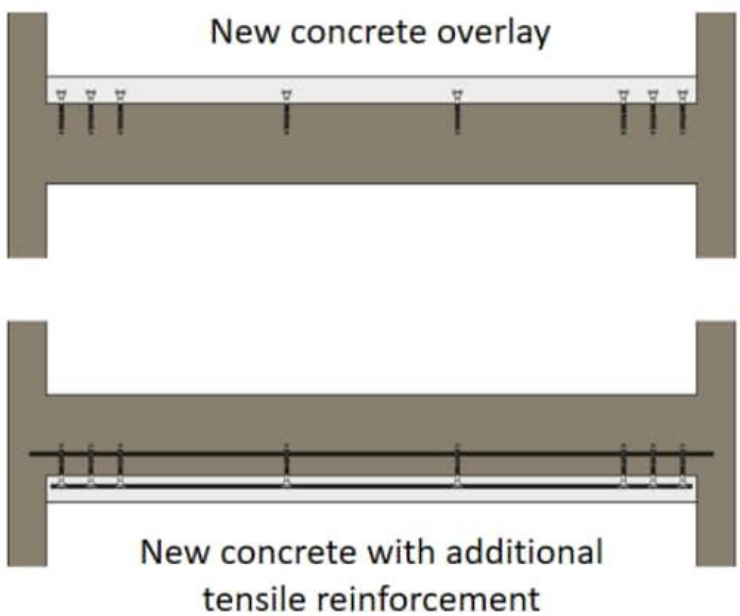


Figure 4 Concrete Overlay

2.4.2 Flexural Strengthening of RC beams

RC beams can be strengthened by adding new concrete to lower face of the beam. In this technique the beam depth increased due to strengthening of the tension zone of a beam through concrete underlays. In order to accomplish force transfer between old and new concrete, roughening of the surface of the old concrete is required, as well as welding of connecting bars to the existing bars and new reinforcement.

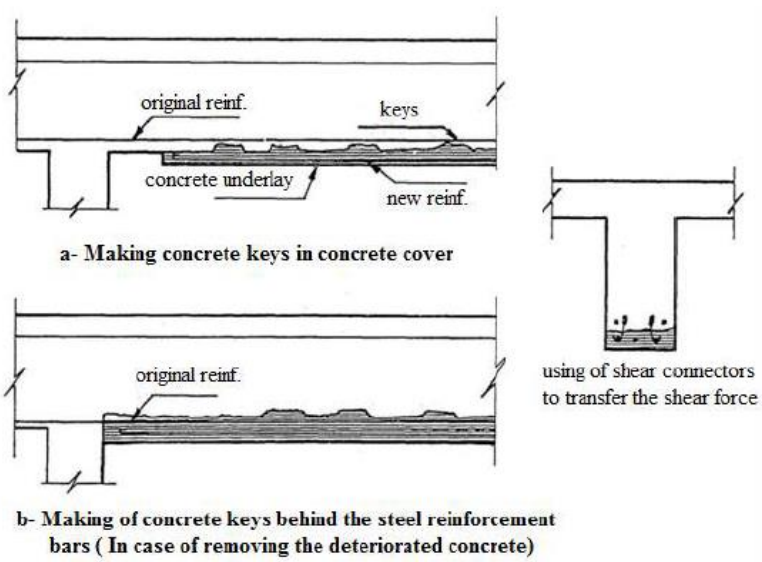


Figure 5 Flexural Strengthening

The technique of bonding steel plates to the surface of concrete has been used on a number of structures throughout the world to enhance load carrying capacity (Rodríguez et al., 2006). With this technique, the bonded steel plates act as external reinforcement. The effect of bonding a plate to the tension face of a RC beam is to increase the depth from the compression face to the neutral axis and the area of effective reinforcement, thus, increasing the moment of resistance of the section. The operation can be undertaken without additional support to the member.

The bonding of steel plates to concrete members has been undertaken by several methods, using epoxy adhesives or using bolts. The choice of method being dependent upon the particular circumstances. Figure 6 shows the strengthening of a bridge girder using externally bolted steel plate.

Figure 6 External Steel Plate

Addition of CFRP rods or Sheets (Composite Section) can be also a promising solution to enhance the load bearing capacity of RC beams using different techniques (such as near surface mounted NSM or externally bonded laminate EBR), the CFRP can increase the stiffness and ultimate bearing capacity of corroded RC beams repaired with CFRP NSM rods. (Almassri et al., 2014)

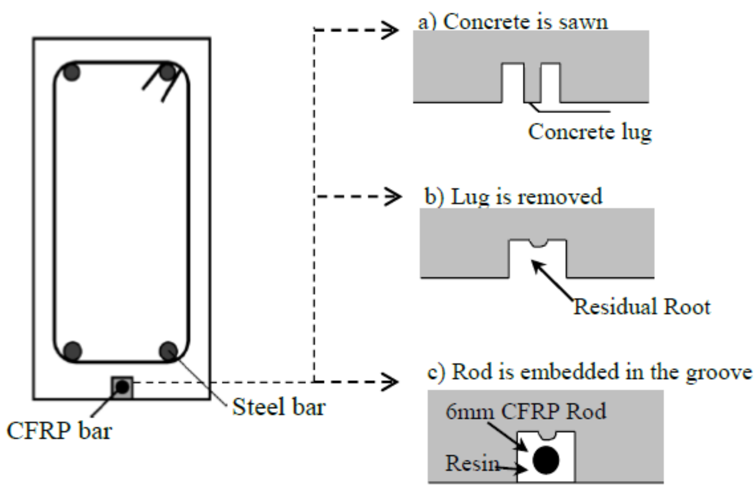


Figure 7 NSM CFRP rods

2.4.3 Shear Strengthening of RC beams

The technique of addition of external stirrups and or external steel plates can be accomplished using high strength steel bolts that distributed along the beam length at predetermined distances (represent stirrups) connected with steel plates or steel sections such as C- channel as shown in Figure 8. These bolts and steel sections must be protected against environmental condition and from corrosion with a coating. Also, the new reinforcement is encased in conventionally placed concrete or in shotcrete if there are no aesthetic restrictions.

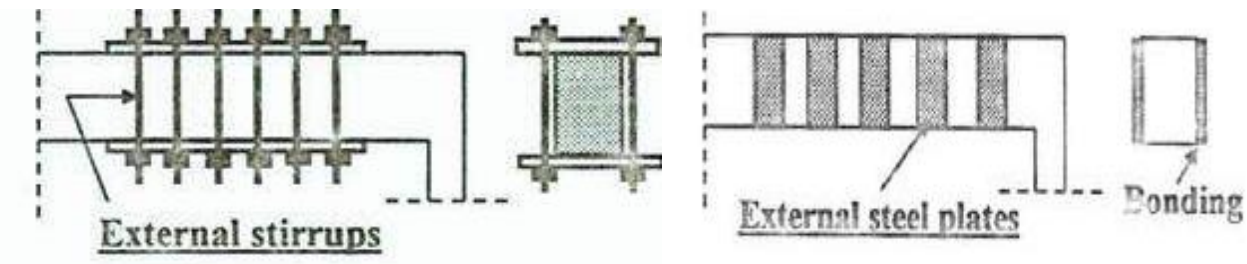


Figure 8 Addition of steel stirrups / steel plates to support shear resistance of RC beams

Adding CFRP bars or sheets to support the shear capacity of RC beams have been an interesting area of study as well for several researches, (Almassri et al., 2016) tested some corroded RC beams which repaired in shear using NSM CFRP rods, it showed that repairing against shear using NSM FRP rods significantly decreased the maximum slip of the tensile steel bars for control RC beams and increased the ultimate shear capacity of the beams.

Figure 9 Adding CFRP rods to support shear to tested beams (Almassri et al., 2016)

2.4.4 RC Jacketing

RC jackets can be applied by adding new concrete to three or four sides of the beam (Kappos et al., 2002). In order to accomplish force transfer between old and new concrete, roughening of the surface of the old concrete is required, as well as welding of connecting bars to the existing bars and new reinforcement. RC beam jacketing on all four sides of the beam is the most effective solution. The thickness of the concrete that is added to the upper face is such that it can be accommodated within the floor thickness (maximum: 50—70 mm). The placement of the ties is achieved through holes, which are opened in the slab at closely spaced distances and are a so used for pouring the concrete. The longitudinal reinforcement bars of the jacket are welded to those of the old concrete. Jackets on three sides of the beam are used to increase the flexural and shear capacity of the beam for vertical loading, but not for seismic actions, given that strengthening of the load-bearing capacity of the section near the supports is impossible. The key to the success of such an intervention is the appropriate anchorage of the stirrups at the top of the sides of the jacket.

Supplemental members are new columns, beams, braces, or infilled walls that are installed to support strengthened structural members. The supplemental members are typically placed below the failure or deflected areas to stabilize the structural framing.

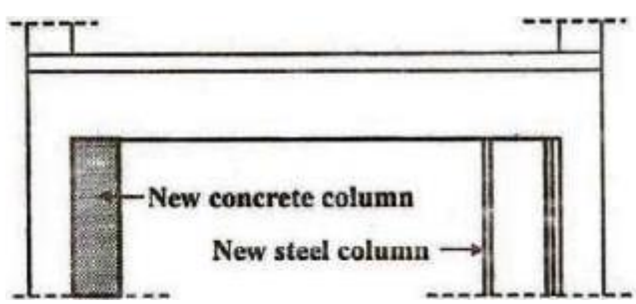


Figure 10 Span Shortening

2.5 Section Enlargement studies

(Diab, 1998) carried out an experimental program to evaluate the effectiveness of repairing RC beams with a layer of sprayed concrete. Nine specimens (three series) were tested in total. The first series includes the testing of three reference beams (PR1-PR3) to failure. In series two, three beams (PR1-PR3) 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 three beams (PR4-PR6) have same dimension with P1 and tested in the same manner with series two, except that the reinforcing layer was performed with fibrous concrete.

The experimental results indicate that jacketing using sprayed concrete to strengthen RC beams can effectively increase their load carrying capacity or stiffness and the strengthened beams showed high ductility before failure as shown in Figure 11.

Furthermore, additional metallic glass ribbon fibers in sprayed concrete improved the crack pattern and ultimate capacity of RC beams. Adding metallic glass ribbon fibers to RC beams improved flexural strength, enhanced cracking pattern, reduced tensile stress and greatly increased the first cracking moment.

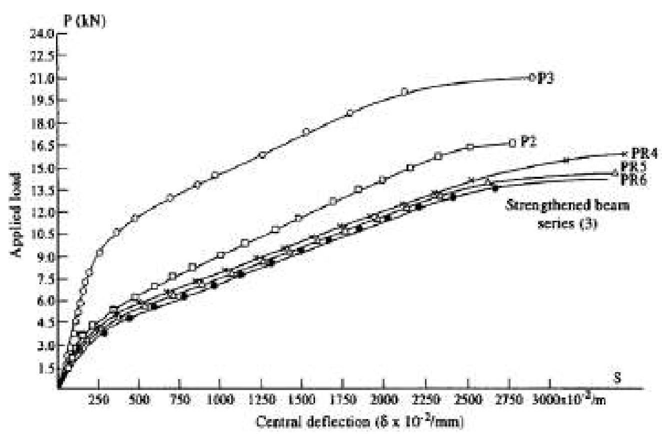


Figure 11 load deflection curve for strengthening techniques

(Mahdy et al., 2004) showed that the strengthened beams of additional stirrups exhibit typical failure with a ductile manner and with enhancement in strength reach 233% of the control beam. While, the strengthened beam without additional stirrups fails in brittle manner and by separation of the added concrete layer with strength enhancement reach 132% of the control beam.

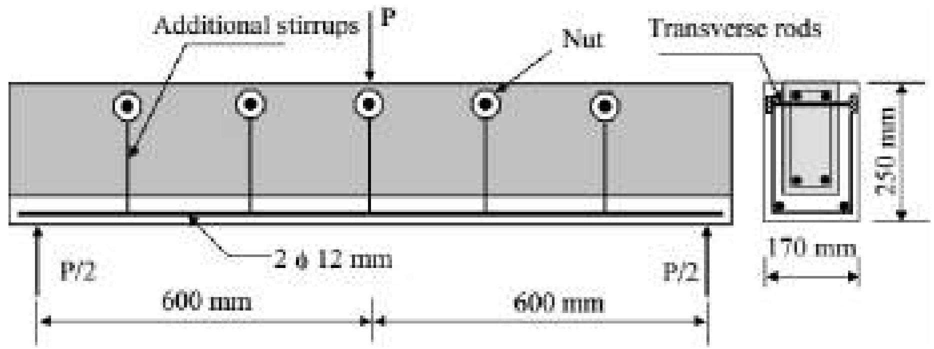


Figure 12 Jacketing by (Mahdy et al., 2004)

(Altun, 2004) showed that damaged RC beams would behave similar to the ordinary RC beams of same dimensions with added RC jackets. However, the beam with highest ductility ratio is the most efficient since the section area is relatively less as compared to the section resisting the maximum Ultimate Load (UL). This reduces the amount of cost of the jacketing material.

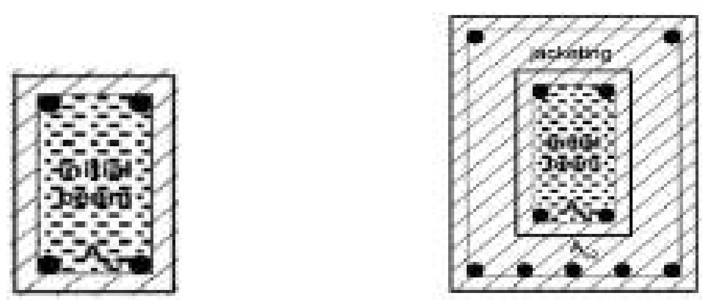


Figure 13 RC beam section before and after Jacketing (Altun, 2004)

Different researchers have employed various methods of jacketing for reinforced concrete (RC) elements. The jacketing of RC beams was done by using additional reinforcement and for connection between lateral and longitudinal reinforcement bar of old and new beam Z bars were introduced before concreting. Better mechanical behavior of the jacketed RC beams was observed as compared to that for ordinary RC beams of the same dimensions, despite the fact that the core parts of the jacketed RC beams were damaged. Surface preparation plays important role before jacketing for superior performance of RC jacketed beam. Difference in the behavior of jacketed beams was observed whose interfaces. Very less amount of information is available in the literature regarding the requirement of the surface of the RC beam during execution of the jacketing process. Also, it is essential to find more information on behavior of RC beams when jacketed using different methods of jacketing in order to avail overall enhancement of its performance. Therefore, ten RC beams of 150 mm x 300 mm x 2100 mm have been cast in (Raval and Dave, 2013). The surface of four beams is kept as cast and the surface of other four beams is chipped up to 10-15 mm all around the beams. Two beams have been considered as the control beam. Four different methods have been employed for jacketing of the RC beams. These methods include use of dowel connectors and micro-concrete, bonding agent and micro-concrete, combined use of dowel connectors & bonding agent and micro-concrete and only the use of micro-concrete. All four methods have been employed for jacketing of the RC beams with the smooth surface as well as the chipped surface. As an outcome of investigation, for smooth surface RC beam, superior performance was observed for the beam jacketed using combined dowel connectors and bonding agent with micro-concrete. For chipped surface RC beams, superior performance was observed for the beam jacketed using only micro concrete and without use of dowel connectors and bonding agent.

Self-consolidating concrete is a new category of high-performance concrete that exhibits a low resistance to flow to insure high flowability, and a moderate viscosity to maintain a homogeneous deformation through restricted sections, such as closely spaced reinforcement. Self-consolidating concrete is used to improve the productivity of casting congested sections and to insure the proper filling of restricted areas with minimum or no consolidation. Such concrete can improve the homogeneity of highly flowable concrete that is necessary to insure good bond development with reinforcing steel, adequate structural performance, and proper durability. (Khayat, 1999) reviews the benefits of using self-consolidating concrete to facilitate the casting of densely reinforced sections and improve productivity and on-site working conditions. Workability requirements necessary to secure self-consolidation and the principles involved in proportioning such highly flowable concrete are discussed. Field-oriented tests useful in evaluating the deformability, filling capacity, and stability of self-consolidating concrete are presented. The performance of concrete mixes proportioned according to two main approaches needed to insure high deformability, low risk of blockage during flow, and proper stability are compared. Such approaches involved the proportioning of concrete with a moderate water-to-cementitious material ratio (w/cm) of 0.41 and using a viscosity-enhancing admixture to increase stability, as well as mixes without any viscosity-enhancing admixture, but with lower w/cm of 0.35 to 0.38 to reduce free water content and provide stability. Mixes with both moderate and high contents of ternary cementitious materials were evaluated. The performance of each concrete was compared to that of a flowable concrete with 250-mm slump

2.6 FE Modelling applications on different strengthening techniques

In the past few decades, finite element (FE) modelling considered a promising solution in several civil engineering challenges which have a widespread application worldwide for the aim of reducing significantly the experimental cost, time and effort (Oleg and Linar, 2020). Furthermore, the performing of FE analysis is also paramount in principle structural elements particularly beams, columns, piers, girders and slabs to investigate the different mechanical and structural properties such as strength, deflection, ductility, stiffness, strain, cracking, energy absorption and modes of failure (Al-Abdwais and Al-Mahaidi, 2020; Nayak et al., 2022). The applicability and accuracy of the FE model depend mainly on achieving a FE modelling solution that approaches considerably to the experimentally obtained results (Almassri et al., 2016; Godat et al., 2020; Sakr et al., 2019; Zhang and Teng, 2014). Thus, the FE analysis should take into consideration all affecting parameters precisely to optimize the best numerical solution (Al-Abdwais and Al-Mahaidi, 2020; Almassri and Halahla, 2020).

(Oleg and Linar, 2020) presented a research article which studied the joint behavior under load of steel fiber concrete strengthening jackets (SFRC) and reinforced concrete beams at all loading stages. It was recommended that further development of calculation methodology for this strengthening method for members subjected to bending. Experimental results presented the strength, stiffness, crack resistance and failure behavior with a crack propagation pattern for the examined samples (two with strengthening jackets and two reference non-strengthened samples). It has been found that the use of an SFRC jacket 45 mm in thickness with 2.5% fiber content (at the rate of 196 kg per cubic meter) increases the failure load by 20%, the stiffness –3.4–11 times in the course of loading, and crack resistance – about 2.6 times. The results showed that the computer simulation in ANSYS PC: the discrepancy between the cracking load, failure load and deflection values for full scale samples and the computer model were found to be within 6.3 %.

Several studies have been conducted on flexural strengthening using epoxy adhesive for both externally-bonded and Near-Surface Mounted carbon fibre reinforced polymer (NSM CFRP) composites. (Al-Abdwais and Al-Mahaidi, 2020) conducted a FE numerical modelling in order to evaluate the experimental results of flexural behavior of RC beams retrofitted with NSM CFRP textile and laminate using modified cement-based adhesive. The research findings presented important and noticable increase in flexural strength, reaching the same results gained from epoxy adhesives. A previous and recent study was presented by (Almassri and Halahla, 2020) evaluated the experimental results using FE numerical model for corroded RC beam repaired with NSM CFRP rod in flexure, that beam was previously tested experimentally and showed a premature mode of failure by the separation of concrete cover, in order to prevent this mode of failure, an external steel plate was proposed to this beam so this hybrid strengthening and repair technique was used to change the mode of failure which happened early so the NSM CFRP strengthening technique can by well employed in order to optimize the strengthening process.

(Sakr et al., 2019) presented repaired reinforced concrete (RC) shear walls which are considered one of the main lateral resisting members in RC buildings. Ultra-high performance fiber reinforced concrete (UHPFRC) was used as an advanced cement composite material, which is characterized by high tensile and compressive strength, ductility, durability and fracture toughness. Nevertheless, few studies on the application of

UHPFRC for retrofit/strengthening structural elements especially under lateral loading like earthquake. This study analyzed the behavior of strengthened RC shear walls by a FE numerical model using UHPFRC and reinforced UHPFRC (R-UHPFRC) jacketing under lateral loading using a two-dimensional (2D) model. First, behavior of RC and UHPFRC shear walls subjected to lateral loading is investigated using the proposed 2D model. It is stated that the strengthening procedure improved diagonal tension shear strength of the reference weak RC wall.

2.7 Jacketing of RC beams using SCC/SWM

The use of reinforced concrete (RC) jacketing has become a widespread structural technique applied within a wide variety of civil engineering applications such as retrofitting, rehabilitation and strengthening and even in repairing of several structural elements. Usage of jacketing in major structural members having self-compacting concrete (SCC) reinforced with steel wire mesh (SWM) is gaining wide acceptance because of its significant effect on both ductility and the ultimate carrying capacity. Members constructed from SCC/SWM jacketing is also exhibited a noticeable enhancement in the energy absorption capacity, cracking resistance and stiffness (Maraq et al., 2021; Tayeh et al., 2020).

(Maraq et al., 2021) showed some experimental tests which have been conducted up to failure, eleven strengthened samples, four control beams poured monolithically, and three original control beams. The eleven specimens are strengthened using the U-Jacketing technique in which a relatively thin reinforced SCC layer is applied for the bottom width and both vertical sides of the original beams. The strengthened beams are categorized into two groups A and B based on test variables, namely, the SWM properties and the bonding mechanism. In this research, the flexural capacity, ductility, stiffness, crack width and deflection are also clarified. Based on achieved test results, all strengthened beams were designed to fail in a ductile manner. The first group of strengthened beams restored on average 110% of the original control beams load capacity, whereas the second strengthened group resorted to 163% on average. Moreover, it is found that the strengthened beams acted in the same manner of the monolithic control beams and acted as a single unit. Accordingly, it is concluded that this strengthening technique can be used confidently in real-life applications, especially for low-priced constructions.

However, the studies concern with validation of this strengthening technique numerically is still quite limited. SWM frequently used in various structural applications namely: shell structures, precast elements, bridge deck slab, concrete road pavement, underground tunnels, water tanks, concrete sewer pipes, culverts, chimneys and even masonry walls. SCC is one of the innovative types of concrete that have gained considerable attention in the recent decade and proper for the production of reinforced concrete which has the ability to flow under its own weight (Adesina, 2020; Huseien and Shah, 2020; Sasanipour and Aslani, 2020). SCC provides an opportunity to produce reinforced concrete by eliminating the need for excessive vibration, particularly in highly congested reinforcement within concrete structures in a less energy-intensive manner. Also, SCC has been shown to exhibit lower permeability due to its composition, which is mostly made up of fine particles resulting in a more densified microstructure (Long et al., 2016; Sasanipour and Aslani, 2020; Si et al., 2018). Thus, more resistance to severe environmental exposure.

2.8 Hybrid strengthening techniques

The recent advances related to structural upgrading have contributed to the growth of hybrid strengthening techniques, the most common two materials, in particular, are steel plates and fiber reinforced polymers (FRP) (El Refai et al., 2015; Elsanadedy et al., 2021; Zheng et al., 2019) because of having a positive contribution to both the ultimate strength and ductility. FRP attracted a large number of researcher due to its superior properties such as shape flexibility, corrosion resistance, lightweight, durability and high strength to weight ratio (Arafa et al., 2018; Meier, 1995; Teng et al., 2002). A new hybrid strengthening technique was proposed by (Almassri and Halahla, 2020) where an external steel plates in addition to CFRP NSM rods were used to retrofit a corroded RC beam in flexure, the addition of external steel plate was in order to prevent the early failure happened by the separation of the concrete cover. There is hardly any research in the literature on the hybrid strengthening technique integrating SWM/SCC jacketing and steel plates. These two materials compensate each other in terms of structural properties. SCC jacketing is heavy in weight, having brittle properties and having architectural limitations, while steel plates are relatively lightweight, ductile and having acceptable architectural considerations. On the other hand, steel plates have some shortcomings varied from weak corrosion resistance to debonding failure (Khalaf, 2015). However, steel plates have the ability to enhance the flexural strength of the strengthened samples and can delay the propagation of first cracks, increasing the stiffness, as well as reducing the crack width (Zheng et al., 2019).

Zhao et al. 2012, investigated numerically using ANSYS software the shear performance of RC beams upgraded by using U-shaped polymer mortar reinforced with SWM. The experimental tested results were compared with the obtained numerical ones in terms of crack pattern and the strains in both the longitudinal reinforcement bars and the stirrups. Two models namely: the separated model and the composite model were carried out using ANSYS for this aim. The test results revealed that the strain numerical results are in good agreement for both longitudinal and transverse reinforcement of the two models (i.e. separated and composite models) with the experimental results except that stirrups' strains in the composite model. The crack patterns are not obvious when comparing the numerical results with experimental ones. However, this research lacks studying flexural strength, deflection, stiffness, ductility or even conducting a parametric study.

Similar results have been validated by an effort by Elsanadedy et al. but focused mainly on flexural capacity enhancement. In this paper, the authors used multilayers of textile reinforced mortars and carbon fiber-reinforced polymer (CFRP) as an external U-shaped flexural strengthening of RC beams. From the obtained lab results, the flexural load-carrying capacity and the bending stiffness were increased significantly. Besides the experimental test program, a numerical analysis was conducted using a nonlinear FE analysis investigation on the LS-DYNA software program. Based on the validation of FE results, a good agreement was gained between the experimental analysis and the numerical analysis. Moreover, the FE modelling was extended beyond the validation process by performing a parametric study for the aim of upgrading the flexural strength of the RC beams using different end anchorages and more layers of TRM.

In a recent research, (Zheng et al., 2020) studied the RC beams performance improvement due to shear capacity. As for practical work, five RC beam specimens were strengthened with Basalt Fiber Reinforced Polymer (BFRP) mesh combining with Engineered Cementitious Composite (ECC) versus one conventional RC beam as a reference control beam. In the test programs, there are two main parameters, the BFRP grid reinforcement ratio and the shear-span ratio. Based on achieved test results, it was found that the shear strength was highly enhanced and greatly affected by the two parameters. Moreover, for the purpose of validation of the experimental work in terms of shear strength a FE modelling was also carried out based on ABAQUS software. The FE analytical results revealed that it can agree well with the measured experimental data, concluding that FE analysis has the ability to anticipate the shear capacity of the RC strengthened samples with the ECC/BFRP hybrid materials.

2.9 Conclusion from literature:

- FEM study need to be validated to study some beams repaired with SCC SWM Layers.
- There is a lack in the literature in the parametric study of the RC beams strengthened with SCC SWM.
- The literature did not employ this technique as repair technique for old and deteriorated RC beams.

2.10 Research Significance:

The present study follows up on the work conducted by Abu Maraq et al. (Maraq et al., 2021), a well-known FE commercial software ABAQUS is adopted to conduct numerical analysis. The validity of FE numerical analysis will be illustrated in anticipating the flexural performance of RC beams with SCC jacketing reinforced with SWM layers. Numerically obtained results will be validated to those experimental counterparts in terms of crack patterns and the load-carrying capacity versus the mid-span deflection. The validated FE model was then widened to analyze the influence of adding external steel plates to the lower surface of the jacketed specimens on both the ultimate capacity and stiffness. The significance of the study arises from the fact that if an approach of FE can be validated, designers can predict the structural performance of various hybrid strengthening techniques on RC/SWM/SCC beams without the need for long and expensive experimental testing programs.

Chapter 3: Research Methodology and FE Modelling

3.1 Experimental context

A comprehensive experimental testing program involving eighteen tests on flexural RC beams. The samples were strengthened and tested after they had been primarily loaded up to 30 per cent capacity of the control beam. The eighteen beams are categorized into 3 groups namely, control beams, strengthened group A beams and strengthened group B beams. The classification of the strengthened specimens is arranged based on both the bonding mechanism and the SWM' properties.

3.2 Test Program Description

The geometric characteristics for all initial core beams (i.e. before jacketing process) are similar. The total beam length is 1200 mm and with a width to depth of 100 mm x 150 mm as well as a shear span of 450 mm, as illustrated in Figure. 14. The RC beams are designed according to ACI-318 code thereby the top longitudinal steel reinforcement is 2Ø6 mm, while the bottom longitudinal steel reinforcement is 2Ø10 mm and the shear reinforcement is also provided using a 6 mm diameter mild steel bar at an equal spacing of 50 mm.

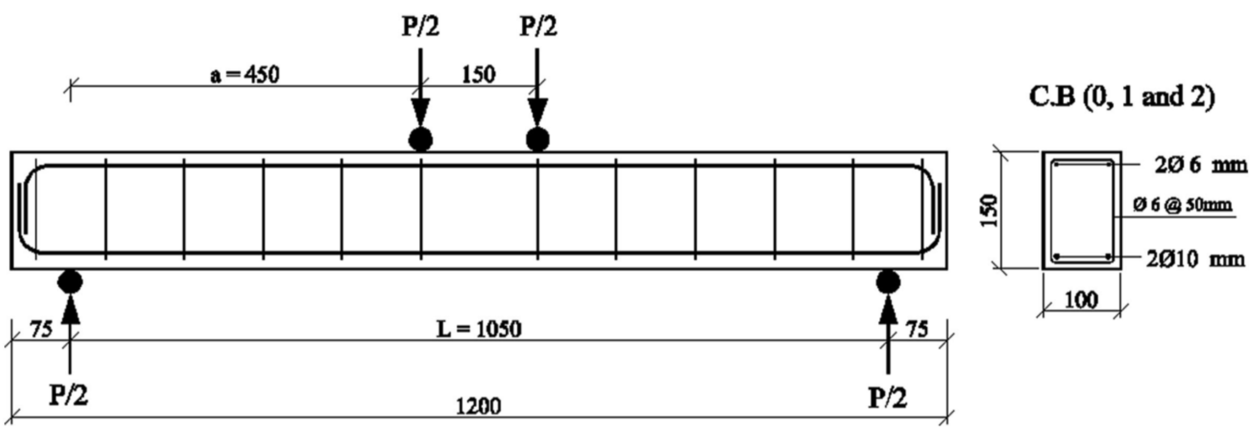


Figure 14 Typical beam geometry and cross-section detailing (dimensions in mm).

The test program includes an eighteen relatively small RC beam that tested experimentally to study the flexural capacity under a 4-point bending load test configuration until failure with a 1050 mm clear span. Three beams, denoted as C, are used as reference control beams with a typical cross-section, as seen in Figure. 14, with a width to depth of 100 mm x 150 mm. Four beams, denoted as M, are used as reference control beams when compared with their SCC jacketed counterparts' specimens, and are cast monolithically with the similar reinforcement cage of type C beams as well as SWM reinforcement, as seen in Figure. 15, with a width to depth ratio of 160 mm x 200mm.

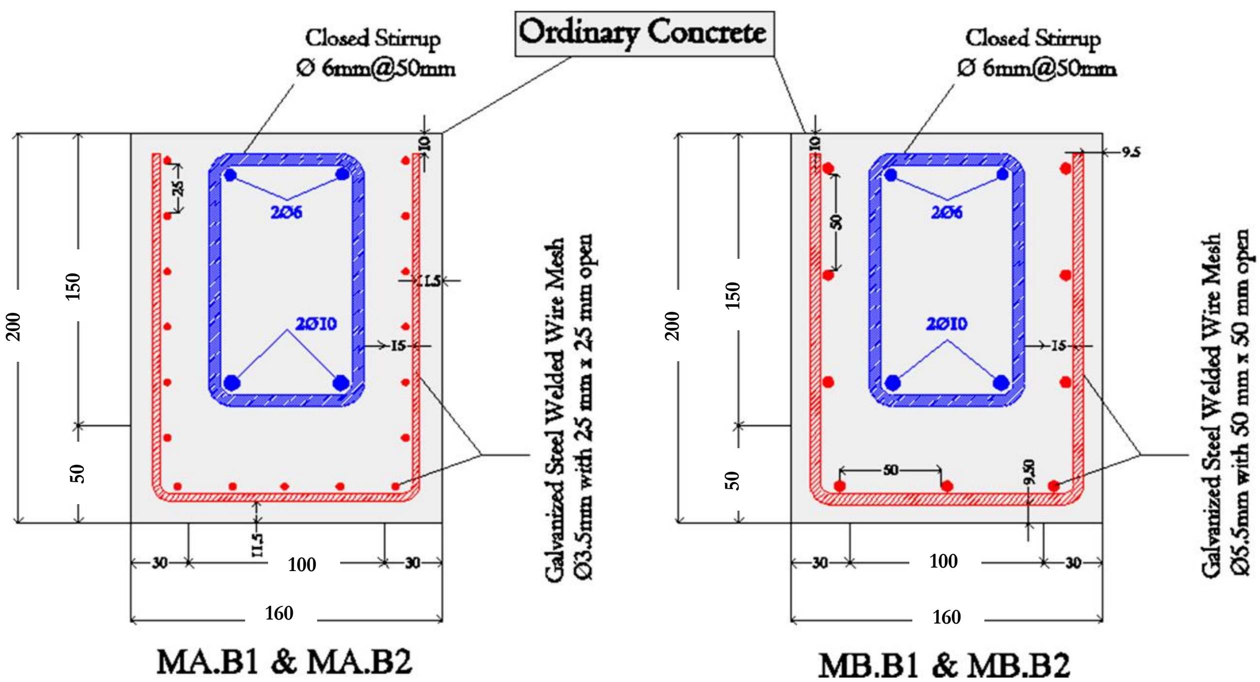


Figure 15 Monolithic beams cross section (mm).

The last eleven beams are broken into two groups, denoted GA and GB, and used as strengthened samples. The initial typical beams are strengthened externally through the application of a U-wrapping jacket for three out of four surfaces of the beam namely: the two beams sides and the lower beam soffit. The strengthened specimens have a cross-section of 160 × 200 mm with a total length of 1200 mm. The effective depth of Group A and Group B samples equal to 183.25 mm and 182.25 mm, respectively, as shown in Figure.15 and Figure. 16. The jacket reinforcement of the strengthened specimen of Group

A is Ø3.5 mm of 25 mm square opening galvanized SWM, whereas in Group B it is Ø5.5 mm of 50 mm square opening galvanized SWM with three different bonding mechanisms. The three bonding techniques applied in both group aiming to prevent or delaying the inter-laminar shear at the interfaces surfaces are Ø 8mm expansions bolts, I-shape Ø8 mm diameter steel dowels and surface roughening. The cross-sectional geometric characteristics of both groups (i.e. after the jacketing process) are shown in Figure. 16 and Figure. 17.

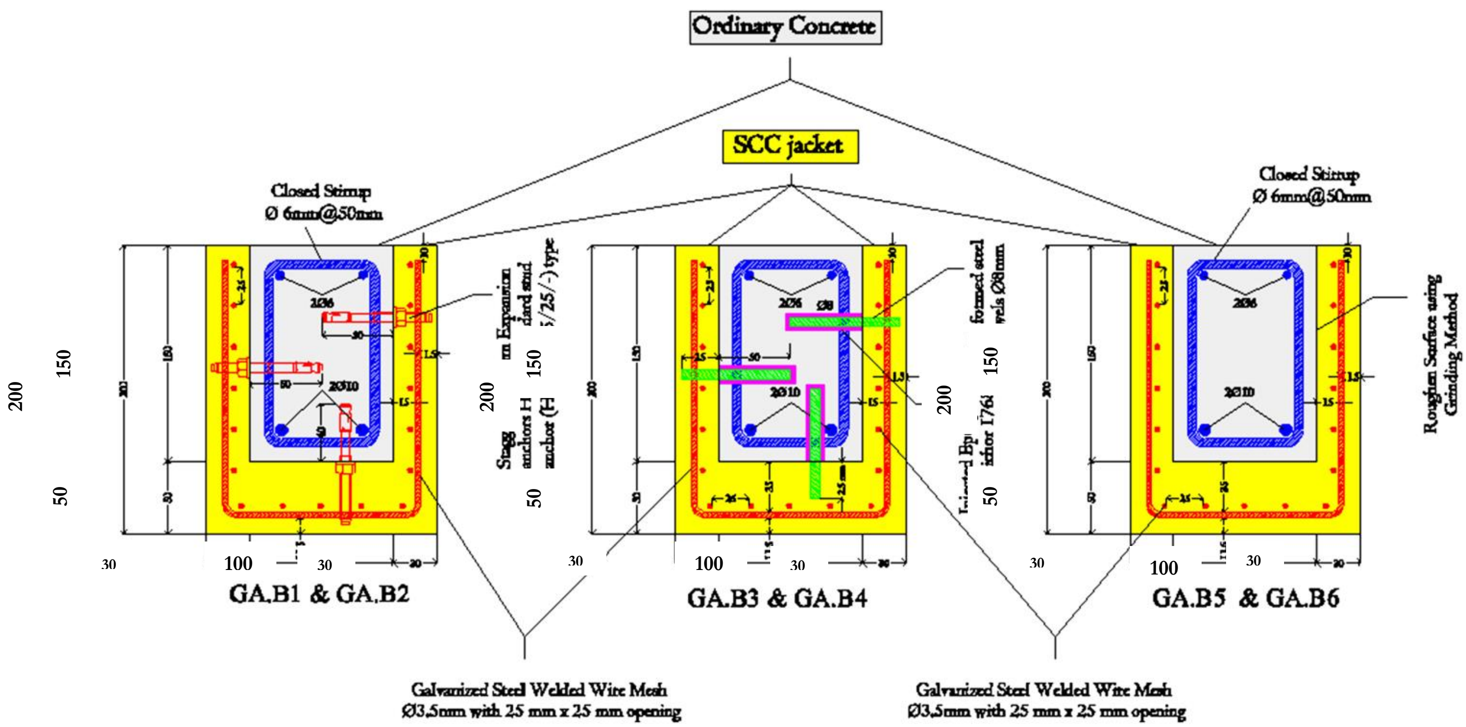


Figure 16 (Group A) strengthened beams (dimensions in mm).

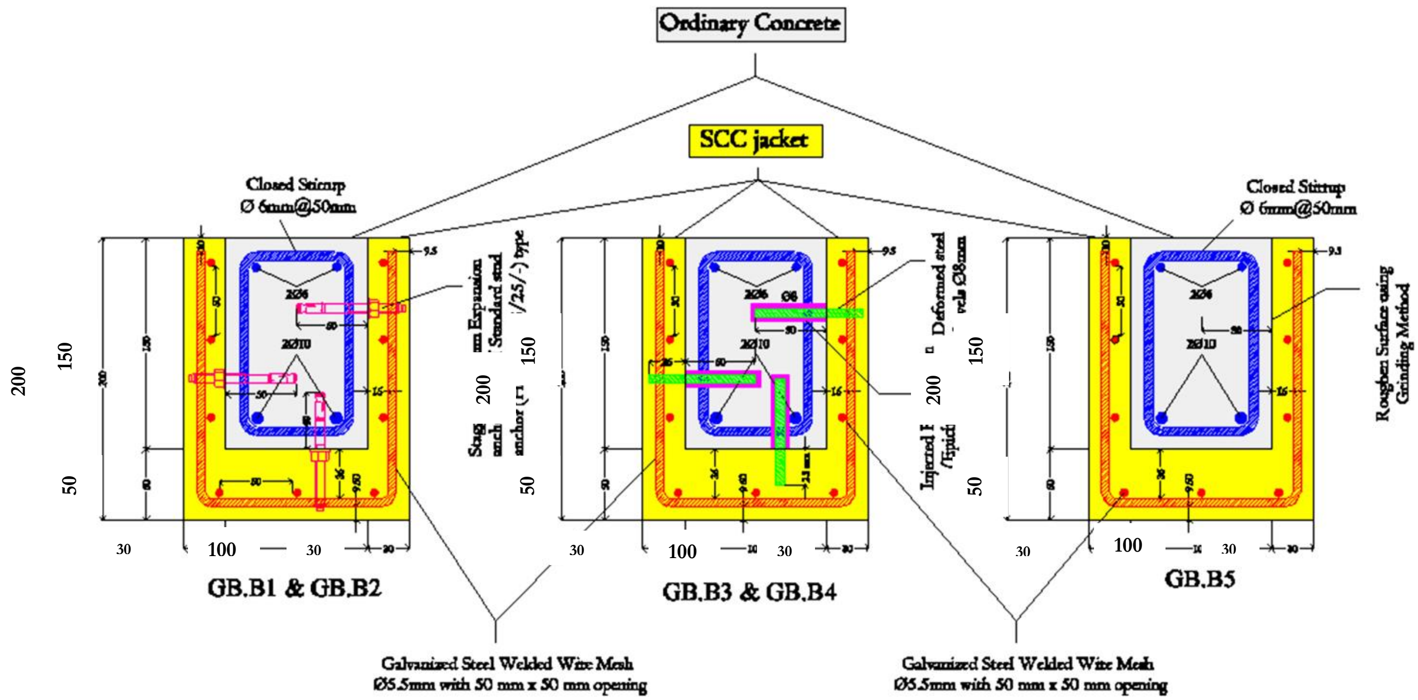


Figure 17 (Group B) strengthened beams (dimensions in mm).

3.3 Materials Mechanical Properties

Similar mechanical properties of materials which were used in preparing the initial core beams and the final shape of the strengthened specimens (i.e. U-shaped jackets) of the experimental test program are used in FE analysis. The following sub-sections summarized these properties.

3.3.1 Compressive and tensile strength of concrete

The mechanical properties of the ordinary concrete and the SCC specifically the compressive strength and the tensile strength are determined experimentally using three cubes and three cylinders for each testing. The following tables summarized the proportions of the materials job mix design that used in producing the ordinary concrete and the SCC.

For ordinary concrete (used in core beams):

Table 1 Ordinary concrete proportions (kg/m3)

Material	Proportion (kg/m3)
Cement (CEM II/AM-SVL 42.5N)	350
Water	175
Coarse Aggregate (0.15-19 mm)	1197.90
Fine Aggregate (dune sand)	616.60
W/C ratio: 0.50 , Slump: 25-100 mm	

For SCC (used in jacketing process):

Table 2 SCC proportions (kg/m3) according to EFNARC recommendations.

Cement (CEM II/AM-SVL 42.5N)	Limestone Powder (< 0.075 mm)	Free water	Superplasticizer - Sika Viscocrete 5920	Coarse Basalt Aggregate (2-9 mm)	Fine Aggregate (dune sand)
522.5	27.50	141.47	13.75	868.85	894.26
(Water/Powder) by volume = 0.89, Powder content = (Cement +Limestone Powder) Slump flow test (mm)=765.00 T500 slump flow (Sec.)= 2.95 L-box = 1.00 V-funnel (Sec.) = 5.00					

3.3.2 Steel properties

For steel reinforcement (used in core beams):

Table 3 Steel reinforcement test results.

Diameter (mm)	Average yield Stress, fy (MPa)	Average ultimate Stress, fu (MPa)	(%) Elongation
10	444.70	689.90	18.33
6	412.23	749.51	18.00

For SWM:

Table 4 SWM test results (used in jacketing process).

Diameter (mm)	Average yield Stress, fyw (MPa)	Average ultimate Stress, fuw (MPa)	(%) Elongation
5.50	300.58	418.60	6.42
3.50	250.74	280.55	8.20

For shear connectors:

The two types of shear connectors used in the experimental investigation are deformed steel bars of Ø8 mm diameter and the expansion bolts of Hilti type (HSA M8 35/25/-) with mechanical properties tabulated in Table 5. EPICHOR 1768 a two-part epoxy resin was used to equip the Ø8 mm dowels into the beam's body at a depth of 5 cm into a 1 cm hole diameter. The process of installation of both types is presented in Figure. 18 and Figure. 19. It is worth mentioning that, the number of shear connectors calculation was done according to Daly AF. (2004). The spreading of the shear connector at both beam sides and the beam's lower surface is shown in Figure. 20.

Table 5 Shear connectors' properties (used in jacketing process).

Type	Diameter (mm)	Average yield Stress, fy (MPa)	Average ultimate Stress, fu (MPa)	(%) Elongation
5.50	8	676.41	835.56	16.00
Hiliti Expansion bolts (HSA M8 35/25/-)	8	464	580	-

Figure 18 Ø 8mm dowels installation.

Figure 19 Hilti type shear connectors installation.

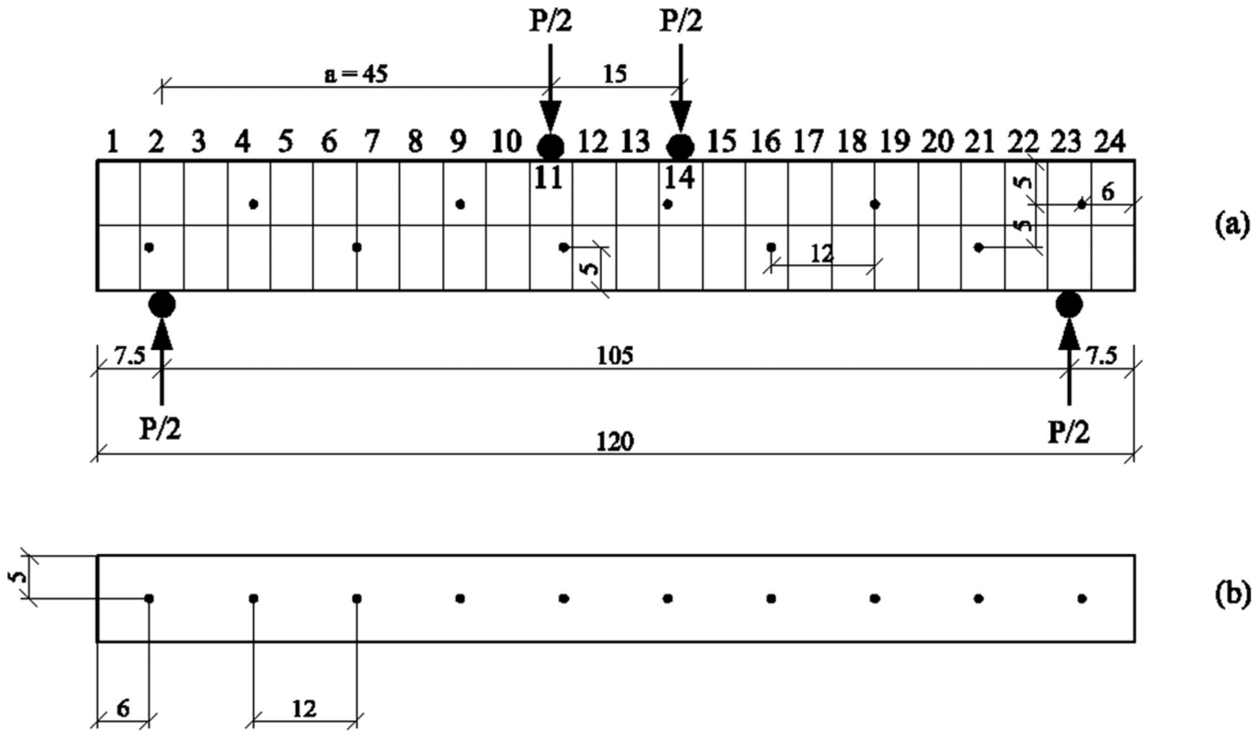


Figure 20 Spreading of both types at (a) beam's sides, (b) beam's lower surface.

3.4 Strengthening Technique

In the first stage, the initial core specimens should be produced by using the wooden moulds as shown in Figure. 21 that were painted with the form release agent properly to ease removing the samples. Then, the steel cages were inserted within these moulds, after that the ordinary concrete was poured according to Table 1 design proportions. All beams were stored under ambient conditions at nearly 25°C in the lab after they had been removed from their moulds. Quality control cylinders and cubes were also taken during each casting day and all of them were also kept under the same ambient condition. Potable water was used to cure the beam specimens for 14 days after removing the moulds.

Figure 21 Production of the initial core beams.

In the second stage, the three control beams were loaded up to failure and the analysis of the specimens' response was recorded to emulate the service load in practice. The remaining samples were primarily loaded to about 30 per cent capacity of the control beam. Then, the wooden moulds were prepared after being painted with a proper release agent to produce the enlarged beams (i.e. jacketed specimens). Both the SWM's cage and the initial core beams were inserted within these moulds carefully to ensure the required concrete cover in the up-side-down shape to ease the pouring process of the SCC as shown in Figure. 22. After that, the SCC was poured according to the design proportions in Table 2 as shown in Figure. 23. Quality control cylinders and cubes were also taken during each casting day and potable water was used to cure the enlarged beam specimens for 14 days after removing the moulds.

Figure 22Preparation of the wooden moulds.

Figure 23 SCC pouring process.

3.5 Testing Set-up and Loading

As illustrated in Figure. 24, all beams are loaded with two symmetric concentrated loads and edge-supported on two simple rollers on the hydraulic loading machine of a capacity of 200 kN. Then, the loads gradually applied to the beams in leaps of 2.35 kN until failure. All instruments are precisely prepared for monitoring the responses of test specimens throughout the investigation. The load and its corresponding mid-span deflection, first crack load, failure pattern and ultimate load are also conducted for each beam after they had originally bleached in order to observe the crack propagation during the testing.

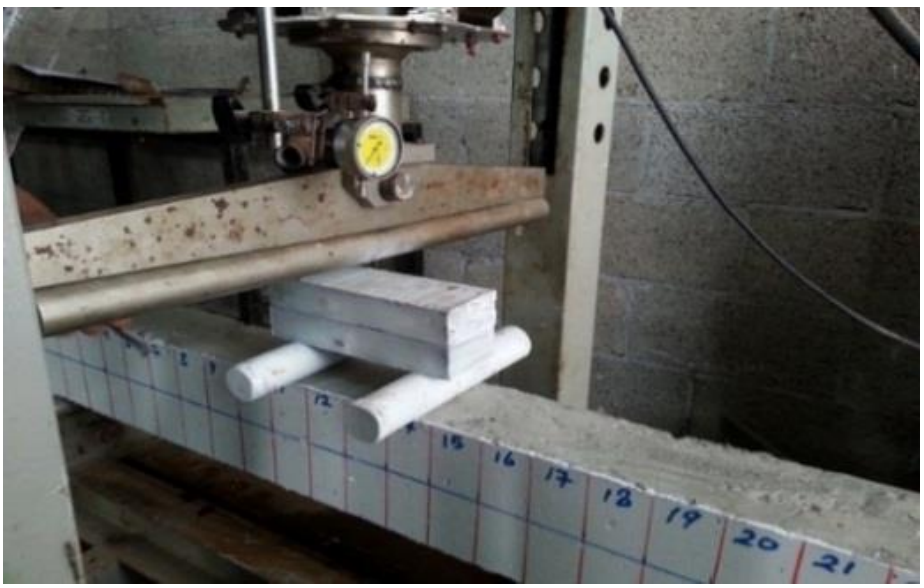


Figure 24 Test setup.

3.6 FE Numerical Model

In the present study, the nonlinear finite element (FE) is used through ABAQUS to build a 3-D model for control RC beam (CB) which was previously tested experimentally, strengthened beams from both groups A and B were also simulated, (GA,B and GB,B), one more beam was proposed numerically by using an external steel plate, (GA,BS and GB,BS). This innovative hybrid repair system is proposed in order to increase the flexural capacity of the strengthened beams in order to reach the maximum efficiency of this strengthening technique. The verification of the FE model is first implemented on the beams which were tested experimentally, then the external steel plate is added to the FE model in order to simulate the global behavior of strengthened beams, different reinforcement ratios of the SWM were used in order to study the relationship between ductility and stiffness in each strengthening technique.

3.6.1 Materials properties

In this model, the ordinary concrete and SCC were simulated as deformable solid element, both types of concrete were defined using the concrete damaged plasticity model CDP, the steel bars, steel connectors, SWM and the external steel plate were simulated using a deformable beam element, whereas steel stirrups are modeled using truss elements. The chemical adhesive is neglected in this model because by referring to the previous study of Sena Cruz et al. (2006), it showed that the influence of the epoxy adhesion on the global behavior and the crack pattern is very low and can be neglected.

3.6.2 Concrete Properties

Mainly, there are two material modeling approaches for concrete in ABAQUS, which are the concrete smeared cracking and the concrete damaged plasticity model (CDP). Interchangeable use of both models is valid in the case of plain concrete as well as reinforced concrete. In the present study, concrete damage plasticity model is adopted for modelling the ordinary and SCC concrete. The mechanical properties of concrete are shown in Table 6.

Table 6 Properties of Hardened Concrete Specimens used in FE model

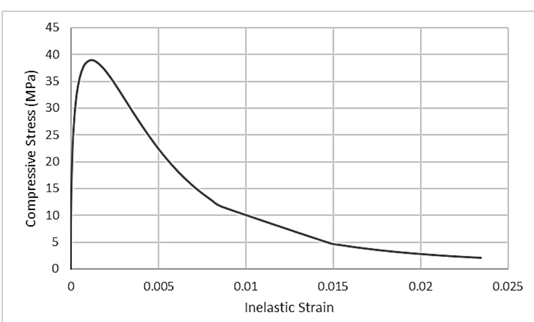
Item	f_c' (MPa)	ft (MPa)	E_c (MPa)	υ
Value	40	3.5	34000	0.2

Modeling of concrete requires considering a set of parameters according to the CDP model to be able to capture the behavior of concrete accurately. These parameters are summarized in Table 7. These parameters were used by many researchers and the results they obtained had a good agreement with the experimental tests for different structural elements from previous research. The compression damage parameter (dc) in the CDP model represents the decay in the elastic stiffness due to compressing the concrete, while the tension damage parameter (dt) represents the decay in the elastic stiffness due to tensioning the concrete. Both parameters are calculated following the method proposed by Lima et al. (2015).

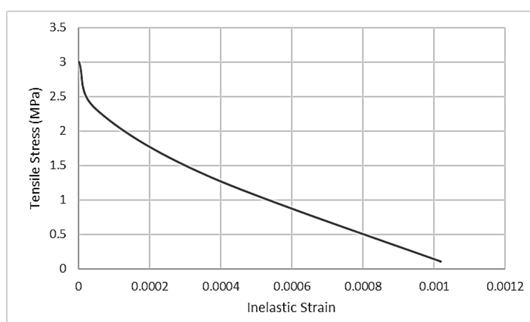
Table 7 Parameters of the damage-plasticity model

Parameter	Value
Dilation angle (ψ)	36°
Eccentricity (e)	0.1
f_{b0}/f_{c0} (ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress	1.16
K (the ratio of the second stress invariant on the tensile meridian)	0.667
μ (viscosity parameter)	0.0005

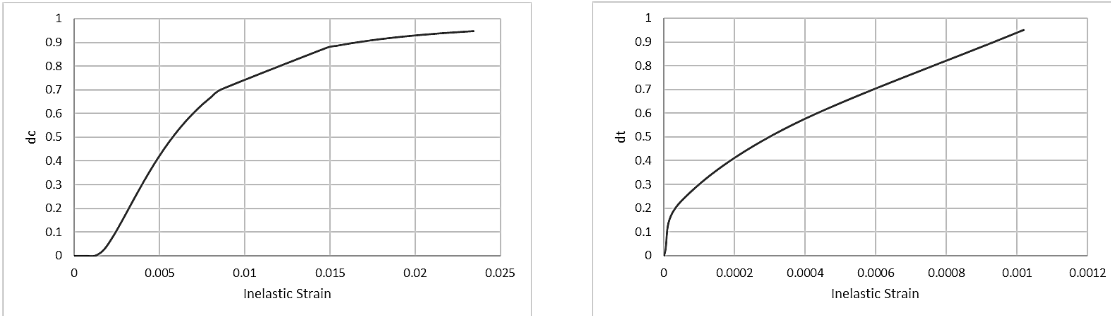
The concrete used to build the current FE models is given a compressive strength of 40 MPa and an elasticity modulus of 34000 MPa. However, Figure. 25 presents the data needed in defining the concrete material in ABAQUS. Figure. 25(a) shows a curve of uniaxial compression stress versus inelastic strain of concrete, while Figure. 25(b) shows a curve of tension stress versus cracking strain of concrete. The curve in Figure. 25(c) displays the relation between the compression damage parameter and the inelastic strains, while Figure. 25(d) shows the change in the tension damage parameter at various cracking strains.



(a) Compressive stress vs. Inelastic strain



(b) Tensile stress vs. Cracking strain



(c) Compressive damage vs. Inelastic strain (d) Tensile damage vs. Cracking strain strain

Figure 25 Definition of concrete parameters for damage-plasticity model

3.6.3 Steel Properties

The behavior of the steel reinforcing bars and steel stirrups is assumed elasto-plastic. Table 8 shows the average values adopted in the numerical model for both the steel reinforcement and the steel wires. The detailed specimens testing procedure is described in the experimental study published paper.

Table 8 Steel properties adopted in the FE model

Specimen Type	Young's modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
Steel bar (10mm)	200	444	690
Steel bar (6mm)	200	412	750
Steel Wires (5.5mm)	200	300	419
Steel Wires (3.5mm)	200	250	280

3.6.4 External steel plate

Metwally (2014) implemented a FE model using ABAQUS in order to investigate the behavior of the strengthening technique using epoxy-bonded steel plates. The study found that by increasing the steel plate thickness, the stiffness of the RC element increases. In order to have a failure load less than the shear design capacity, a steel plate thickness of 1.5 mm and width of 80 mm are assumed for both proposed beams GABS and GBBS.

ACI -318 proposed an equation Eq. [1] which can predict the ultimate moment capacity of RC beams strengthened with epoxy steel plates:

$$M_n = A_{s1} f_{y1} \left(d_1 - \frac{\beta_1 c}{2}\right) + A_{sp} f_{yp} (d_p - \frac{\beta_1 c}{2}) \quad (1)$$

The proposed beam section which is strengthened using both (SWM SCC and External steel plate) is shown in Figure. 26, full contact was assumed between old and new concrete surfaces, since there was no debonding noticed in the experimental results moreover the staggered expansion anchors which used experimentally made the contact assumption between the two surfaces is acceptable.

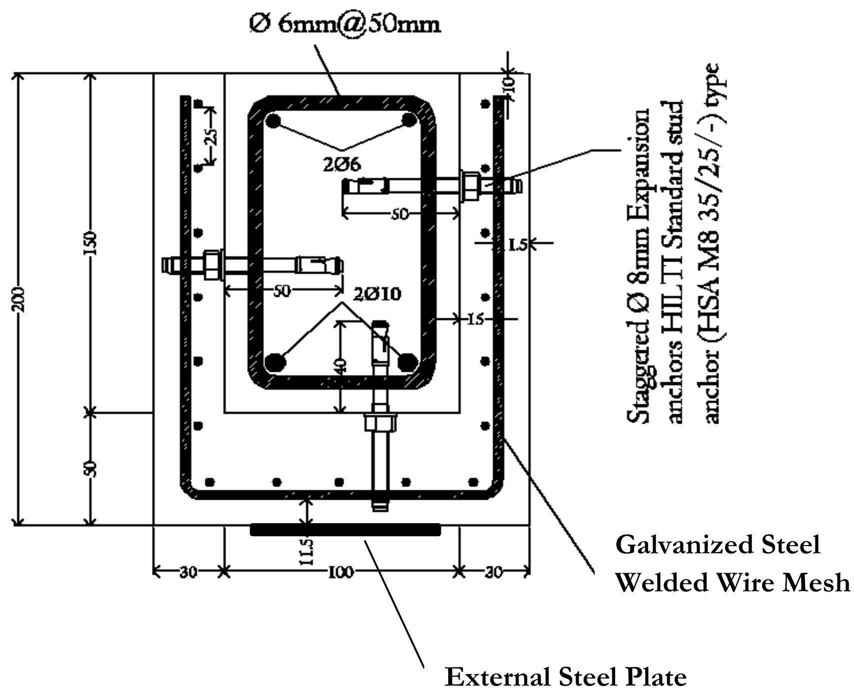


Figure 26 Proposed beam Section strengthened using both SWM SCC and external steel plate (GABS and GBBS)

Five beams were modeled using the commercial software ABAQUS, including different strengthening techniques, the properties description of all beams studied are shown below in Table 9.

Table 9 Properties of all beams (Experimental and FEM)

Beam	Cross Section	SWM Properties		External Steel Plate	Strengthening Technique
	(b × h) (mm)	Diameter (mm)	Open (mm)	(b × h) (mm)	
CB1	100 × 150	-	-	-	-
GAB1	160 × 200	3.5	25 × 25	-	SCC + SWM
GBB1	160 × 200	5.5	50 × 50	-	SCC + SWM
GABS	160 × 200	3.5	25 × 25	80 × 1.5	SCC + SWM + External Steel Plate
GBBS	160 × 200	5.5	50 × 50	80 × 1.5	SCC + SWM + External Steel Plate

Chapter 4: Results and Discussion

4.1 Load Deflection Curves

The FE model predicts the global behavior of the beams (GAB1, GBB1, and control beam CB1) which were studied experimentally. The FE load deflection curves recorded from the FE model using ABAQUS are in good agreement with the experimental results. This can be observed from the load-deflection curves for all beams presented in Figure 27. The behavior of new proposed models GABS and GBBS are also presented along with the behavior of other beams in order to observe the change occurred in the behavior and the load capacity due to this innovative hybrid strengthening technique which uses an external steel plate in addition to SWM.

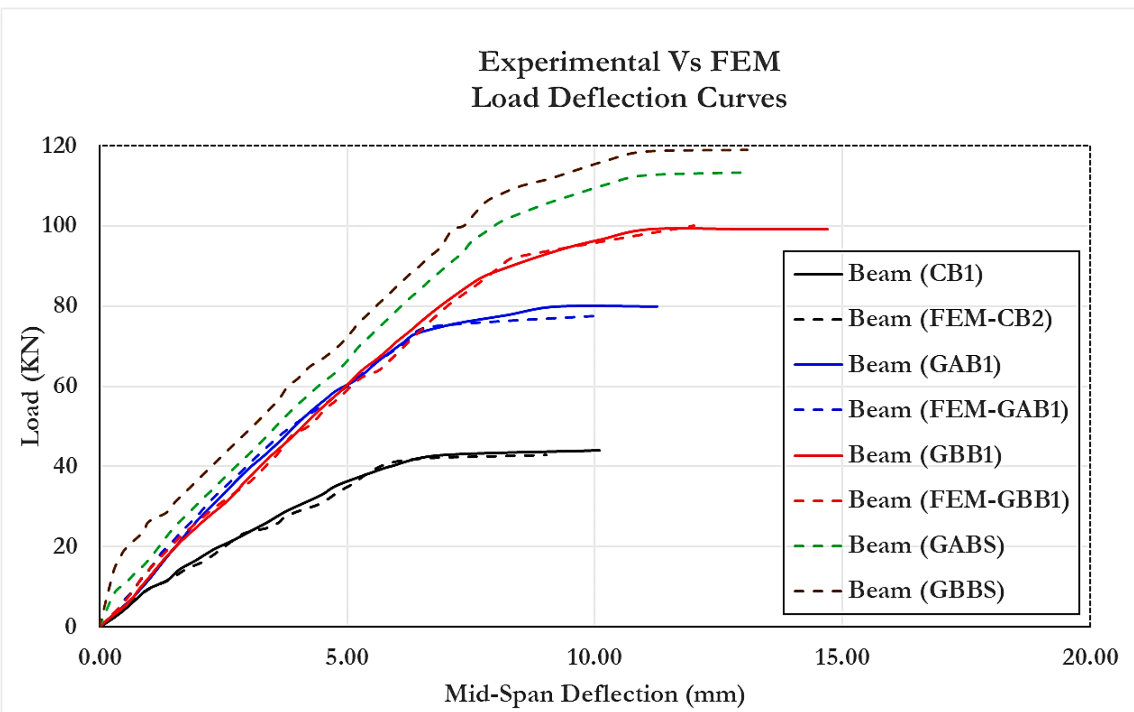


Figure 27 Load-deflection curves for all beams (Experimental and FE results)

The ultimate load capacity for the new proposed beam GABS from group A (SWM diameter of 3.5 mm was used) in addition to external steel plate was 113 kN, the load capacity increased by 33 kN compared to GAB1, On the other hand, if it is reinforced with

5.5 mm (Group B) in addition to external steel plate, the ultimate load capacity was 119 kN which was increased by 19 kN compared to GBB1. The first beam GABS using this innovative strengthening technique (SWM and external steel plate) restored on average 150% of the original control beam load capacity, whereas the second proposed beam GBBS resorted 172% of the original control beam load capacity on average.

4.2 Ductility and Stiffness

The proposed models GABS and GBBS (strengthened with SMW and external steel plates) are noticed to have less ductility index ($\varepsilon_u/\varepsilon_y$) than the beams which were repaired using SWM only (GAB1 and GBB1). A ductility index of 1.2 was calculated for both beams GABS and GBBS while the experimental and FE ductility index values for GAB1 were found 1.8 and 1.6, respectively, the experimental and FE ductility index values for GBB1 were found 1.9 and 1.5, respectively. On the other hand, the stiffness of the new proposed models GABS and GBBS was found increased as it was observed in the linear stage. The same result was found by Almassri et. al (2020), as the external steel plate was used to repair corroded RC beam which was repaired with NSM CFRP rod in bending. Figure. 28 shows the ductility index values for all beams and Figure. 29 presents the stiffness ratio (slope after strengthening / slope before strengthening) for both strengthening techniques (SWM and external steel plate).

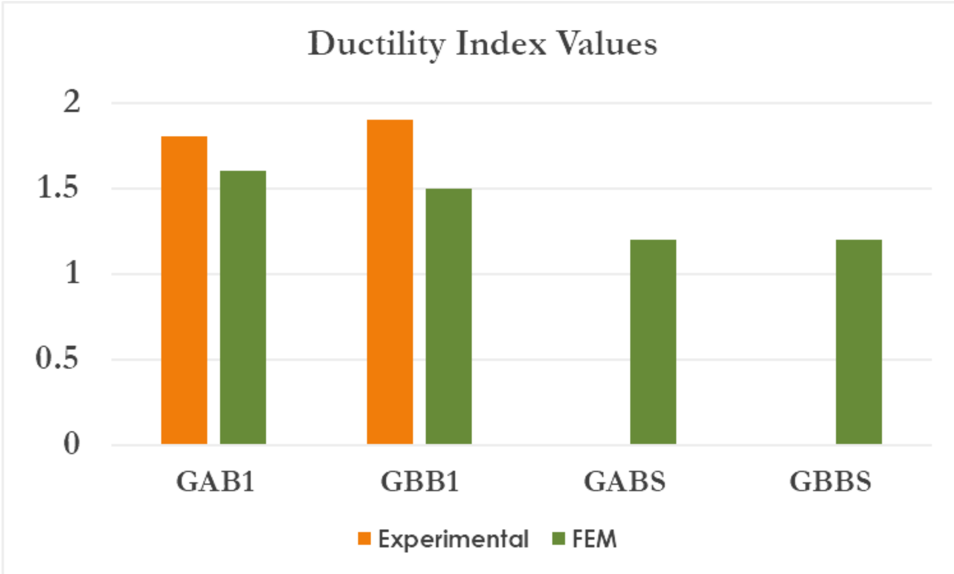


Figure 28 Ductility index values for all studied beams (Experimental and FE results)

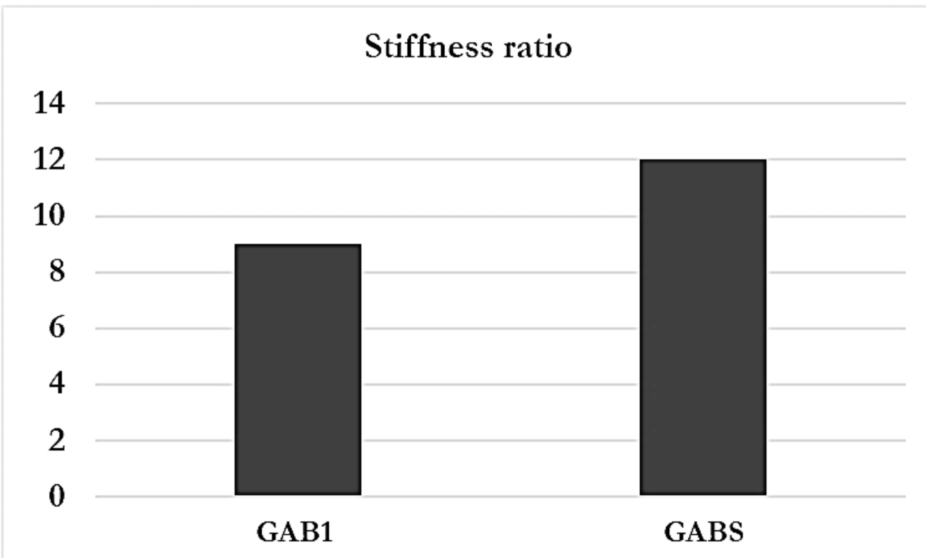


Figure 29 Stiffness ratio for different techniques compared to control beam

4.3 Modes of Failure and Crack Patterns

The failure cracking patterns of the strengthened beams with SWM only which tested experimentally (see Figure 30 (a)), taken from the visual observations during the experimental tests. This figure shows a typical mode of failure, which was noted for almost all of tested specimens, all specimens presented flexural cracks which extended from the lower surface of the specimen to the center of the bearing plate. Furthermore, flexural cracks located at the mid-span where the maximum flexural moment occurred that indicates jacketed samples using SWM exhibited ductile mode of failure and pure flexural cracks pattern. Figure. 30 (b) shows how the FE model well predicted the mode of failure which was recorded experimentally.

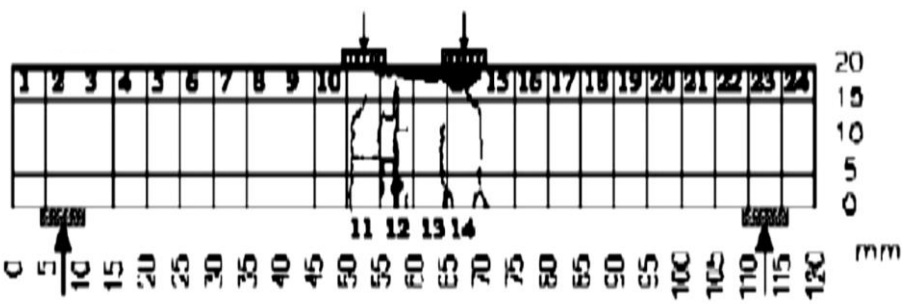


Figure 30. (a) : Experimental crack pattern for all tested beams

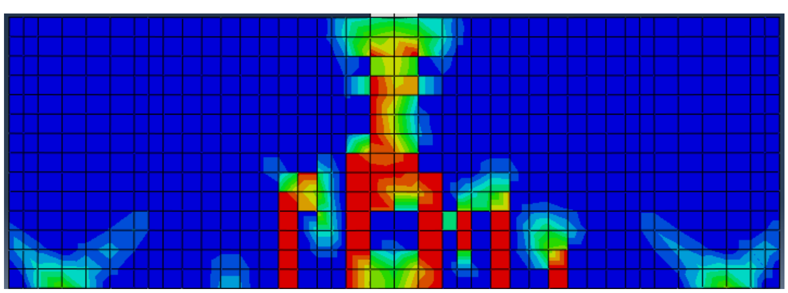


Figure 30 (b): FE crack pattern from ABAQUS for GAB1 and GBB1 beams

Furthermore, the proposed models GABS and GBBS which were strengthened using an external steel plate in addition to SWM SCC, the mode of failure changed from flexural cracks at the middle to large diagonal shear crack failure as shown in Figure 31.

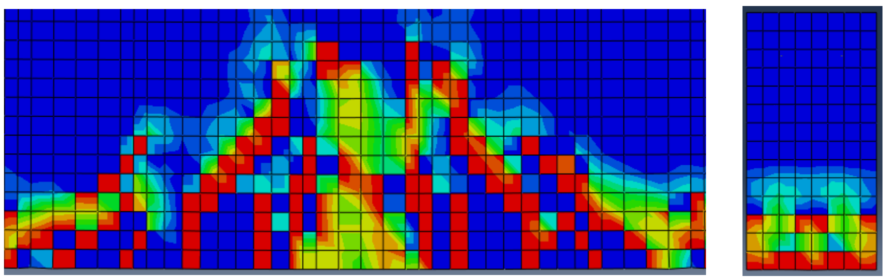


Figure 31 FE crack pattern from ABAQUS for GABS and GBBS beams

4.4 Parametric study

4.4.1 Thickness of steel plate

A numerical analysis was carried out on the GABS beam which was theoretically strengthened using both SCC and external steel plate with increasing the thickness of strengthening plate to 3,5, and 7 mm. The results are shown in Figure 32. It can be seen that prior to yielding point, increasing of thickness of plates does not influence the load-deflection characteristics. However, after yielding, the load deflection curve becomes quite stiffer specially for beams strengthened with external steel plates have 3, 5 and7 mm thickness. The load deflection curves also show that for a given load, the deflections generally decrease with increasing thickness of steel plate. Also, increasing the plate thickness caused remarkable growth in capacity of beams till thickness equal 5mm beyond this limit the load decreased (at t = 7 mm) as shown in Figure 32. This refers to higher stiffness of strengthened beams which make it easy to fail by the crushing of the concrete in the compression area.

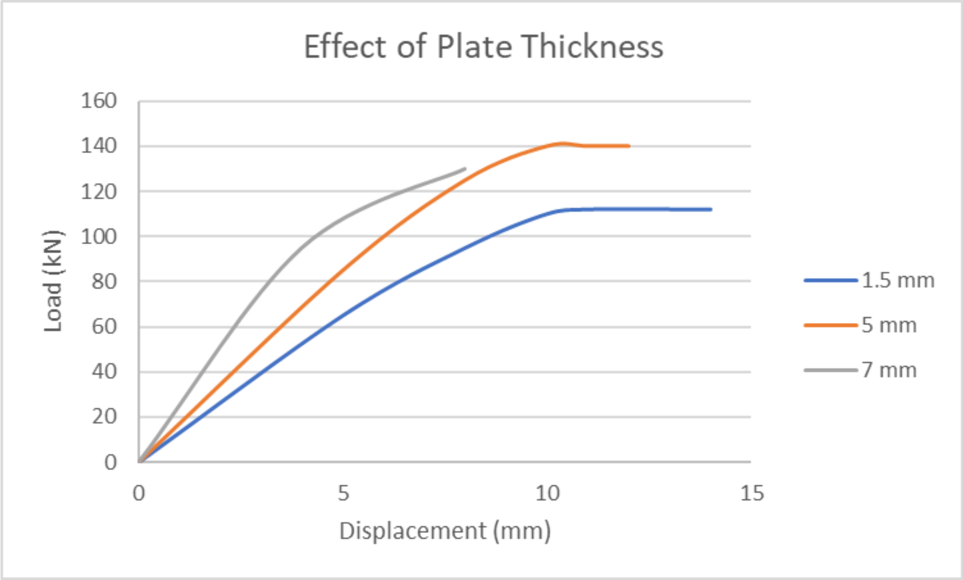


Figure 32 Effect of Steel Plate Thickness

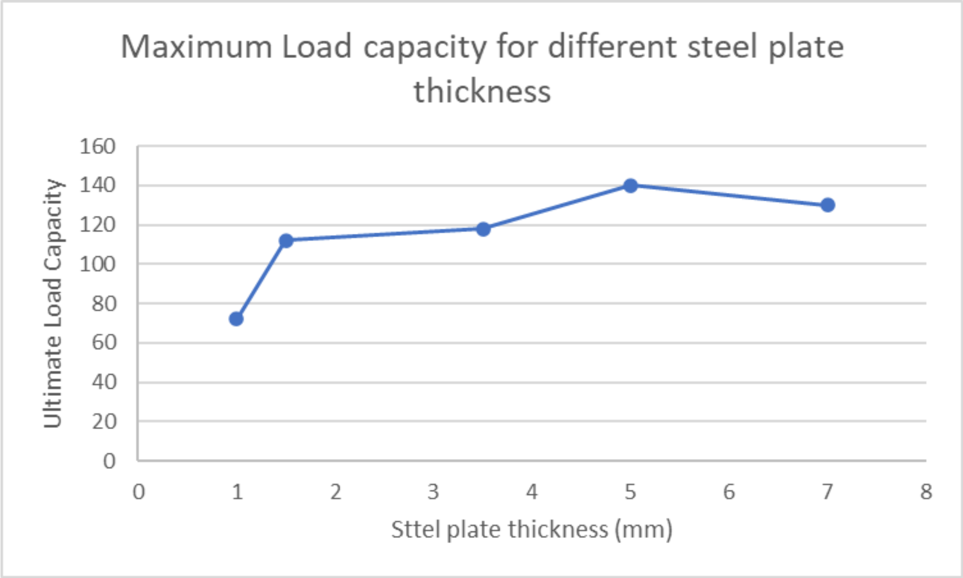


Figure 33 Maximum Load Capacity for different plate thickness values

Figure 33 shows the ultimate load capacity for different steel plate thickness values, the optimum load capacity was found when the thickness was 5 mm, while less than 1.5 mm gave much lower load capacity values than the range between 3-7 mm, after 7 mm the ultimate load capacity was dropped down due to in the stiffness increase in RC beams.

4.4.2 Width of steel plate

This part of the parametric study deals with the effect of width of the bonded steel plates on behavior of strengthened RC Beams which were repaired before using the SCC. Previous studies strongly recommended that it is very necessary to study this topic in the future, as it is related to the splitting the steel plate in strengthening process. In this FE model the adhesive layer which connect the concrete with steel plate was not defined, even though there are not any investigation upon this issue till now, So, it is necessary to focus on it. Some models were established by ABAQUS with various plate widths.

Figure 34 presents the results of the ultimate load capacity values of the GABS beam using 6 proposed steel plate width values (40,60,80,100,130 and 160mm), the plate length (1200 mm) and thickness (1.5 mm) were fixed here at this point. Figure 34 shows that the variation of the width has not nearly any effect on the ultimate load capacity and stiffness (Figure 35) (which it ranges from 100 to 113 kN for ultimate load capacity).

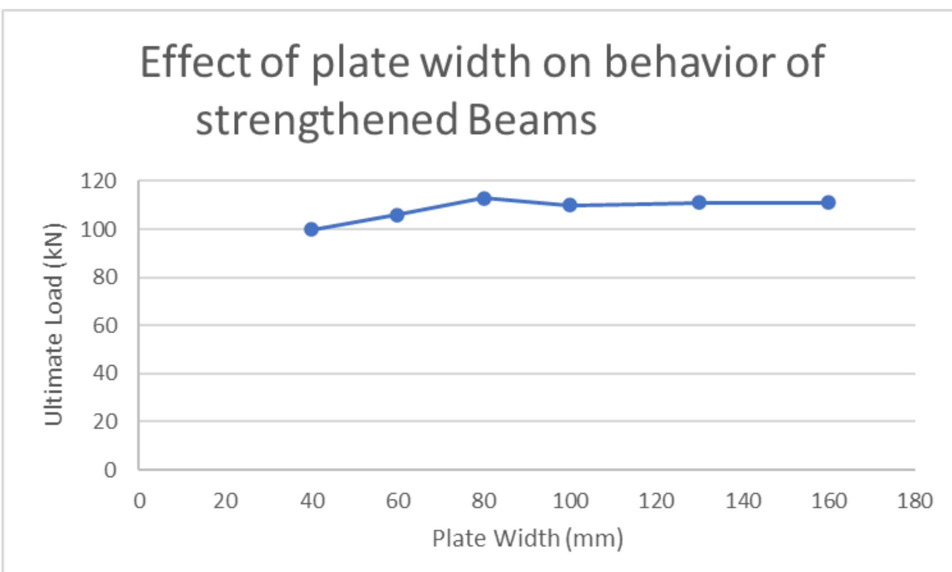


Figure 34 Effect of Plate Width on Results

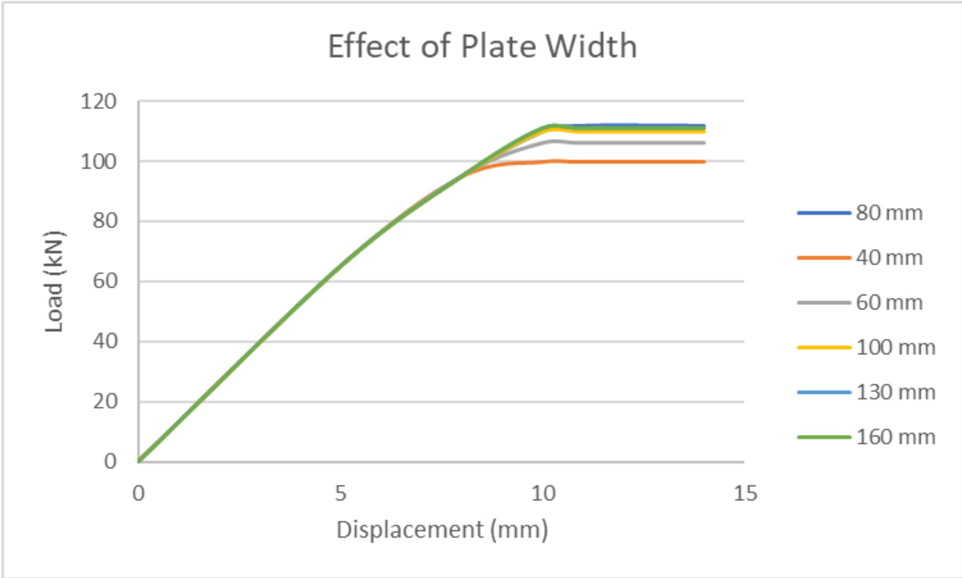


Figure 35 Load Displacement Curves for different Plate Width Values

Figure 35 shows an identical stiffness value for different plate width values, even for steel plate width less than 60 mm the load capacity values did not give as much values as for 80-160 mm.

4.4.3 Concrete Compressive Strength

At this part, three compressive strength values will be used (21 MPa, 32 MPa and the one which was already used and fixed in all previous sections 40 MPa), the change in Fc' will be applied to GABS beam, the concrete compressive strength factor will be studied along with the external steel plate, the steel plate is fixed to be 80 mm width and 1.5 mm thick. Figure 36 presents the load-displacement curves for various proposed concrete compressive strength values; it is clear that using Fc'=40 MPa will give the optimum load capacity value for repaired beam, while for Fc'=32 MPa there was only 8 kN difference compared to 40 MPa concrete, the stiffness of 40 MPa reached its highest value.

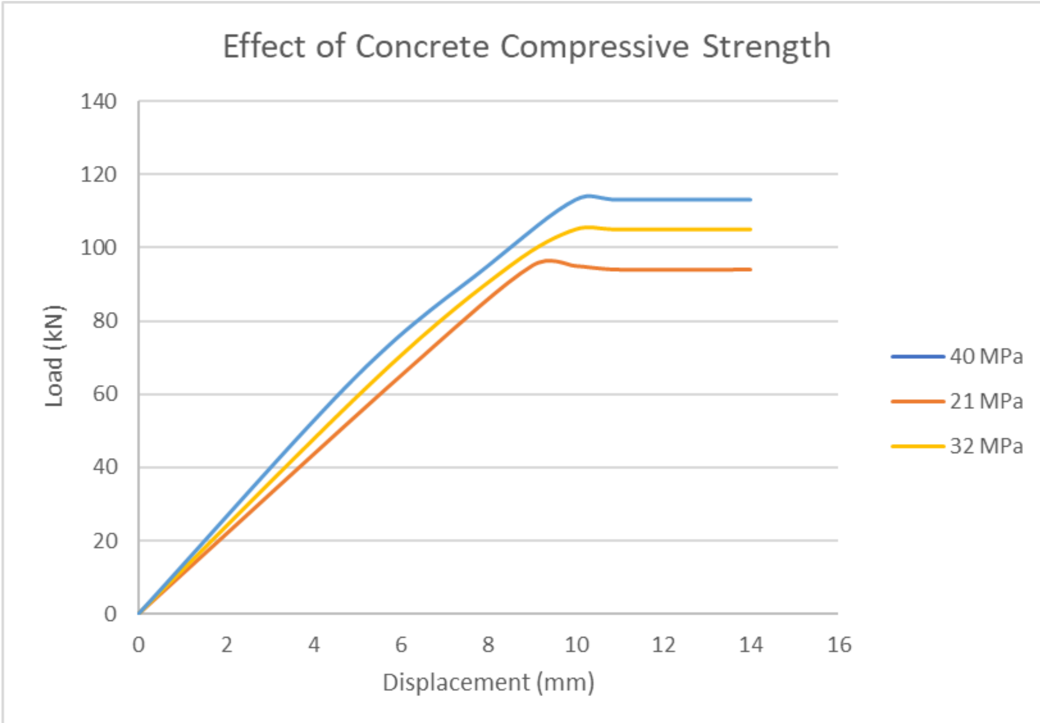


Figure 36 Effect of Concrete Compressive Strength Fc'

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

The final conclusions of this study can be cast in the following points:

- The first group of strengthened beams (using SWM SCC only) restored on average 110% of the original control beams load capacity, whereas the second strengthened group resorted to 163% on average.
- The FE results showed that the strengthened jacketed samples (with SWM SCC in addition to an external steel plate) restored on average 150 % and 172 % of the original control beams load capacity for groups A and B, respectively.
- The three-dimensional FE model shows a good agreement with the experimental results in terms of the mechanical behavior as well as the failure modes.
- Using an external steel plate as an assistant strengthening technique for the RC beams strengthened using SWM SCC jacketing changes the failure mode form ductile mode of failure by flexural cracks into brittle one by large diagonal shear cracks.
- Using an external steel plate slightly increases the stiffness and decreases the ductility for the tested beams. Even though it increased the ultimate load capacity of the strengthened beams with SCC.

A parametric study was conducted on the RC beams strengthened with an extra steel plate:

- The maximum load capacity was found when the thickness was 5 mm, when the thickness is increased over 5 mm, the stiffness is increased while the ultimate load capacity is decreased significantly due to the early failure of RC beams.
- The variation of the steel plate width has not nearly any effect on the ultimate load capacity and stiffness values of the repaired RC beams.
- Using 40 MPa concrete strength will give the highest stiffness and load capacity values with an increase 25 % compared to Fc'=32 MPa.

5.2 Recommendations and Future Work

- The study concluded the FE modelling work taking into account the non-linearity of materials (Concrete, Steel, and others) but it did not take into account the bond strength of those materials due to the short period of this research, so further studies are highly recommended in the near future taking into account the bond strength between the hybrid techniques and old concrete.
- This thesis opens the door for future studies on using innovative hybrid strengthening techniques taking into account all the of the changing parameters like the strength of the adhesive material (epoxy) which make the contact surfaces between old and new concrete as well as using different materials as supporting strengthening techniques like different materials than steel.
- This promising hybrid techniques can be applied to slabs, bridges and even for existing old buildings, this needs to be verified experimentally first.

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