Retrofitting Of Reinforced Brick Concrete Structures

Final Year Project

Report by

Muhammad Ali (336210)

Roshaan Hanif (344103)

Sheraz Ahmed (344526)

Talha Abid (339774)

In Partial Fulfillment of the Requirements for the degree Bachelor of Civil Engineering

(BECE)

School of Civil and Environmental Engineering Science National University of Sciences and Technology Islamabad, Pakistan

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DECLARATION

We hereby declare that this project report entitled **"Retrofitting of Reinforced Brick Concrete Structures"** submitted to the "School of Civil and Environmental Engineering (SCEE)", is a record of an original work done by us under the guidance of Supervisor "**Lec. Muhammad Hamza Sabir**" and Co-Supervisor "**Lec. Arslan Mushtaq**" and that no part has been plagiarized without citations. Also, this project work is submitted in the partial fulfillment of the requirements for the degree of Bachelor of Civil Engineering

Team Members

Muhammad Ali

Roshaan Hanif

Sheraz Ahmed

Talha Abid

Supervisor:

Lec. Muhammad Hamza Sabir

Co-Supervisor:

Dr. Arslan Mushtaq

This is to certify that the Final Year Project

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Muhammad Ali (336210)

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Has been accepted towards the requirements for the award of the undergraduate degree.

Bachelor of Engineering in Civil Engineering

Advisor Eng. Muhammad Hamza Sabir

Co-Advisor Arslan Mushtaq

Lecturer

Structural Engineering Department

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Science and Technology, Islamabad, Pakistan

DEDICATION

We would like to dedicate our work to our teachers,

and parents, without whom this could not have been possible.

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We would like to wholeheartedly thank our advisor Lec. Muhammad Hamza Sabir and co-advisor Lec. Arslan Mushtaq for helping us throughout this final year project. Without their keen guidance and support, it would not have been possible for us to meet the scope of the project in time.

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ABSTRACT

The architectural heritage of the subcontinent is richly adorned with Reinforced Brick Concrete (RBC) structures, a testament to a construction tradition that prevailed until the late 1990s before the advent of Reinforced Cement Concrete (RCC). However, the relentless march of time has not been kind to these edifices. The once robust RBC structures now exhibit signs of diminished durability and strength, necessitating urgent intervention to restore their former resilience. This thesis delves into the critical process of retrofitting these aging structures to meet contemporary safety and performance standards.

Our investigative journey commenced with the casting and testing of an RBC beam, followed by an RBC column, to establish a baseline understanding of their structural integrity. Subsequently, we harnessed the analytical prowess of ABAQUS software to simulate the behavior of these elements under various stress conditions. The insights gleaned from this computational analysis laid the groundwork for the next phase of our exploration.

In a pioneering effort to enhance the structural fortitude of RBC, Carbon Fiber Reinforced Polymer (CFRP) was employed as a retrofitting material. The transformative impact of CFRP was meticulously evaluated by modeling retrofitted beams and columns within the ABAQUS environment. This simulation enabled a direct comparison between the performance of retrofitted and non-retrofitted RBC components, illuminating the efficacy of CFRP in reinforcing the structural framework.

The culmination of our research presented a comprehensive comparative analysis between retrofitted RBC and its modern counterpart, RCC. This comparison not only highlighted the viability of retrofitting as a preservation technique but also underscored the potential of CFRP in bridging the gap between historical construction practices and current engineering standards.

Through rigorous empirical testing and advanced computational modeling, this thesis establishes a compelling case for the retrofitting of RBC structures. It advocates for the integration of modern materials and techniques to safeguard our architectural legacy while ensuring the safety and functionality of these structures for future generations. The findings of this study serve as a beacon for conservationists and engineers alike, championing the fusion of tradition and innovation in the realm of structural rehabilitation.

Chapter 1

1. INTRODUCTION

Reinforced Brick Concrete (RBC) is a type of concrete which has been used in the construction as a construction material in the early 1900s to the early 1990s. In this type of concrete, the bricks, aggregate, cement, and steel bars are used to create a composite material having some enhanced structural properties. In this concrete, the brick is used as a filler material. In beams, the bricks are placed inside the steel cage while in the columns, the bricks are placed on the outside perimeter of the whole column. It showed significant advancement during its time in the construction industry by mixing the use of brick masonry with the structural abilities of reinforced concrete. (Maia de Souza et al., 2016) This type of concrete uses the compressive strength of bricks and concrete and the tensile strength of steel reinforcements that is embedded in the concrete to create structures that are economically cheaper that that of RCC.

The research will start by giving some historical background of the Reinforced Brick Concrete, some discussion about its development and how this concrete was adapted and used in the construction industry for a number of years. There will be some discussion about the retrofitting techniques that will be used for the betterment of the concrete by highlighting the best practices that can be adopted and some suggestions on how to improve it further. Our goal is to provide the best retrofitting technique for Reinforced Brick Concrete that can be used in the industry so that there is no need for older structures to be demolished and then reconstructed.

Reinforced Brick Concrete was used extensively in the subcontinent. It was mostly used in those areas which are now Pakistan, India, and Bangladesh. Before the partition, during the British colonial era, the use of Reinforced Brick Concrete was favoured due to its cost effectiveness and some structural benefits. It was used mostly in constructions of factories, mills, and some public buildings. The combination of bricks, concrete and steel provided just the right amount of strength that was required by the structure. Some of the notable buildings in the subcontinent constructed using Reinforced Brick Concrete are Lahore High Court (Pakistan), University of Dhaka (Bangladesh), The Victoria Terminus (India) etc.

Despite its early popularity, the use of RBC has been significantly declined over the years. Several reasons have contributed towards the decline of the use of Reinforced Brick Concrete which includes the emergence of new construction materials, changes in the building's standards and codes, development of more efficient and better strength techniques, and advancement in the construction technology. The use of RCC has been made more normal because of its superior strength, durability, ease of use and more flexural strength as compared to that of Reinforced Brick Concrete. (KULKARNI et al., 2014)

Overtime, the structures that were made using the Reinforced Brick Concrete has experienced wear and tear due to some various environmental factors such as weathering, moisture and temperature fluctuations which has caused gradual degradation of materials. Moreover, the aging of the bricks, concrete and steel used in the Reinforced Brick Concrete decreases the structural strength of it. Moreover, more increased loads on the building with time and due to changes in building use also have further stressed the existing structures. Due to these reasons, the structures have lost most of their strength.

So due to this, there is a need to strengthen the structures and the buildings because we cannot reconstruct the whole buildings and structures and moreover some buildings also have historical and architectural significance due to which we cannot replace them. Also reconstructing would not be cost effective and it would require a heavy amount of money. So, the best thing in our interest to do would be to retrofit the structures. By retrofitting, the integrity and appearance of building would be maintained, and it would also prove to be cost effective as it would not require a hefty amount of money as it would only require strengthening and repair the existing structure which can be done by using lesser resources and at a lower cost. Also, by retrofitting the structure, it brings it to the current safety and building code standards. We know that the Reinforced Brick Concrete structures were constructed way before the modern seismic design codes were established so by retrofitting the seismic performance can also be enhanced. Also, by retrofitting the structure, its usable lifespan is increased. This ensures that the structure will continue to serve for the intended purpose for a longer lifespan for many more years. This will ensure the safety of the structure and not demolishing it will also give environmental benefits.

The retrofitting is done and emphasized in order enhance the longevity, safety, and functionality of the already existing Reinforced Brick Concrete. (Hejazi & Esfahani, 2021) This research is focused on the urgent development of proper strengthening and retrofitting techniques. The contribution of this study is establishment of a comprehensive framework targeting the reinforcement and enhancement of reinforced concrete brick buildings for structural engineering.

1.1 Background:

The main area of study was Koh e Noor Steel Mills which is in Rawalpindi, Pakistan. The steel mill contributes to industrial growth and local economy in the region. This steel mill was constructed using the Reinforced Brick Concrete which involves the use of bricks, concrete and steel reinforcements. The tensile strength of reinforced bars is used, and the compressive strength of bricks and concrete is used. For many years in the subcontinent, this concrete proved to be durable and cost effective.

However, over some years, the Koh e Noor Steel Mills building has faced serious degradation, due to some environmental and aging factors. Some environmental factors include the weathering, constant exposure to moisture, and constant difference in temperatures which has led to the deterioration of the RBC. With time, bricks and concrete lost their strength and steel reinforcements have corroded. Due to these issues, the structural capacity of the building has decreased. (Maia de Souza et al., 2016)

Moreover, the natural aging of the building has increased these problems. The age of bricks, concrete, and steel continued to increase which has decreased its ability to withstand the building's load and the ability to withstand environmental loads have decreased too. The increased load demands have also weakened the structure. All these problems have led to wear and tear in the structure.

As Koh e Noor Steel Mills play a critical role in the local economy so demolishing the structure and reconstructing the whole building does not seem to be a feasible solution. This approach will cause in financial loss as well as it would disturb the industrial activities and the livelihoods of many people are dependant on this.

So, to extend the lifespan of the building, we need to come up with a solution that does not involve the reconstruction of the building.

1.2 Problem Statement:

The existing Reinforced Brick Concrete (RBC) structures in Pakistan fail to meet the required strength and standards that are being used by the RCC structures nowadays. This difference in standard and strength puts a risk and threat on safety, durability, and functionality of the RBC structures. Therefore, it is required to retrofit the existing RBC structures to enhance their sustainability and their resilience. Hence, this would ensure the increased lifespan of the building.

1.3 Objective:

The three main objective of our project are:

1. Comparative analysis of RBC and RCC: A detailed comparison of Reinforced Cement Concrete (RCC) and Reinforced Brick Concrete (RBC) will be conducted while the main focus of comparison will be on structural strength, durability, cost effectiveness and environmental performance. This analysis will give the pros and cons of using RBC structures.
2. Elemental-Based Non-Linear Analysis in ABAQUS: An elemental based nonlinear analysis will be performed in ABAQUS to study the RBC structures behaviour under the different load conditions.
3. Suggesting Retrofitting Scheme: A retrofitting scheme based on the comparative analysis and elemental based nonlinear analysis will be developed. This scheme will suggest the techniques and materials that will be needed to increase the strength of durability of the RBC structures, ensuring that they meet the current standards.

1.4 Scope:

The scope of this project is that a study will be done on the structural integrity of the Koh e Noor Steel Mills. Over time the strength and durability of the structure has decreased so given the constraints and impracticalities that the structure cannot be demolished and reconstructed, this project aims to develop such practical retrofitting schemes that will enhance the structure's durability and increase its life.

First, structural assessment of Koh e Noor Steel Mills will be done to identify the main areas of concern in the building. Then, a material analysis will be done in order to focus properties and performance of RBC that was used in the original construction. Then we will be doing the analysis on the ABAQUS software and after that a retrofitting scheme will be suggested.

Significance:

The significance of this project is that it will be used to address safety, economic and environmental concerns that are associated with the Reinforced Brick Concrete Structures. The Koh e Noor Steel Mill that was constructed using the Reinforced Brick Concrete, has experienced, due to passage of time, a reduction in strength. So, this project which mostly focuses on retrofitting of the RBC structures, carries several important implications.

First, this project aims to improve the safety measures for the people that are working in the steel mill. By retrofitting such structure, the chance of structure failure can be eliminated, therefore preventing any unfortunate and potential accidents which pose a threat to human life. Moreover, demolishing and reconstructing a facility like a steel mill would not prove to be cost effective and it would require a lot of money, time, and resource expenditure. So, the retrofitting offers a cost-effective alternative in which we do not need to demolish anything, and the lifespan of the structure can be increased in this way.

Moreover, by developing such retrofitting schemes and strategies, it encourages innovation in engineering world. Successfully retrofitting the steel mill will boost confidence among the stakeholders, employees, investors, and regulatory bodies. Overall, the significance of this project goes beyond structural improvements to ensure safety, economic, environmental, and technical benefits, which contributes to the sustainable development and advancement of industrial infrastructure practices.

Chapter 2

2. LITERATURE REVIEW

The RBC and retrofitting of RBC has been a subject of a lot of research, which represents its long use and the need to improve and enhance its performance over the time. The structural strength of RBC structures has been compromised and reduced due to a lot a factor that includes the aging, material degradation, and some environmental conditions. This review shows the key findings and studies that has shaped the methodologies and the understandings of retrofitting the RBC structures.

The seminal work on combined bending and axial loading done by Elvind Hognestad in 1951 gives the foundation for understanding various complex interaction of concrete under various load conditions. The experimental and analytical investigation by Hognestad provided some critical insights into the behaviour of Reinforced Concrete that provided fundamentals to the retrofitting practices that was aimed at increasing the load bearing capacity of the soil. (Eivind Gognestad., 1951)

The 2019 research that was done by Boudjamaa Roudane, Süleyman Adanur, and Ahmet Can Altunişik, used the numerical modelling methods to examine the masonry infilled with reinforced concrete buildings structures, done during different stages of the construction by using the ABAQUS software. This research mainly highlighted the significance of using the Finite Element Analysis (FEA) in predicting and improving the structural behaviour of concrete, mostly when it is used with the masonry elements. These findings from this research shows the use of advanced simulation tools that are effective in planning retrofitting strategies. (Roudane et al., 2019)

Suresh Kumar Paul and Pukhraj Sahu in the year 2020 did research on doing the retrofitting of reinforced cement concrete with the Carbon Fibre Reinforced Polymer (CFRP) by using the finite element analysis in ABAQUS software. This research showed the major improvements that were brought in the load carrying capacities and in the stiffness of Reinforced Concrete beams that are retrofitted with the Carbon Fibre Reinforced Polymer. Also, this study also gave some valuable data regarding the distribution of stresses and strains of the retrofitted structures which offers a scientific basis for CFRP applications in improving the structural strength of the RBC buildings. (Kumar et al., 2020)

T. Yu, J.G. Teng, Y.L. Wong, and S.L. Dong in 2010 while furtherly exploring the finite modelling done on reinforced concrete, they introduced a plastic damage model, that explained the damage evolution that is done within a confined concrete element. This study helped understand the damage mechanics, which includes the cracking and the crushing which, for retrofitting of RBC structures, are critical considerations. (Yu et al., 2010)

Dudley Charles Kent and Robert Park in 1971 did a study which focused on the flexural members that had confined concrete, revealing enhancements in the flexural capacity, ductility, and overall structural performance due to confinement. Their work mostly gave importance to the role of confinement done in improving the resiliency of the concrete members, which is a key concept in retrofitting. (Kent et al., 1971)

Son Thai, Drac Tran-Tien, and Minh Tuan Ha in 2023 made a 3D numerical model. It simulated the behaviour of reinforced concrete frames that were infilled with open brick walls. This study provided the perception int the elastic and the plastic behaviour of the joints, by using the ABAQUS software, between bricks and crushing of bricks under compression. In accurately predicting the structural responses, the application of Drucker-Prager plasticity model was crucial which helped in design of effective retrofitting measures. (Thai et al., 2023)

In the context of the Koh e Noor Steel Mills, the above studies gave a comprehensive framework for help us to understand the structural difficulties and challenges and giving us the potential retrofitting solutions. The steel mill's reduction of the initial strength and the reduction of durability requires a detailed study of the response of the load under the current conditions.

Chapter 3

3. METHODOLGY

The methodology for this study on the retrofitting of reinforced brick concrete (RBC) is meticulously structured to ensure comprehensive analysis and reliable results, encompassing several critical phases, from the procurement of materials to advanced nonlinear analysis. Initially, the procurement phase involved sourcing essential materials, including 53-grade cement, which was selected due to its superior early strength, making it highly suitable for load-bearing applications. Type B bricks were chosen for their standard quality and structural reliability, essential for the integrity of the RBC structures. For the coarse aggregate, a size passing through a 1/2-inch sieve was used, which was specifically selected to achieve an optimal balance between workability and strength. This size ensures adequate interlocking within the concrete mix while maintaining a manageable viscosity, crucial for ensuring the structural performance of the beams and columns. The fine aggregate was sourced from the laboratory, ensuring consistent quality and gradation, which is vital for the homogeneity of the concrete mix.

Following the procurement of materials, the next step involved the casting of beams. Three RBC beams were cast, each measuring 6 x 10 inches with a length of 5 feet. The casting process involved constructing a steel cage using #2 bars for reinforcement, with stirrups spaced 6 inches apart. The mix proportion used for the concrete was 1:2:4, which denotes the ratio of cement, sand, and aggregate, respectively, and a water-cement ratio of 0.35 was maintained. This specific mix proportion was chosen to ensure adequate strength and durability of the beams while maintaining workability. Bricks were strategically placed inside the steel cage to occupy space, which helps in reducing the weight of the beams and potentially improving their structural performance. After casting, the beams underwent a curing process for 28 days. Curing is a critical step in the concrete casting process as it ensures that the concrete attains its desired strength and durability by maintaining adequate moisture content.

Upon the completion of the curing period, midpoint flexure testing was performed on the beams. The midpoint flexure test, also known as the three-point bending test, involves applying a load at the midpoint of the beam and measuring the deflection until failure occurs. This test is essential for evaluating the bending resistance, flexural strength, and ductility of the beams.

The results from this test provide valuable insights into the structural performance of the RBC beams, particularly their ability to withstand bending forces. Based on the test results, moment-curvature curves were developed. These curves graphically represent the relationship between the bending moment and curvature, offering a detailed understanding of the beams' nonlinear behaviour and potential failure modes. Moment-curvature analysis is crucial in structural engineering as it helps predict the performance of structural elements under different loading conditions.

The next phase involved the casting of a column. An 18 x 18-inch column with a length of 4 feet was cast, with the outer perimeter covered by bricks. The concrete mix used for the column had the same proportion of 1:2:4 and a water-cement ratio of 0.35. Steel reinforcements comprised #2 bars with stirrups spaced at 4-inch centre-to-centre intervals. The reduced spacing of stirrups in the column, compared to the beams, was intended to enhance the column's shear strength and overall stability. The column, like the beams, was cured for 28 days to ensure adequate strength development. After curing, the column was subjected to compression testing using a compression testing machine. This test is fundamental for determining the column's load-bearing capacity and compressive strength, which are critical parameters for assessing the structural integrity and safety of the column.

The data collected from the beam and column tests formed the basis for the subsequent phase, which involved conducting an elemental-based nonlinear analysis using ABAQUS software. ABAQUS is a sophisticated finite element analysis (FEA) software that allows for detailed simulation and analysis of complex structural behaviours under various loading conditions. This advanced analysis provided a comprehensive understanding of the structural performance of the RBC beams and columns, particularly under scenarios that mimic real-life conditions. The nonlinear analysis was instrumental in identifying potential failure modes and areas where retrofitting could enhance structural performance. Based on this analysis, a retrofitting model was developed, aiming to improve the resilience and longevity of RBC structures. The retrofitting model proposed in this study is designed to address specific weaknesses identified through testing and analysis, thereby enhancing the overall structural integrity and safety of the RBC structures. This comprehensive methodology, from material procurement through advanced nonlinear analysis, underscores the rigorous approach adopted in this study to achieve reliable and impactful results, contributing significantly to the field of structural engineering and the development of effective retrofitting strategies for RBC structures.

Chapter 4

4. MATERIAL TESTING

4.1 Casting of beams:

Beams measuring 10 inches by 6 inches were cast, utilizing number two steel bars for reinforcement. This choice of reinforcement is pivotal as it provides the necessary tensile strength to support the beams under various loads.

To optimize material usage and reduce weight, bricks were strategically placed within the beam mold, serving as a filler material. This innovative approach not only economizes the construction but also contributes to the sustainability aspect by potentially reducing the concrete volume required. The bricks, being less dense than concrete, offer a unique composite behavior when encased in the concrete matrix.

The concrete mix used for filling the molds was carefully designed with a water-to-cement ratio of 0.35, ensuring a balance between workability and strength. The selection of aggregates is equally significant, and in this case, aggregates passing through a #4 sieve were employed. This specific aggregate size distribution is crucial for achieving a dense and uniform concrete, which is essential for the structural performance of the beams.

The concrete mix proportion followed the classic 1:2:4 ratio (cement:sand:coarse aggregate), a time-tested formula that provides a harmonious blend of strength and durability. The meticulous process of layering the concrete in the molds involved tapping each layer with a rod 25 times. This compaction technique is instrumental in eliminating air pockets and voids, leading to a more homogenous and structurally sound final product. (Abou Rachied et al., 2023)

Post-placement, the beams underwent a 28-day curing period, a vital phase in the concrete life cycle. Curing is paramount as it allows the concrete to reach its intended strength and durability. During this period, the hydration reaction continues, and the concrete gradually transitions from a plastic state to a robust and rigid structure capable of bearing the designed loads.

Figure 1: Casting of Beam 1

Figure 2: Casting of Beam 2

4.2 Testing of beams:

The casted beam was subjected to mid point loading. The beam was subjected to a loading rate of 0.25 MPa/s, as per the machine's specifications. The test culminated in a maximum load capacity of 22.925 KN, a figure that signifies the beam's ability to endure substantial stress before failure. This outcome is particularly noteworthy as it reflects the structural resilience imparted by the reinforcement and the quality of the concrete mix utilized.

The testing adhered to the ASTM standard, which delineates the methodology for determining the flexural strength of concrete specimens. The standard specifies the use of a simple beam with center-point loading, as outlined in Test Method C293-02. It emphasizes the importance of uniformity in measurement units, either SI or inch-pound, to avoid discrepancies that could lead to non-conformance with the standard. Moreover, the standard mandates the establishment of appropriate safety and health practices, underscoring the significance of a secure testing environment.

Referenced documents within the ASTM standard provide a framework for the preparation and curing of concrete test specimens, both in the field (C31/C31M) and the laboratory (C192/C192M). Additionally, practices such as C617 for capping cylindrical concrete specimens and C1077 for evaluating testing agencies contribute to the integrity of the testing process.

The significance of the test method lies in its ability to ascertain the modulus of rupture for specimens prepared in accordance with the referenced practices. The results obtained can inform compliance with specifications and guide the proportioning, mixing, and placement operations.

The apparatus used for testing conformed to the requirements of Practices E4, ensuring a continuous and uniform application of load without shock or interruption. The loading apparatus applied forces perpendicularly to the specimen's face, maintaining the span length and central position of the load-applying block within precise tolerances. (Bernard & Xu, 2007)

The meticulous testing procedure involved the positioning of the specimen on the support blocks and the application of an initial load to assess any gaps between the specimen and the load-applying or support blocks. The load was then applied continuously to the breaking point, with the rate of increase in maximum stress on the tension face maintained between 0.9 and 1.2 MPa/min. (*Flexural test on concrete - significance, procedure and applications* 2017)

Post-testing, measurements were taken across the fractured faces to calculate the modulus of rupture, with the width and depth recorded at the edges and center of the cross-section. These measurements are crucial for an accurate determination of the beam's flexural strength.

Figure below shows the experimental setup of reinforced brick concrete beam subjected to mid point loading

Figure 3: Midpoint Testing of Beam

Figure 4: Result of Test

4.3 Casting of columns:

The column in question was designed to be encased within a steel cage measuring 7x7 inches, utilizing #2 bar for the steel reinforcement. This choice of reinforcement is pivotal, as it provides the necessary tensile strength to support the column under load-bearing conditions. The concrete core of the column was fashioned to be 10x10 inches, a dimension carefully calculated to ensure the column's robustness and durability.

Surrounding this core, Type B bricks were methodically laid on all four sides, culminating in the overall dimensions of the column reaching 18x18 inches. The selection of Type B bricks is not arbitrary; these bricks are known for their compressive strength and ability to withstand various environmental factors, thereby contributing to the column's longevity.

The concrete mixture used in the casting process was composed with a water-cement ratio of 0.35. This specific ratio was chosen to optimize the hydration process of the cement, leading to a denser and more durable concrete. Furthermore, the aggregate size was determined to pass through a #4 sieve, ensuring a uniform and consistent mix that would enhance the structural properties of the column. (Wang et al., 2017)

Moreover, the concrete mixture adhered to a ratio of 1:2:4, signifying one part cement, two parts sand, and four parts gravel. This proportion is a standard in the industry, known for producing concrete with excellent workability, strength, and finish.

The curing process, which spanned 21 days, is a testament to the commitment to quality in the construction process. Curing is a vital step that allows the concrete to reach its maximum potential strength. During this period, the concrete undergoes a chemical reaction known as hydration, which is crucial for the development of its mechanical properties.

Figure below shows an in place casted 4 ft long reinforced brick concrete column:

Figure 5: Casting of Column

4.4 Testing of column:

The 18x18in column was subjected to an eccentric point load, incrementally increased by 1 ton. This methodical increase in load was intended to assess the column's load-bearing capacity and to identify the onset of structural failure.

At a critical juncture, when the load reached 24 tons, the column exhibited its first signs of distress, manifesting as cracks. Intriguingly, these fissures were confined exclusively to the brick components of the column, sparing the concrete and reinforcement.

The phenomenon observed can be attributed to several factors inherent in the materials and the construction process. Bricks, being discrete units, are more susceptible to localized stress concentrations, particularly when the load is applied eccentrically. This eccentricity introduces bending moments, exacerbating the stress experienced by the bricks. Moreover, the interface between the bricks and the concrete matrix is a critical zone where stresses are often amplified, leading to crack initiation. (ACI, 2000)

The reinforcement within the column, typically consisting of steel bars, serves to resist tensile stresses and maintain the structural integrity of the column. However, the effectiveness of this reinforcement is contingent upon the bond strength between the steel and the surrounding concrete. In scenarios where the load is applied eccentrically, the reinforcement's role becomes even more crucial, as it must counteract not only the compressive forces but also the bending moments induced. (Mohamed Sayed et al., 2020)

The experimental setup, including the reaction floor, is designed to replicate the conditions that a column would face in a real-world scenario. The reaction floor provides a stable and controlled environment to apply the loads and measure the column's response accurately. The incremental loading allows for a detailed observation of the column's behavior at each stage, offering insights into its performance under gradually increasing stress.

The study's findings have significant implications for the construction industry. The selective cracking in the bricks underscores the need for careful consideration of material properties and load application methods in the design of composite structures. It also highlights the importance of thorough testing and evaluation to ensure the safety and durability of such structures.

Figure 6: Testing of Column

Chapter 5

5. ANALYSIS ON ABAQUS

5.1 Non-Linear Analysis of RBC Beam in ABAQUS

Abaqus is one of the most suitable and accurate software available for the nonlinear analysis of structural components. Nonlinear analysis is a complex task that requires extensive material modelling. A proper material model should be comprehensive enough to represent the material's behaviour in both elastic and plastic regions (Hamid Sinaei, 2012). We followed the concrete-damaged plasticity approach for finite element analysis, providing all the necessary values collected from research papers and testing. The analysis was done primarily to compare the results obtained in the Y-axis deflection with the experimental results obtained from laboratory testing.

The plastic behaviour of concrete is predefined in various literature sources. Thus, we used the same procedure to define the concrete material model (Roudane et al., 2019). For accurate results, complete values were required. Furthermore, as a reinforced brick concrete beam was being analysed, the Drucker-Prager model was used to define the brick material model. The primary purpose of the analyses was to check the behaviour of the beam by providing a CFRP strip at the point of most significant damage with longitudinal loading in the Y-axis. As our research aims to present a retrofit model of the RBC beam, we first performed a nonlinear analysis of a simple RBC beam. Then, we provided a CFRP strip at the bottom. We compared the results using the load/deflection curves with the experimental and analysis data obtained using the software.

Material models for all the components have been described in the previous paragraphs of this paper. A wide range of CFRP materials is available, so we specifically used T300 CFRP properties to define the CFRP material model in Abaqus. The details of the company manufacturing this CFRP and its properties are provided at the end of the paper. CFRP is a high-strength composite material used extensively in the aerospace industry and for many other purposes. The use of CFRP was the best solution available for retrofitting beams (Wang & Melly, 2017). Further elaborating on the benefits of CFRP, it is already being widely used in the construction industry due to its sustainability (Sen Umesh Mishra & B.S., 2010). Load/ Deflection curves were used as a comparison indicator as they provide valuable insight into the structural performance, strength, and flexibility of various components under different loading conditions.

Load/deflection curves provide valuable insights into the beam's elastic and plastic behaviour. The point at which linearity changes is represented when the structural component fails. They can also indicate the yield point, which can then be compared with experimental data to assess the accuracy of the experimental results. Additionally, they validate material performance, model verification, and parameter sensitivity. When the results were obtained, it was observed that the fracture toughness (Hughes & Fattuhi, 1977) increased after using CFRP, as analysed from the curves.

5.1.1 Modelling in ABAQUS

First, the beam was modelled in Abaqus with the exact dimensions as the beam we cast in our experimental results. The beam's cross-section was 6 inches in the lateral direction and 10 inches in the longitudinal direction. The image below shows the cross-section dimensions of the beam. The beam length was the same as in our experimental results, which was 5 feet.

#2 Steel bars were used in the experimental evaluation, so we modelled the same in Abaqus, with four longitudinal bars placed in the beam with a 1.5-inch cover. Stirrups made of #2 steel with 6-inch centre-to-centre spacing were also used. All the parts were modelled as deformable.

The bricks were placed at the centre of the beam as a layer, as was done in the experimental results. The brick placement was a crucial part of the modelling. A bricklayer was defined as a part in Abaqus and placed around the neutral axis at the centre of the beam.

The steel cage was also formed by defining longitudinal bars and stirrups as integral components of the beam. These bars provide the primary tensile reinforcement, while the stirrups, typically placed perpendicular to the longitudinal bars, offer shear reinforcement. Once defined, these elements were meticulously translated and positioned within the concrete section, ensuring proper alignment and coverage. Careful placement is crucial for maintaining the structural integrity and load-bearing capacity of the beam. Additionally, this method allows for accurate simulation and analysis of RC behavior under various loading conditions.

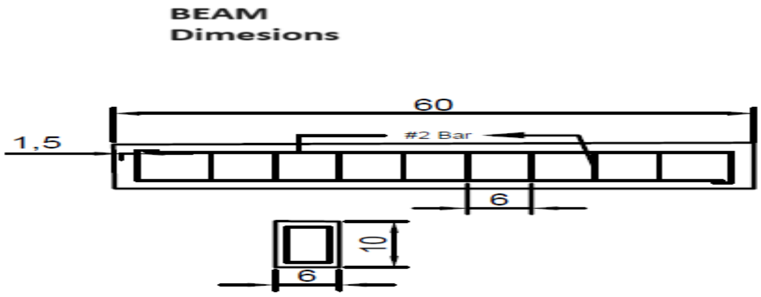


Figure 7: Beam Dimensions

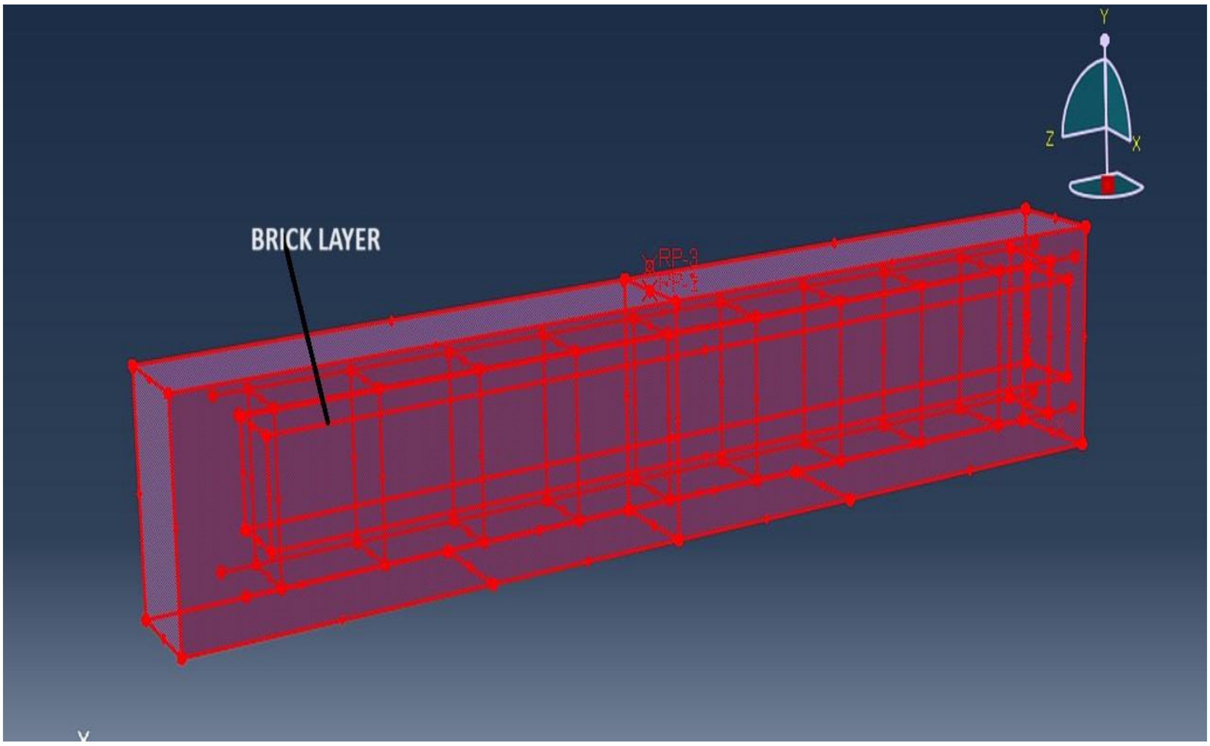


Figure 8: Brick Layer modelled in ABAQUS

To define the CFRP strip geometry, its width was set to that of the beam (6 inches), and its length was equal to one-third of its length. The CFRP was placed at one-third of the length of the beam at the bottom, as that was the area under the most stress. The figure below shows the CFRP placement at the bottom of the beam during modelling.

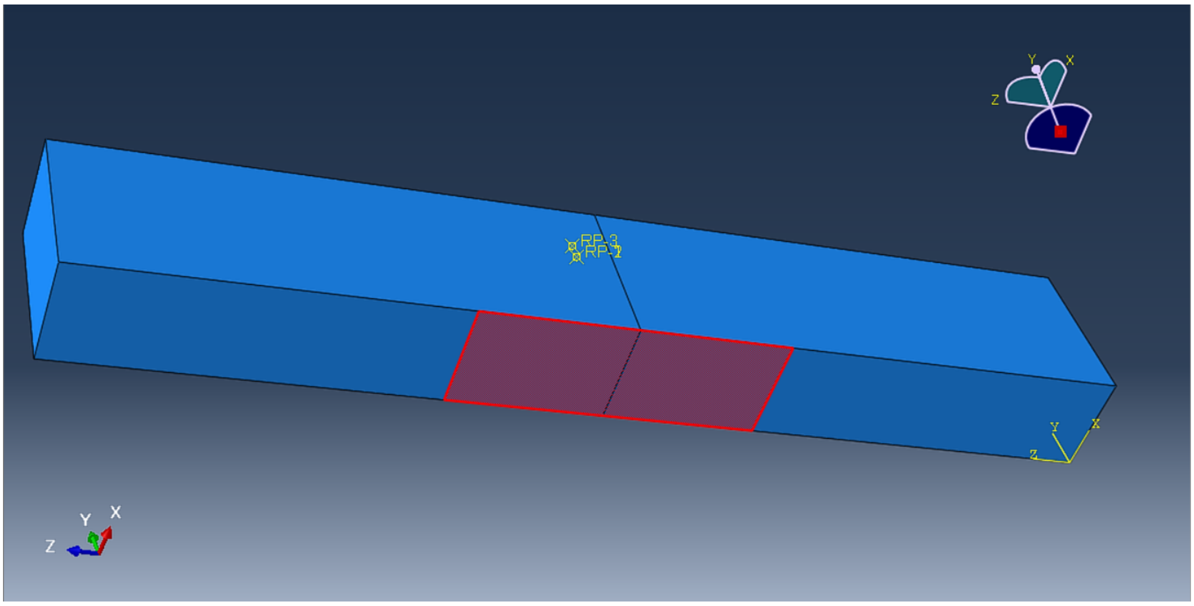


Figure 9: CFRP placement

5.1.2 Material Properties

Material models for each material used in modelling the beam have been discussed in the preceding section. Material properties of concrete were defined in terms of both compression and tension. For nonlinear analysis, values were taken from experimental results and the equations described earlier. For elastic behaviour, Young's modulus was taken as 2.9 × 10^6 and Poisson's ratio as 0.2. For compressive behaviour, inelastic strain values were added for different yield stresses, and tensile behaviour and cracking strain values were added for different yield stresses, all computed using the experimental results.

For bricks, the Drucker-Prager model was used as described before, inputting the values for Drucker-Prager hardening (Rakic et al., 2013) and for the bricks' elastic behaviour. Values for the Drucker-Prager model were taken from different research papers.

For steel, the elastic and plastic material properties were defined using data from the UET database for the #2 bar. The same materials were used for CFRP, taken from the Toray manufacturing company website. Each part modelled was assigned its respective properties for analysis.

5.1.3 Boundary Conditions and Load Applied

A step was created to define the load-interval set to 1 second. During this interval, the load was applied in increments under the default ABAQUS settings for simulation. The maximum load applied was set to 22.94 KN, the same load the beam cracked during testing. Boundary conditions were taken as simply supported for the analysis, and a reference point was created at the top face of the beam in the middle. The load was then applied at the reference point in the middle of the beam.

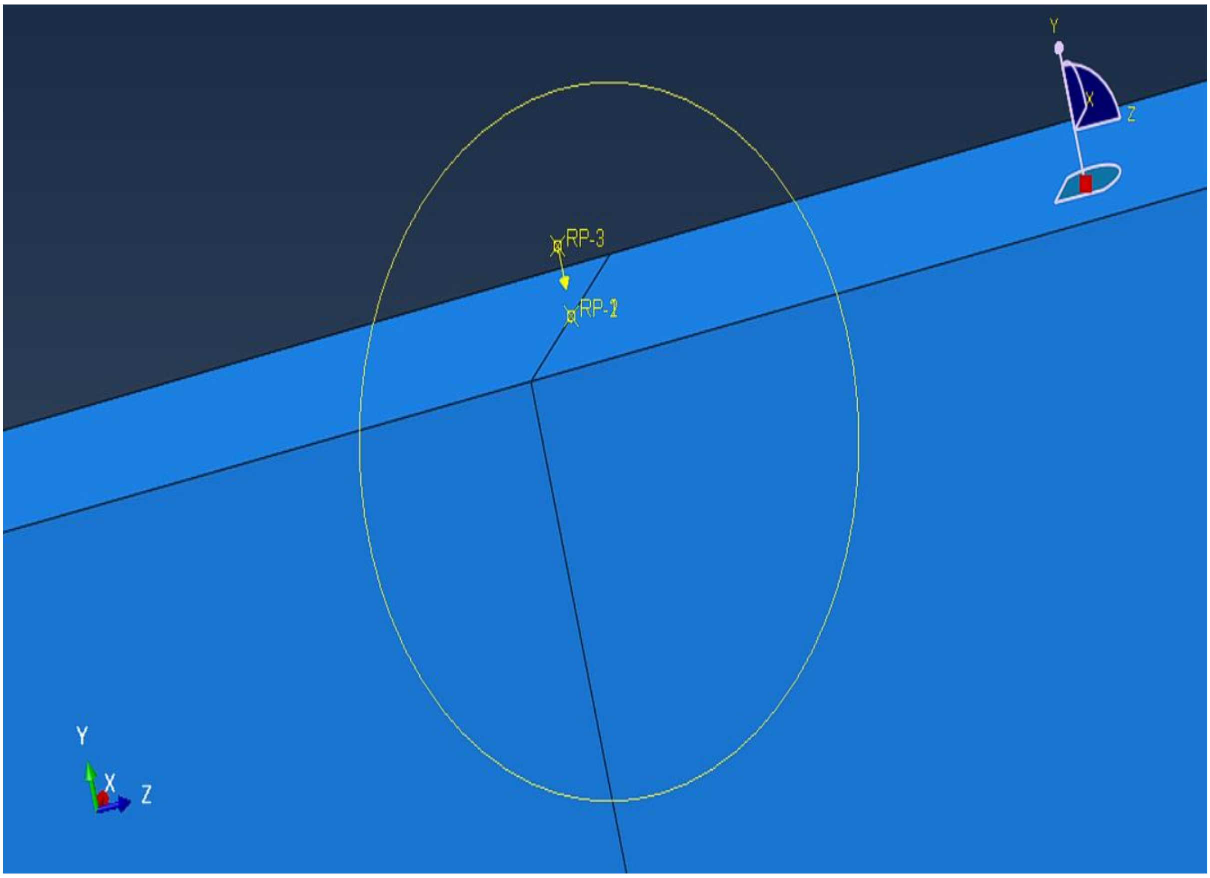


Figure 10: Load Placement

Constraints were then defined to join the bricks and the CFRP strip to the concrete. Embedded and host regions were selected to apply the constraints. Boundary condition and load application are critical steps in finite element analysis (FEA) to get results that properly simulate real-world scenarios.

5.1.4 Meshing

The mesh size was set to 1.8 for each part, as each was individually meshed. The mesh size was kept small to enhance the accuracy of the simulation results and adequately analyse the areas under stress during loading (Hamid Sinaei, 2012).

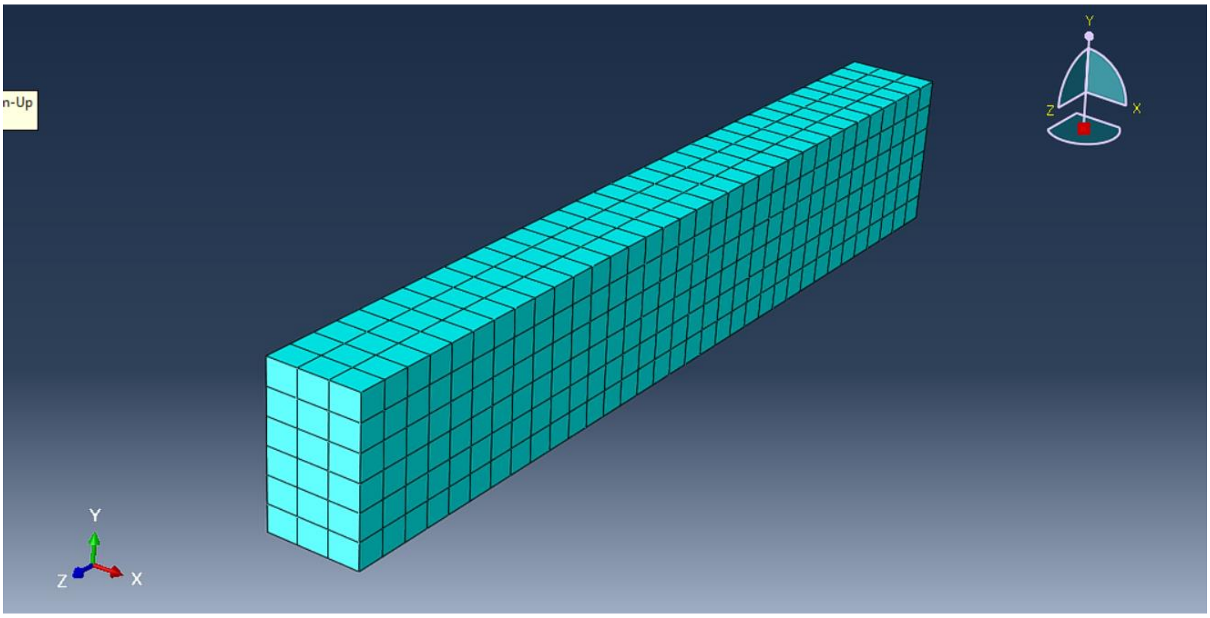


Figure 11: Meshing

5.1.5 Analysis

Analysis was conducted for both models of the RBC beam, with and without CFRP. Their deflection profiles along the Y-axis and plastic deformation, along with many other variables, were compared to monitor the differences caused by using CFRP. Additionally, analysis was performed on a simple RCC beam without bricks but with the same dimensional properties. Load/deflection curves for each beam profile were plotted using ABAQUS and Microsoft Excel.

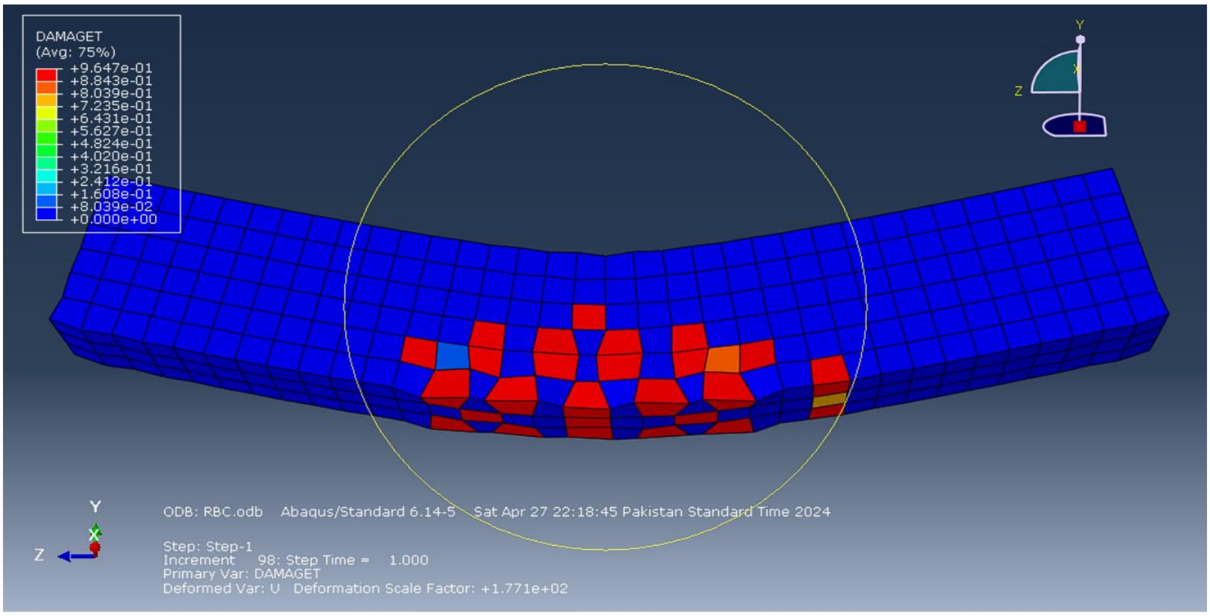


Figure 12:Damaged area of RBC beam without CFRP

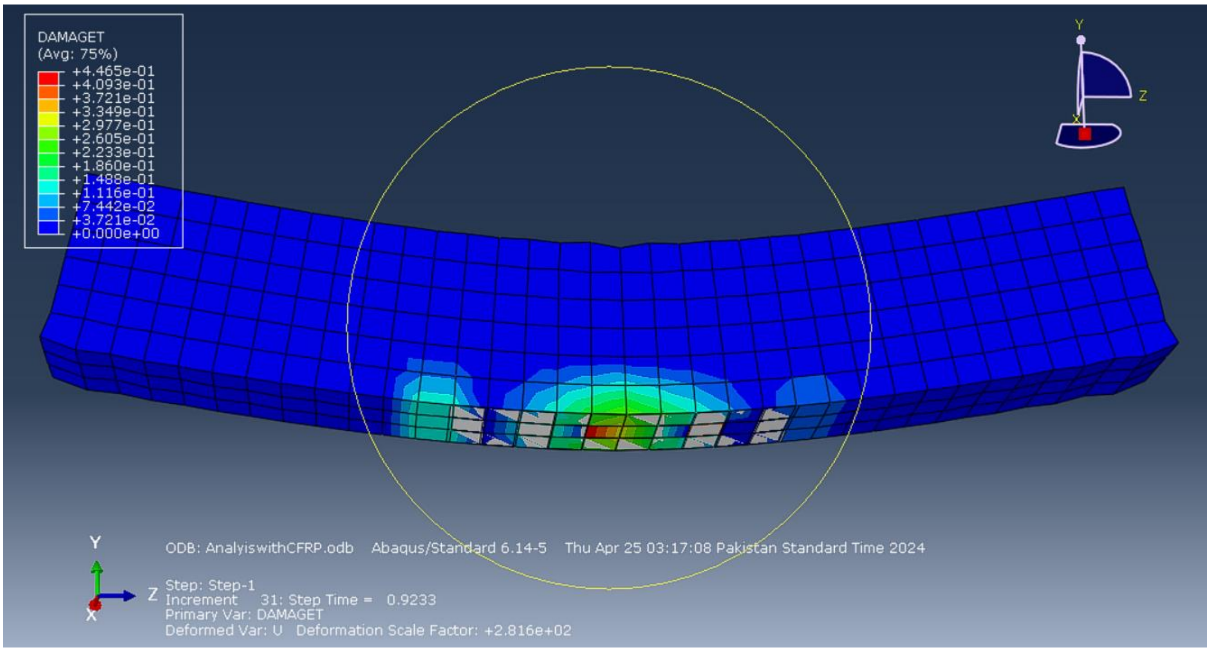


Figure 13: RBC Beam damaged area with CFRP

Both profiles above show the tension damage caused by the applied load. It can be observed that the damage area is far less in the RBC beam with CFRP compared to the simple RBC model. This demonstrates the significant impact of CFRP on the beam's ability to withstand larger loads.

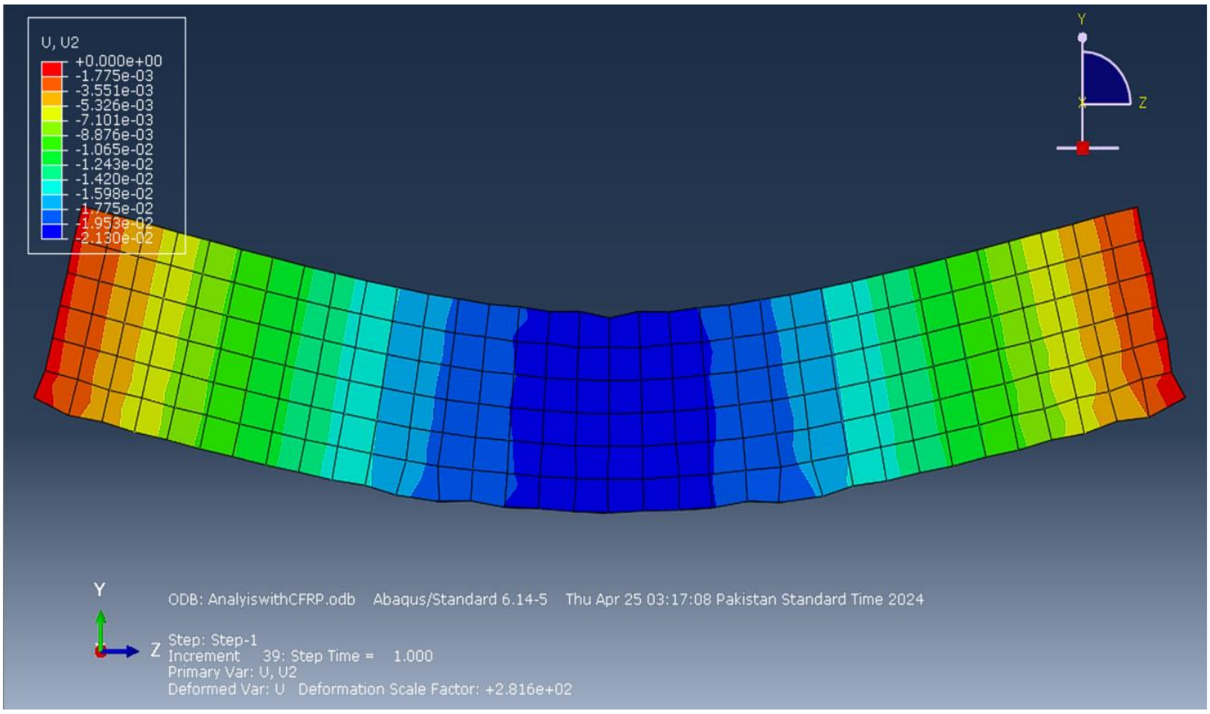


Figure 14: Deflection in Y-axis with CFRP

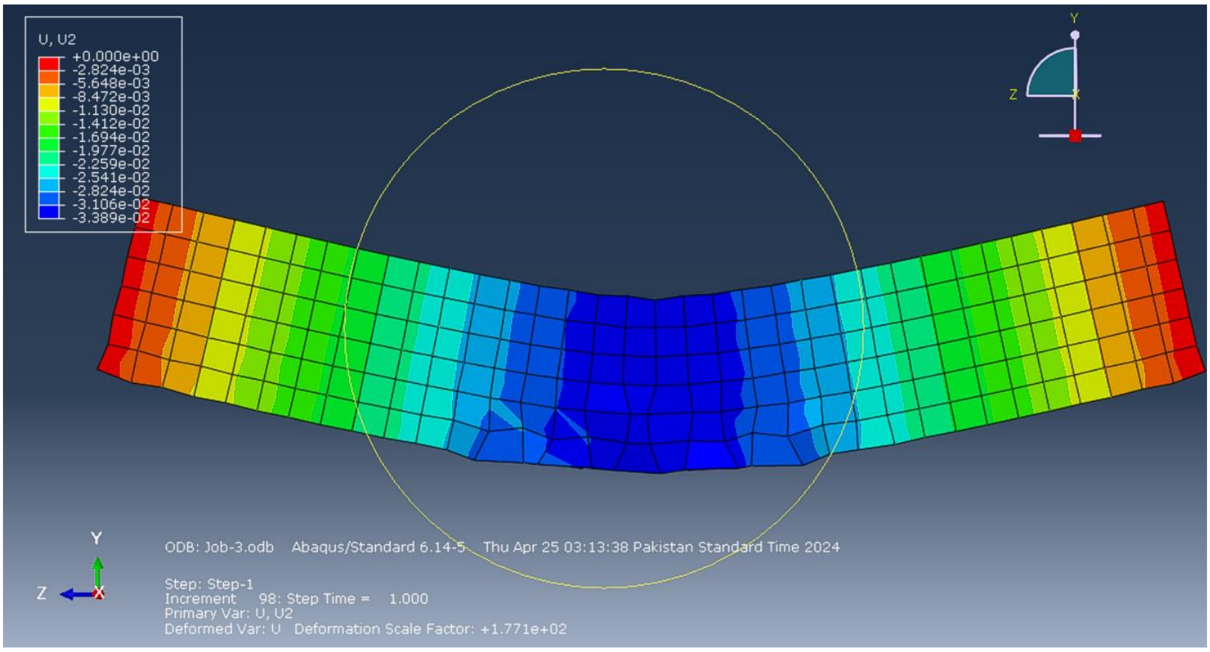


Figure 15: Deflection in Y-axis without CFRP

The profiles above illustrate the maximum deflection at each elemental node under the applied load, with the blue areas indicating the points of highest deflection along the y-axis. Deformation is particularly notable at the bottom of the beam. The deflection values, stated in inches at the top left corner, demonstrate how the incorporation of CFRP has significantly reduced deflection at the beam's bottom. Furthermore, the profiles indicate that the beam with CFRP has not surpassed the elastic region, highlighting its effectiveness in maintaining structural integrity under load.

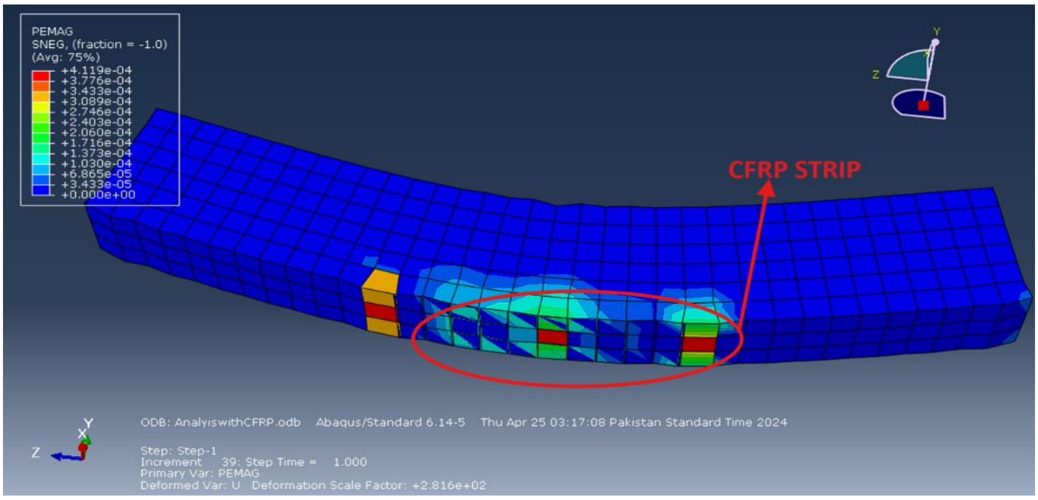


Figure 16: Plastic Strain with CFRP

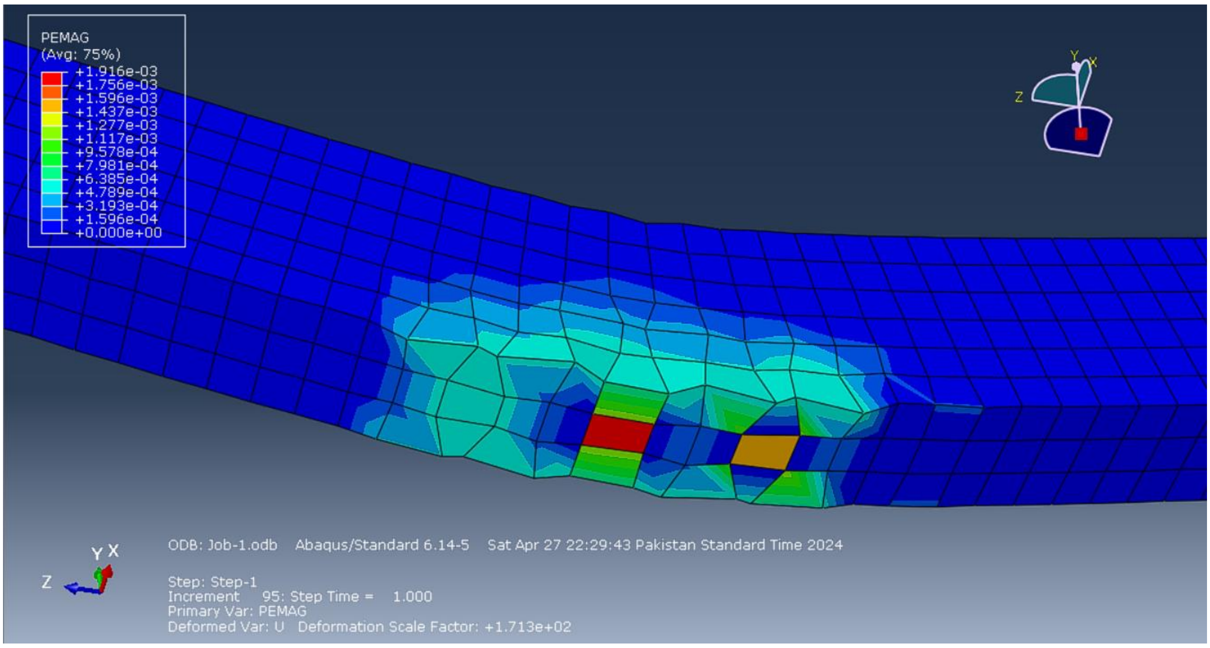
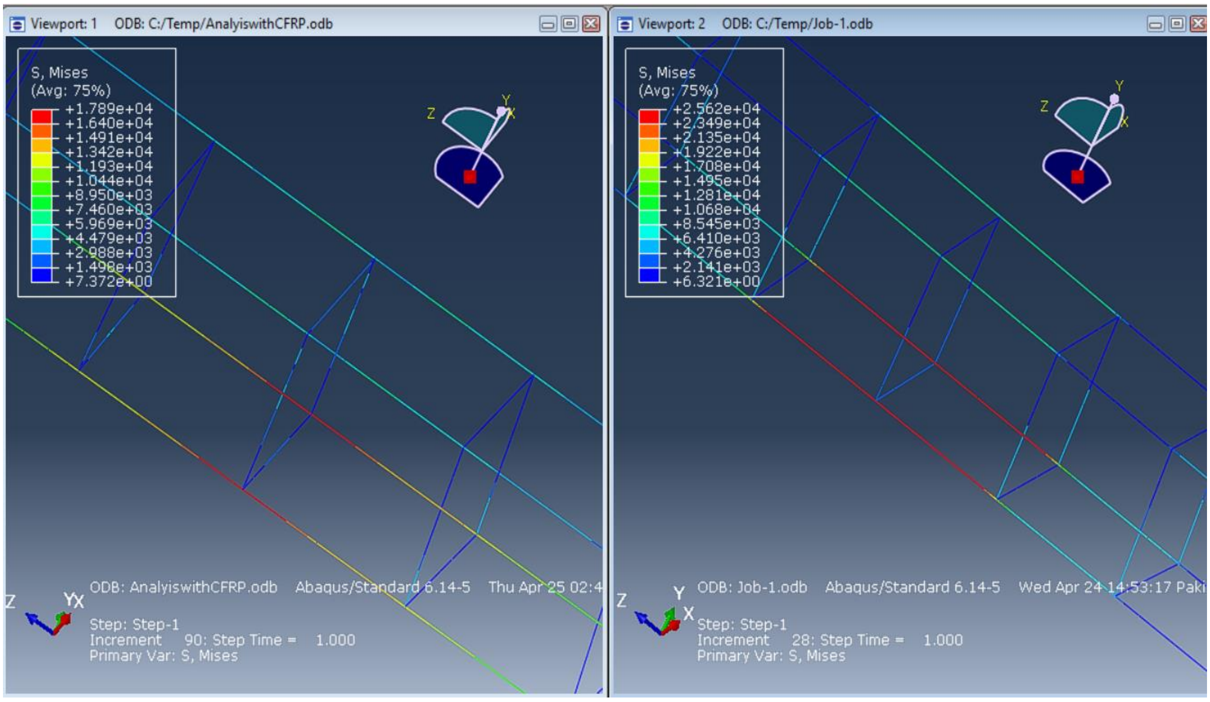


Figure 17: Plastic Strain without CFRP

Nonlinear analysis was conducted, and the figure presented here represents the maximum plastic strain in the beam. Plastic strain is a crucial measure for structural evaluation (Shi et al., 2018). The plastic strain is highest at the points where the most significant damage occurred.



This profile compares stresses in the steel cage with CFRP on the left and without CFRP on the right. As indicated by the red areas, the stress in the steel cage with CFRP is significantly lower than in the steel cage without CFRP. Additionally, the area of maximum stress is reduced in the steel of the beam with CFRP.

5.2 Non-retrofitted Finite element model of RBC

Experimental research on reinforced brick concrete columns is expensive and time-consuming. Therefore, computer-aided analysis of RBC columns using FEA techniques is necessary to expand existing knowledge of the behavior of those columns. That is why we carried out the experimental analysis and imitated its results in our initial non-retrofitted model. Once that was done, we moved on to suggesting different retrofitting schemes and adopted the one that gave the most satisfactory results.

Abaqus was used to make a numerical model of RBC columns using Finite Element (FE) code. The FE model incorporated geometric and material non-linearities. We employed the concrete damage plasticity model which gives both tensile and compressive failures. The steel-concrete and brick-concrete interface was modeled using the built-in option in ABAQUS/Standard.

5.2.1 Part Module

The first step in finite element modeling is to define the parts. In our study, the RBC column has an 18 x 18 in cross-section as shown in the image below. The height of the column is 48 in.

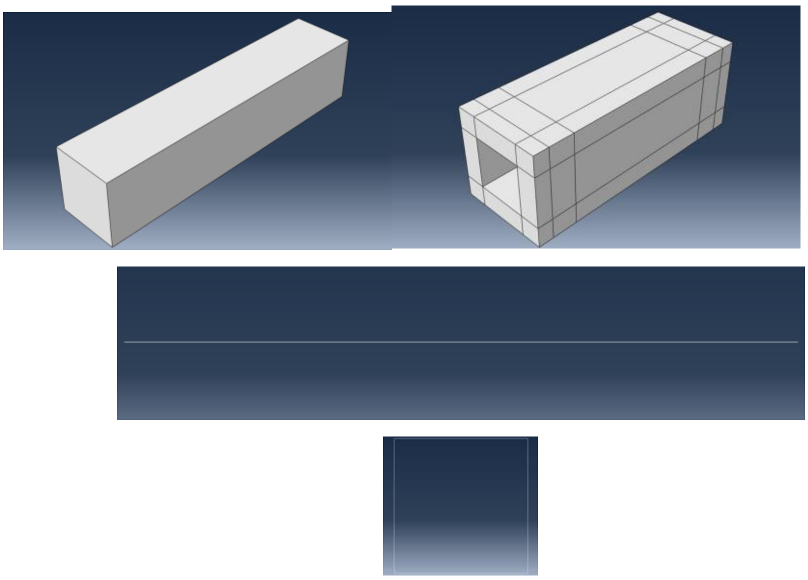


Figure 18: Column Parts Module (Concrete Block, Brick Section, Longitudinal Steel Bar, and Stirrup)

5.2.2 Property Module

Defining the properties of the materials that you have used in your finite element model is one of the most important steps of the entire modeling process. All the material properties used for analysis are shown in the table below. (Roudane et al., 2019)

S. No.	Material	Density(kg/m^3)	Young's Modulus	Poisson's Ratio
1	Concrete	2350	22,000	0.20
2	Brick	2000	1000	0.20
3	Steel	7850	210,000	0.30

5.2.3 Assembly Module

In the assembly module of ABAQUS, you have to create an assembly of different parts. In our case, we first made a cage of longitudinal steel and stirrups. The stirrups were placed at a distance of 4 in c/c as shown in the image below:

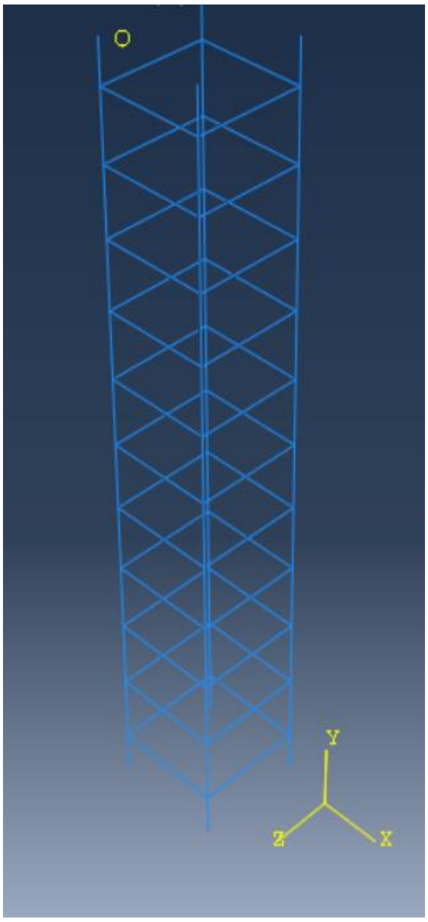


Figure 19: The Steel Cage

Once that was done, we placed this steel cage inside the concrete block. Then, the concrete block and steel cage were placed inside the hollow brick part. The entire assembly is shown below with everything in their appropriate places:

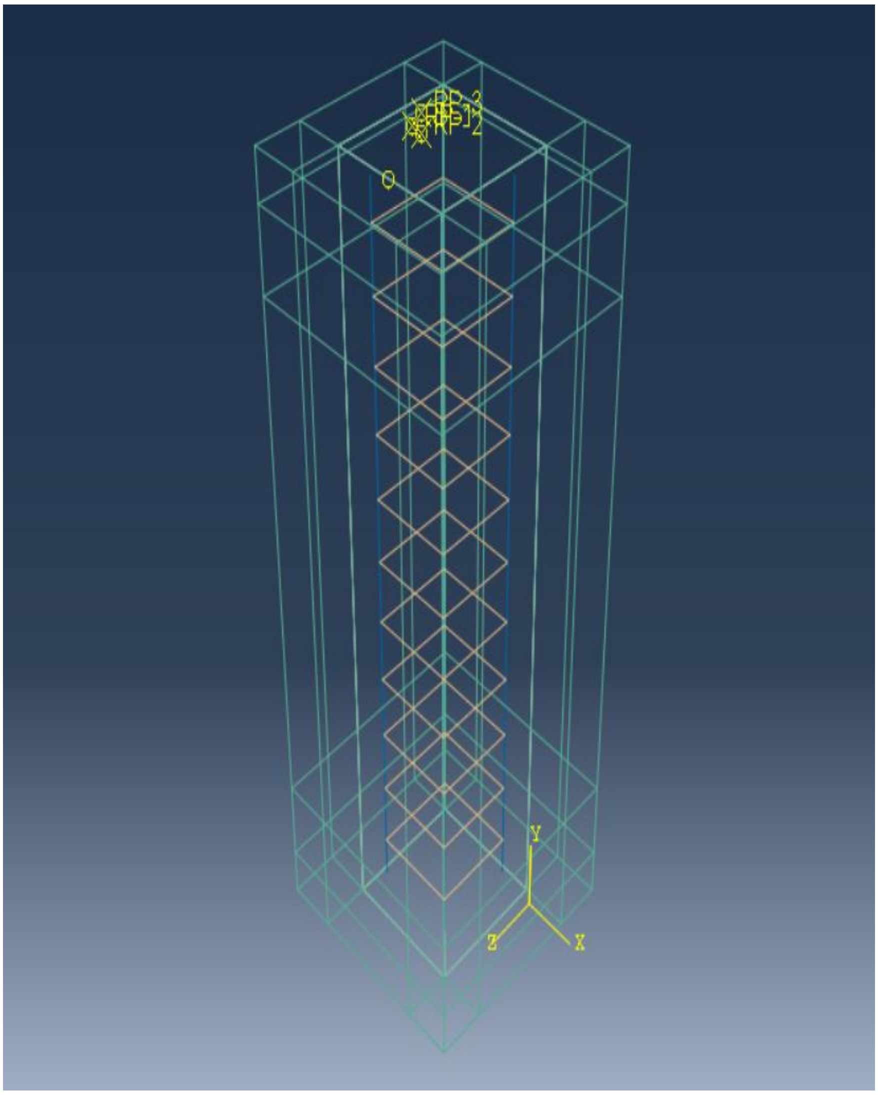


Figure 20: The Entire Assembly (Steel Cage, Brick, Concrete Block)

5.2.4 Step Module

In the step module in ABAQUS, you can define the way your load will be applied and the time for which it will be applied. (Kartheek & Venkat Das, 2020)

The step module of our RBC column is shown in the figure below:

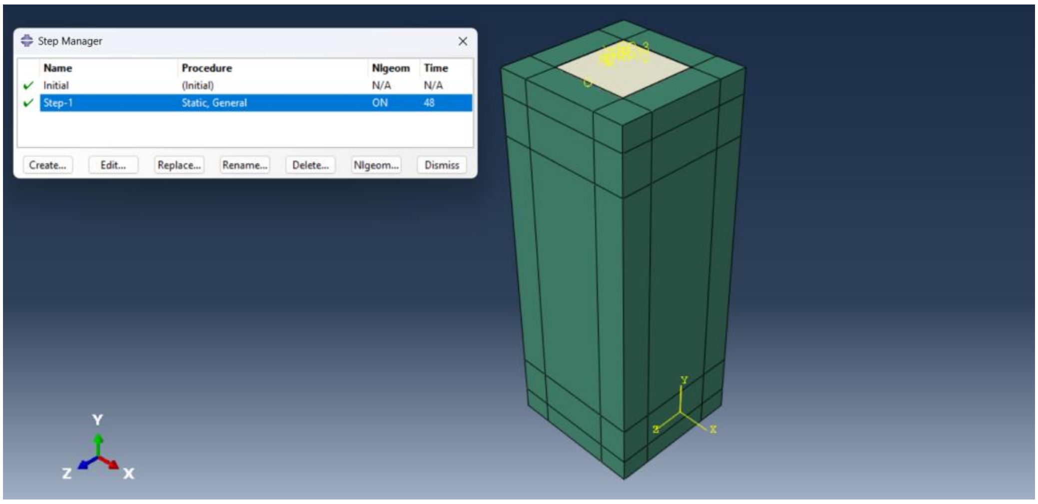


Figure 21: Step Module

5.2.5 Interaction Module

In the interaction module, we gave our FE model different constraints. The first one was that we embedded our steel cage and concrete block inside the brick section of our RBC column. This ensured that overlapping of different volumes did not take place. The second constraint that we defined was that modeled the outer surfaces of the concrete and the inner surfaces of the brick as ties. The outer concrete surface was taken as the 'master surface' and the inner brick surface was taken as the 'slave surface' keeping in mind the load path. This constraint was given on all four sides of our column.

Another constraint that was created was 'coupling'. This was done by introducing a datum point on the point where the load was applied. The datum was introduced exactly at the point where the load was applied during experimental analysis. Then, a reference point was created at 1in above the datum. This reference point was coupled with the top surface of our RBC column as shown in the figure below:

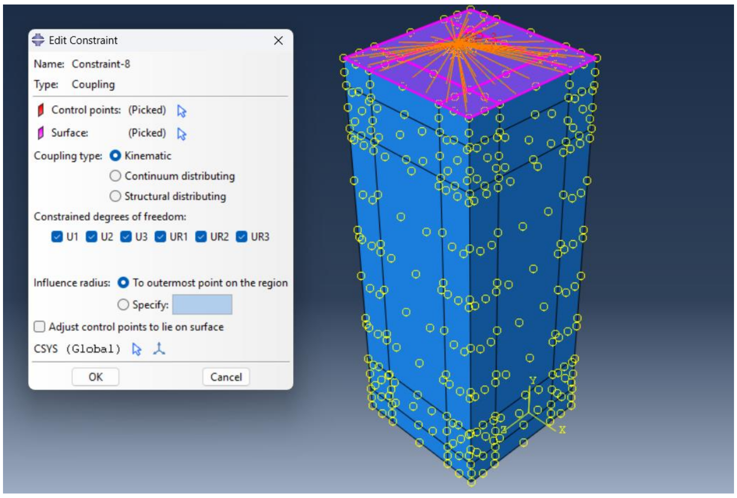


Figure 22: Coupling Constraint

5.2.7 Load Module

In the load module, we defined the load that will be applied to our RBC column. In our case, the load applied was 48,000 pounds as this was the load at which the spalling of bricks started to occur.

In addition to that, we also introduced the boundary conditions for our RBC column in the load module. For our column, we used the fixed boundary condition.

5.2.8 Mesh Module

The most accessible meshing technique in Abaqus is one that does not require pre-defined mesh patterns. While meshing a piece with complex geometry can either be very satisfying or, as often happens, highly frustrating, the creation of a clean and uniform mesh for structural analysis has been made easier by advancements in meshing algorithms and software. This post focuses on using toolsets to enhance mesh quality through partitioning or dividing the geometry.

In this analysis, the mesh size was kept as 4in as shown in the figure below:

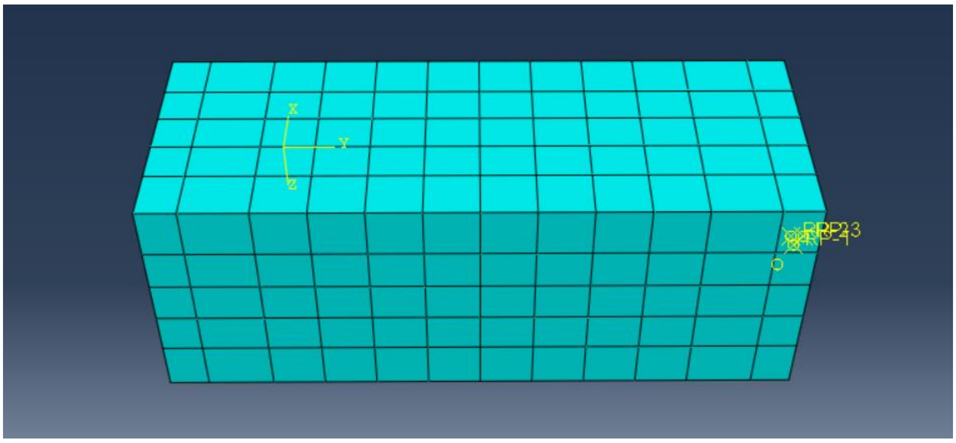


Figure 23: Mesh of our RBC Column

5.2.9 Job Module

Once our model was complete, we created a job and did a 'data check'. This was done to ensure that our model had no errors. Afterward, we submitted our job for analysis and waited for the results to converge.

5.3 Retrofitted Finite element model of RBC

On our non-retrofitted RBC column model, we tested out different retrofitting schemes and employed the one that proved to be the most satisfactory and cost-effective.

5.3.1 Retrofitting Scheme

The retrofitting scheme we employed was 2 steel collars at top and bottom with carbon fiber reinforced polymer (CFRP) between them as shown in the figure below:

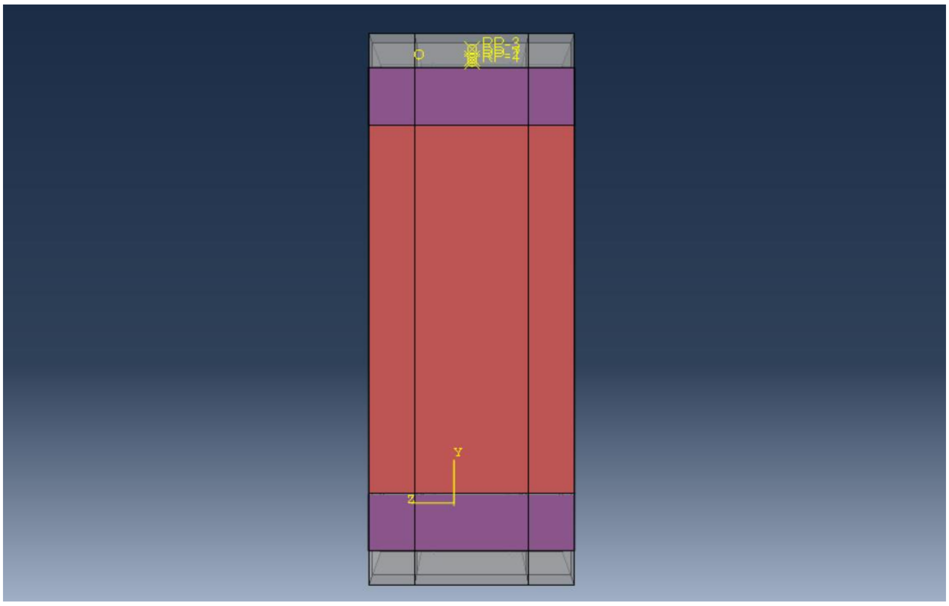


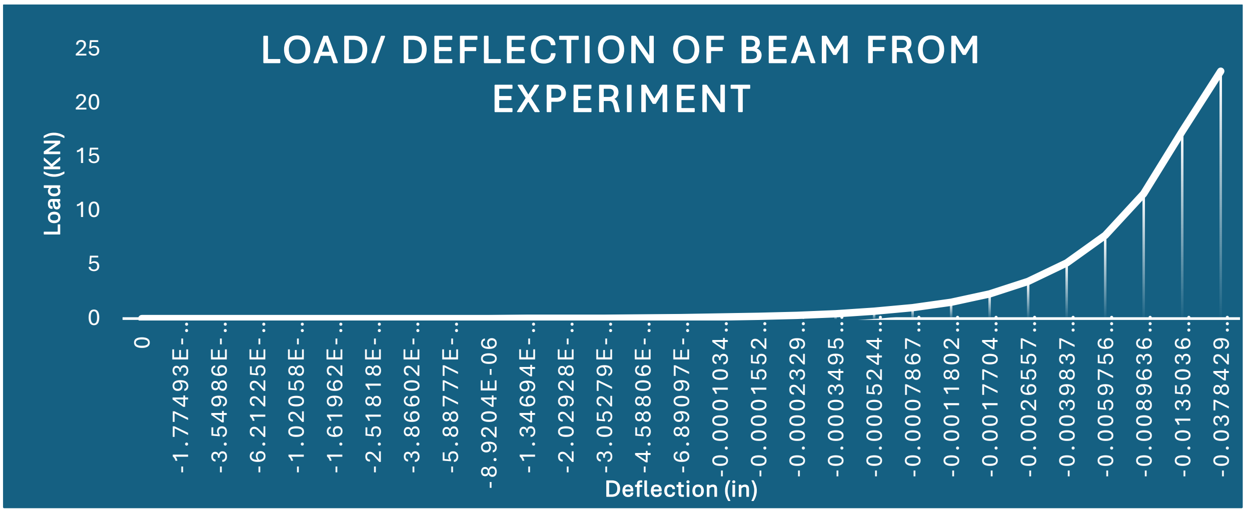
Figure 24: Retrofitting Scheme➔ Steel Collars (Purple) and CFRP sheets (Red)

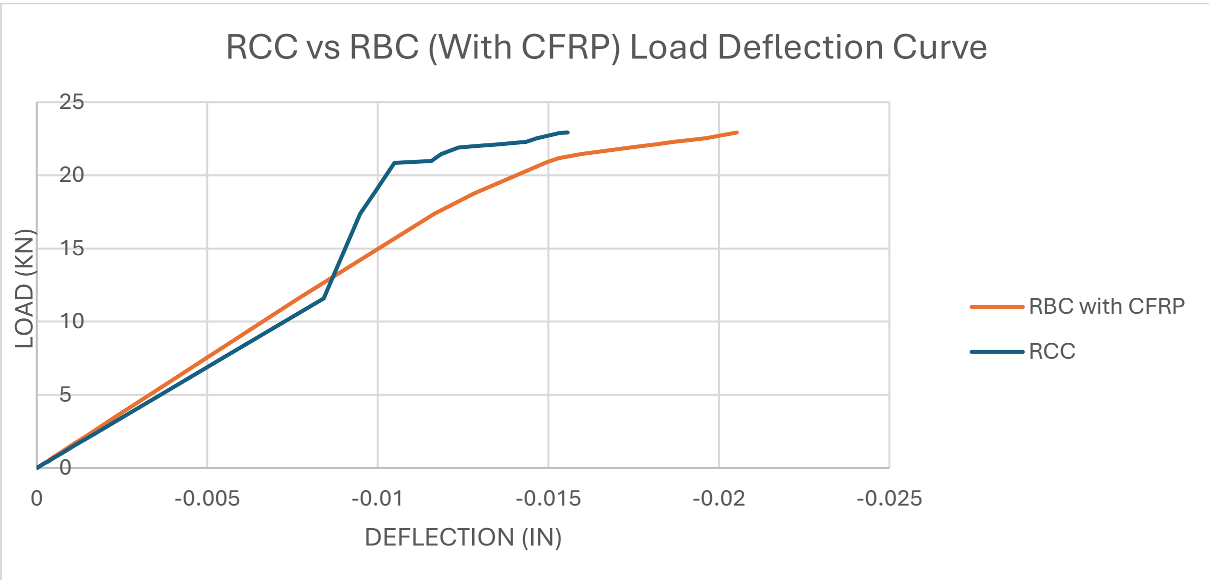
The CFRP sheets and steel collars were modelled as ties with the outer brick surface being selected as the 'master surface' and the inner CFRP sheet/steel collar being selected as the 'slave surface'.

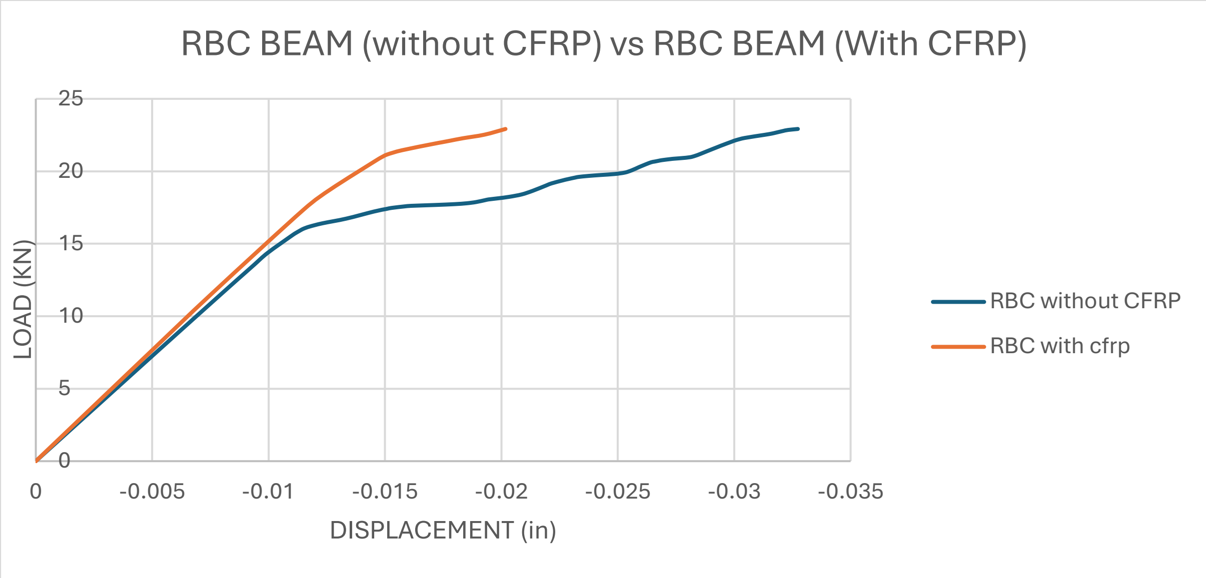
6. RESULTS AND DISCUSSIONS

6.1 Result of Beams

Load/deflection curves for all beams were compared, including those derived from experimental data collected during the testing of the RBC beam. All of the comparisons are shown in the graphs below.

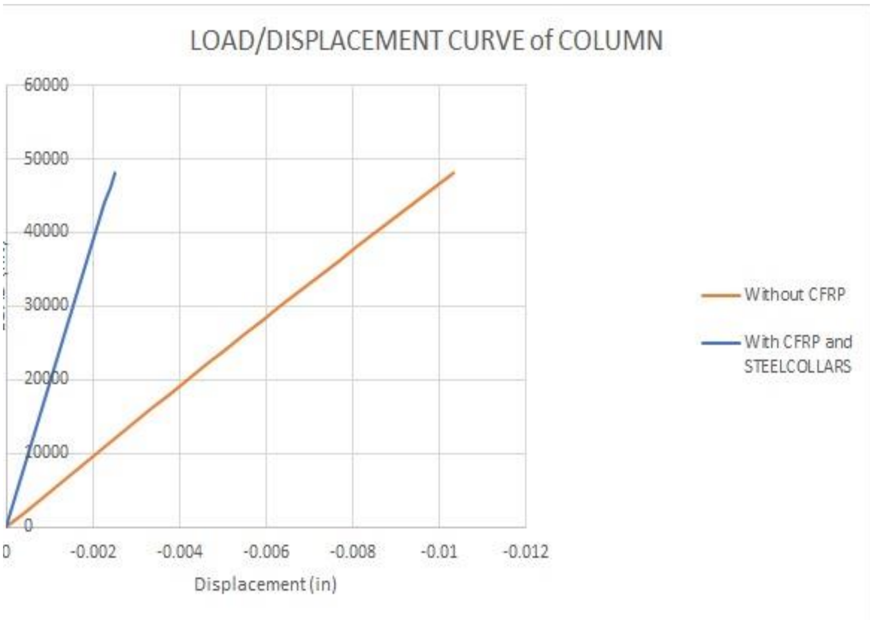






Incorporating CFRP in RBC beams significantly enhances their structural performance by reducing steel components' deflection, plastic strain, and stress. These improvements suggest that CFRP is an effective reinforcement strategy for RBC beams, potentially leading to more durable and resilient structural elements. This study provides valuable insights into the benefits of CFRP and underscores the importance of advanced simulation tools like ABAQUS in structural engineering research.

6.2 Result of Columns

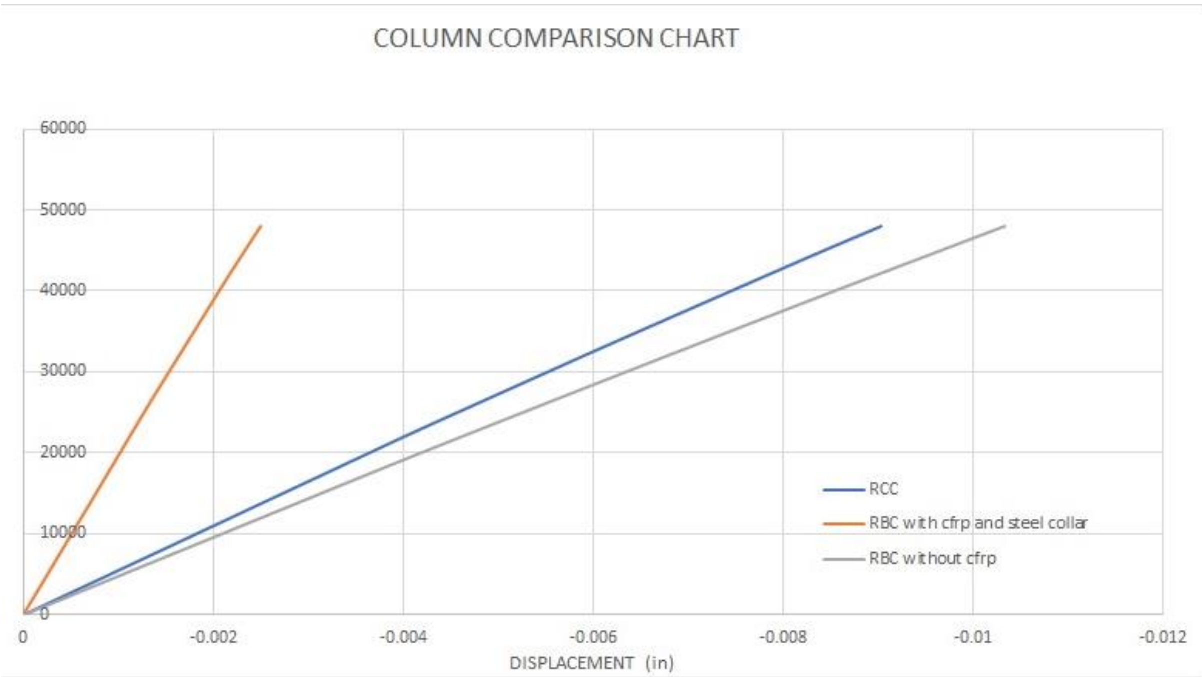


The graph is a Load/Displacement curve for a column, comparing the performance of the column under different conditions. The x-axis represents displacement in inches, and the y-axis represents the load in pounds (lbs). There are two curves on the graph:

1. Orange Curve (Without CFRP): This curve represents the load-displacement behavior of the column without any Carbon Fiber Reinforced Polymer (CFRP) or steel collars. It shows that the column can sustain a load of up to around 48,000 lbs before significant displacement occurs. The curve is linear, indicating a relatively elastic behavior up to this point.

2. Blue Curve (With CFRP and Steel Collars): This curve represents the load-displacement behavior of the column when it is reinforced with CFRP and steel collars. The column shows a higher load-bearing capacity, with the load reaching up to around 48,000 lbs at a much lower displacement. This indicates that the reinforcement significantly increases the stiffness and strength of the column, allowing it to carry higher loads with minimal displacement.

Overall, the graph demonstrates the effectiveness of CFRP and steel collars in enhancing the load-bearing capacity and reducing the displacement of the column under load.



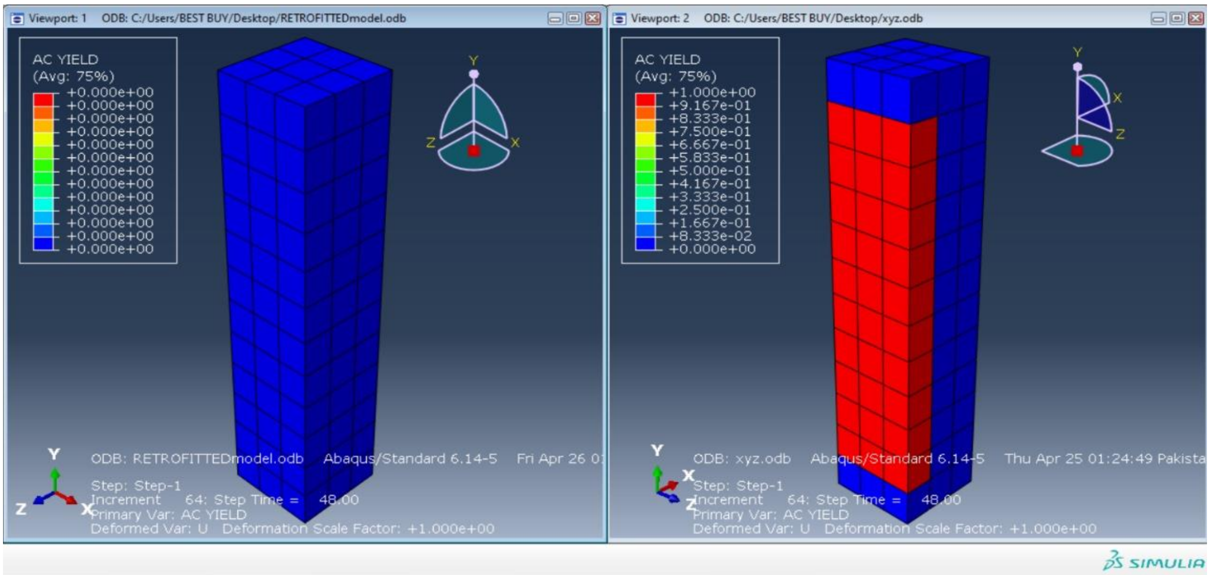
The graph above compares the load-displacement behavior of three different types of columns. The x-axis represents displacement in inches, and the y-axis represents the load in pounds (lbs).

The RBC with CFRP and steel collars (orange curve) demonstrates the highest load-bearing capacity and stiffness, handling up to 50,000 kN with minimal displacement. This indicates that the CFRP and steel collars significantly enhance the structural performance.

The RCC column (blue curve) has a moderate load-bearing capacity, with a linear relationship between load and displacement, showing better performance than the RBC without CFRP but not as good as the RBC with CFRP and steel collars.

The RBC without CFRP (gray curve) has the lowest load-bearing capacity and displaces more under the same load, indicating that it is the least effective in terms of load-bearing compared to the other two columns.

Overall, the addition of CFRP and steel collars to the RBC drastically improves its performance, proving that the suggested retrofitting scheme will give satisfactory results.



The figure above shows that without the retrofitting materials in place, the concrete section of our RBC column is actively yielding. However, with retrofitting materials in place, the concrete section of the RBC column does not yield.

Chapter 7

7. CONCLUSION

The report on the retrofitting of reinforced brick concrete (RBC) structures provides significant insights into enhancing the structural integrity and resilience of existing constructions. The comprehensive methodology, which included the procurement of high-quality materials, precise casting and curing of beams and columns, and rigorous testing, ensured the reliability and accuracy of the results. The midpoint flexure tests on the beams and compression tests on the columns highlighted critical performance parameters, enabling the development of detailed moment-curvature curves and an understanding of the structural behavior under various loading conditions.

The advanced nonlinear analysis conducted using ABAQUS software further contributed to identifying potential failure modes and optimal retrofitting strategies. The proposed retrofitting model, based on the analysis, aims to address the identified weaknesses, thereby significantly enhancing the durability and load-bearing capacity of RBC structures. This study not only demonstrates the efficacy of specific retrofitting techniques but also sets a precedent for future research in the field of structural engineering.

The findings underscore the importance of meticulous material selection, precise construction practices, and advanced analytical techniques in achieving improved structural performance. By implementing the proposed retrofitting strategies, it is anticipated that RBC structures will exhibit enhanced longevity and safety, contributing to the overall resilience of the built environment. This research serves as a valuable resource for engineers and practitioners in the field, providing a robust framework for future studies and practical applications in the retrofitting of RBC structures.

Chapter 8

8. REFERENCES

1. Maia de Souza, D. *et al.* (2016) 'Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls', *Journal of Cleaner Production*, 137, pp. 70–82. doi:10.1016/j.jclepro.2016.07.069.
2. KULKARNI, S.K. *et al.* (2014) 'Elastic properties of RCC under flexural loading-experimental and analytical approach', *Sadhana*, 39(3), pp. 677–697. doi:10.1007/s12046-014-0245-6.
3. Eivind, Hognestad. "A study of combined bending and axial load in reinforced concrete members." ENGINEERING EXPERIMENT STATION, University of Illinois, Urbana, November (1951).
4. Roudane, Boudjamaa, Süleyman Adanur, and Ahmet Can Altunışık. "Numerical modeling of masonry infilled reinforced concrete building during construction stages using Abaqus software." Buildings 9.8 (2019): 181.
5. Hejazi, F. and Esfahani, H.M. (2021) 'Strengthening of the RC beam using CFRP Rods and concrete jacketing', *Solving Complex Problems for Structures and Bridges Using ABAQUS Finite Element Package*, pp. 101–170. doi:10.1201/9781003213369-5.
6. Paul, Suresh Kumar, and Pukhraj Sahu. "Finite element analysis of retrofitting of rc beam with CFRP using abaqus." International Research Journal of Engineering and Technology (IRJET) 7.2 (2020): 1268-1273.
7. Yu, T. et al. (2010) 'Finite element modeling of confined concrete-II: Plastic-damage model', Engineering Structures, 32(3), pp. 680–691. doi:10.1016/j.engstruct.2009.11.013.
8. Kent, Dudley Charles, and Robert Park. "Flexural members with confined concrete." Journal of the structural division 97.7 (1971): 1969-1990.
9. Thai, S., Tran-Tien, D., Ngo-Huu, C., Dinh, H.T., Doan-Ngoc, T.N. and Ha, M.T., 2023, July. Numerical Simulation Of Reinforced Concrete Frame With Open-Infilled Brick Wall. In The International Conference on Sustainable Civil Engineering and Architecture (pp. 1495-1505). Singapore: Springer Nature Singapore.

10. Abou Rachied, T. *et al.* (2023) 'Structural behavior of beams cast using normal and high strength concrete containing blends of ceramic waste powder and blast furnace slag', *Cleaner Materials*, 7, p. 100179. doi:10.1016/j.clema.2023.100179.
11. *Construction methods: The materials: Www.buildinghow.com* (no date) *Construction methods|The materials|www.BuildingHow.com*. Available at: https://debug.pi.gr/default.aspx?ch=16
12. *Flexural Tests* (no date) *What are the strength tests?* Available at: http://overlays.acpa.org/Concrete_Pavement/Technical/FATQ/Construction/Strength_Tests.asp#:~:text=Center%2Dpoint%20loading%20forces%20the,one%2Dthird%20of%20the%20beam
13. Bernard, E.S. and Xu, G.G. (2007) 'A comparison of flexural performance for third-point loaded and centrally-loaded fiber-reinforced concrete beams', *Journal of ASTM International*, 4(3), pp. 1–12. doi:10.1520/jai100430.
14. *Flexural test on concrete - significance, procedure and applications* (2017) *The Constructor*. Available at: https://theconstructor.org/concrete/flexural-test-concrete-procedure-applications/18576/
15. Wang, G. *et al.* (2017) 'Testing and modelling the in-plane seismic response of clay brick masonry walls with boundary columns made of precast concrete interlocking blocks', *Engineering Structures*, 131, pp. 513–529. doi:10.1016/j.engstruct.2016.10.035.
16. *Casting RC column and strengthening procedures with ...* Available at: https://www.researchgate.net/figure/Casting-RC-column-and-strengthening-procedures-with-carbon-TRC-jackets_fig2_343375765
17. 'Strength of tied high-strength concrete columns loaded in concentric compression' (2000) *ACI Structural Journal*, 97(1). doi:10.14359/844.
18. Mohamed Sayed, A., Mohamed Rashwan, M. and Emad Helmy, M. (2020) 'Experimental behavior of cracked reinforced concrete columns strengthened with reinforced concrete jacketing', *Materials*, 13(12), p. 2832. doi:10.3390/ma13122832.
19. Hamid Sinaei (2012) 'Evaluation of reinforced concrete beam behaviour using finite element analysis by Abaqus', Scientific Research and Essays, 7(21). doi:10.5897/sre11.1393.
20. Roudane, B., Adanur, S. and Altunışık, A.C. (2019) 'Numerical modeling of masonry infilled reinforced concrete building during construction stages using Abaqus Software', Buildings, 9(8), p. 181. doi:10.3390/buildings9080181.

21. Standard modulus carbon fiber. Available at: https://www.toraycma.com/wp-content/uploads/T300-Technical-Data-Sheet-1.pdf.pdf (Accessed: 18 May 2024).
22. Hughes, B.P. and Fattuhi, N.I. (1977) ‘Load–deflection curves for fibre-reinforced concrete beams in flexure’, Magazine of Concrete Research, 29(101), pp. 199–206. doi:10.1680/macr.1977.29.101.199.
23. Sen Umesh Mishra, T. and B.S., S. (2010) ‘Nonlinear finite element analysis of retrofitting of RCC Beam column joint using CFRP’, International Journal of Engineering and Technology, 2(5), pp. 459–467. doi:10.7763/ijet.2010.v2.165.
24. Roudane, B., Adanur, S. and Altunışık, A.C. (2019) ‘Numerical modeling of masonry infilled reinforced concrete building during construction stages using Abaqus Software’, Buildings, 9(8), p. 181. doi:10.3390/buildings9080181.
25. Shi, Y.-L. et al. (2018) ‘A fiber model based on secondary development of Abaqus for elastic–plastic analysis’, International Journal of Steel Structures, 18(5), pp. 1560–1576. doi:10.1007/s13296-018-0053-7.
26. Kartheek, T. and Venkat Das, T. (2020a) ‘3D modelling and analysis of encased steel-concrete composite column using Abaqus’, *Materials Today: Proceedings*, 27, pp. 1545–1554. doi:10.1016/j.matpr.2020.03.200.
27. Roudane, B., Adanur, S. and Altunışık, A.C. (2019) ‘Numerical modeling of masonry infilled reinforced concrete building during construction stages using Abaqus Software’, *Buildings*, 9(8), p. 181. doi:10.3390/buildings9080181.