

ADDIS ABABA UNIVERSITY
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ENGINEERING



**Investigation of Flexural Behavior of Beam Strengthened with Textile
Reinforced Concrete Under Cyclic Loading**

A Thesis in Structural Engineering

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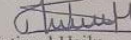
A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

UNDERTAKING

I certify that this research work titled "Investigation of Flexural Behavior of Beam Strengthened with Textile Reinforced Concrete Under Cyclic Loading" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred

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Natinael Hailu

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ABSTRACT

Textile reinforced concrete (TRC) has attracted a lot of interest recently for its potential to improve masonry and reinforced concrete (RC) structures. TRC can also be used to create new, lightweight precast elements or as a secondary building material to support primary building materials. Because these TRC combine strength, durability, and environmental concern, they are becoming increasingly attractive replacement for Fiber Reinforced Polymer (FRP) for a variety of structural and architectural purposes. TRC's primary goal is to strengthened the structure and enhance its shear and flexural capacities. However, as TRC is a recently developed technology, its full potential is yet to be determined.

The behavior of a beam strengthened with TRC for flexural capacity has been studied in this research. The ultimate goal is to investigate the flexural behavior of a beam strengthened with TRC under cyclic loads and to enhance the maximum flexural capacity using different parameters. Mesh applied region, mesh spacing and mesh arrangements are among the investigated parameters. The ABAQUS finite element software was utilized, and the findings from the FE validation closely aligned with the results of the experimental tests for static load. The investigation continues by applying cyclic load based on the ACI 374 (ACI 374.2R-13) cyclic loading application protocol. Based on the results of this investigation, a higher load-carrying capacity under cyclic load can be achieved by increasing the number of textile layers for large mesh spacing and decreasing the spacing between textile strands for a single layer. Additionally, a 45-degree inclined mesh alters the failure mode from sudden to gradual by effectively distributing stress.

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ABBREVIATIONS

ACI- America Concrete Institute

CDP- Concrete Damage Plasticity

CUAS- Carinthia University of Applied Science

FEA- Finite Element Analysis

F/TRC- Fiber-Textile-Reinforced Concrete

FRP- Fiber Reinforced Polymers

NLFEA- Non-Linear Finite Element Analysis

PE- Polyethylene

PVA- Polyvinl Alcohol

TRC- Textile

TRM- Textile reinforced mortar

List of Symbols

f_c' - Compressive Strength of Normal Concrete

f_y - Yield strength of reinforcement

ψ - Dilation angle value

K_C - Shape factor

μ - Viscosity

Δl - Applied displacement at the beam mid

l_b - Length of beam from the support condition to the application point of the cyclic displacement

σ_{bo}/σ_{co} - Stress ratio

ε - Eccentricity

M_n - Flexural moment capacity

M_1 - Flexural moment due to tension reinforcement

M_2 - Flexural moment due to compression reinforcement

b - Width of beam

d - Effective depth of beam

M_{tex} - Flexural moment due to TRC

A_{fib} - area of textile fiber

f_{fib} - Tensile strength of textile fiber

d_{tex} - Depth of textile fiber.

CHAPTER 1 INTRODUCTION

1.1 Background of the Study

Structural strengthening involves enhancing existing structures to improve their performance under existing loads or to increase the load-carrying capacity of structural elements. Revised design code, degradation, change, environmental effects, or inadequacies caused by design and/or construction faults are just a few of the reasons why structural strengthening is required. Selecting a strengthening approach that would increase the structure's strength and serviceability while taking into account constraints like constructability, building operations, and cost is one of the challenges in strengthening concrete structures. Reinforced concrete structures can be strengthened using a variety of methods. The predominant method involves Fiber Reinforced Polymers (FRP), which combines various fiber types—often carbon or aramid fibers—with organic resin to form a composite material layer. Alternatively, epoxy resin can be employed to bond composite laminates together. Both systems rely on organic matrices, which have a number of limitations, including volatile materials that endanger workers' safety, low fire resistance, and unclear long-term performance (D'Ambrisi and Focacci, 2011). The utilization of inorganic matrices for generating such composite solutions has recently ushered in a new era in concrete reinforcement approach.

Textile Reinforced Mortars (TRM) are novel composite materials that achieve robust strength performance by combining various types of fibers with cementitious matrices. New cementitious matrix, while of excellent quality, does not necessitate a highly strict formulation or the use of elements that are significantly different from those used in conventional cements. These days, beams are strengthened with this new material to increase ultimate capacity and flexure.

A four-point bending test was used to assess the flexure of a strengthened beam with TRM. Based on the results, every beam that was exhibited had an increase in the maximum load. However, investigation is still needed on how well TRM strengthening performs under fatigue and cyclic stress.(Giese *et al.*, 2021).

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1.2 Statement of the problem

The ultimate flexural strength of reinforced concrete beams is unquestionably increased by strengthened beams with TRC, but to what extent depends on the shape of the textile material, the number of textile layers, the cross section of the beam, the presence of mechanical anchorage systems, and how these factors affect the strengthening elements' performance. Even if TRC increases its ultimate capacity, different researchers will still find limitations, and the studies have not yet determined its full capability.

Studies made clear that the increase in the load-carrying capacity is clearly an important performance parameter. However, several parameters affect the performance of the TRC strengthening beam. Studies made so far consider parameters such as cementitious materials, number of textile layer, and mechanical anchorages (Hegger *et al.*, 2007) and (Rossi *et al.*, 2021). Other studies indicate that TRC performance is significantly affected by variables such as reinforcement ratio, material properties and strengthening configuration (D'Ambrisi and Focacci, 2011). However, the total capacity of TRC effect with different parameter and under cyclic load is rarely addressed by scientific investigations made so far. This research proposes using inclined carbon mesh to improve stress distribution, addressing the limitations of parallel textile carbon mesh which, despite increasing ultimate capacity, does not effectively distribute stress. Despite the growing interest in TRC, research on its application for structural strengthening remains relatively limited. Specifically, studies focusing on RC beams strengthened in flexure are scarce due to the field's short history (Nguyen and Ngo, 2020).

Most existing research on beam strengthening with Textile Reinforced Concrete (TRC) has observed sudden failure modes. This abrupt failure can be detrimental in practical applications, as it provides little warning before complete structural collapse, posing safety. Another significant gap in the current research on beam strengthening with Textile Reinforced Concrete (TRC) is the lack of detailed guidelines on optimizing mesh spacing to increase flexural capacity. Most studies do not provide specific recommendations on where exactly to reduce spacing and applied strengthening material to achieve the same strengthening effect while being economical.

This investigation utilizes the ACI paper by Rossi et al. (2021), titled "Flexural Strengthening with Fiber-/Textile-Reinforced Concrete" under static load, to validate the

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material properties. Building on this foundation, the research will continue using these materials and apply cyclic loading based on the ACI 374 (ACI 374.2R-13) cyclic loading application protocol. The study will explore various parameters, including mesh arrangement, mesh spacing, and the regions where the mesh is applied, to address the aforementioned concerns. By examining these different configurations, the research aims to enhance the understanding of how these factors influence the overall structural behavior under cyclic loading conditions.

1.3 Objective

1.3.1 General objective

The aim of this research is to numerically analyze the effects of TRC strengthening beam when subjected to cyclic load with different mesh arrangement, TRC applied region, and mesh spacing.

1.3.2 Specific objective

- To analyze the influence of TRC for flexural strength of concrete beam.
- To investigate the impact of cyclic loading on a beam strengthened with Textile Reinforced Concrete (TRC).
- To investigate the effects of various parameters on the ultimate flexural capacity of TRC-strengthened beams.
- Asses the result of variable arrangement of TRC on flexural strengthened of beam.

1.4 Significance of the study

Generally, it will benefit for designer and contractor which arrangement of TRC have more flexural capacity and where to apply it to minimize cost with good flexural capacity. And to know the capacity of TRC under cyclic load it would help to know the full potential of the material. Based on the output of this research further investigation will address and they used as reference.

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1.5 Scope and limitation of study

The primary goal of this study is to evaluate the cyclic load behavior of beams strengthened using TRC. This involves utilizing the finite element program ABAQUS (Simulia 2022) to confirm the experimental results of a beam strengthened with TRC under static load. To determine the influence of several relevant characteristics, a total of 40 specimens were examined. FEA calibrations are carried out using various textile fiber mesh configurations and mesh sizes in various application areas. Only RC beams with enough material section shear capacity and constant reinforcement throughout the research are applicable and the same material qualities, beam dimensions (width, depth, and length), and mortar are used for dynamic analysis.

1.6 Organization

This thesis consists of five chapters, the first of which is the introduction, which discusses beam strengthening with TRC and outlines the objectives, significant, difficulties, and expected outcomes of the investigation. The second chapter discusses previous findings or literature review, which served as important sources of concepts and guidelines for this investigation. The third chapter provides an explanation of the materials used, the techniques used, and the specifics of the study. Chapter Four presents analysis and findings from the analysis and talks about the behavior of the specimens with regard to ultimate flexural capacity, failure and cracked pattern, and load-displacement response. This study's last chapter summarizes the findings and debates from the preceding chapter and suggests for further research.

2.1 General

Textile reinforced concrete (TRC) is a composite material, that combines the benefits of fiber reinforced concrete and conventional reinforced concrete. In recent years, there has been an increase in interest for using textiles as reinforcement for cement component. The mechanical behavior of TRC members is closely linked to the fiber-matrix interface bond behavior, which is determined by matrix properties as well as fabric geometrical parameters such as knitting technique, mesh size, fiber type, and textile surface treatment procedures. Similar to traditional reinforcing steel, textile reinforcement bears the tensile forces that arise during concrete cracking.

Textile reinforced concrete can strengthen existing load-bearing structures. It has a high tensile strength with a thin layer, making it ideal for retrofitting older structures. Textile-reinforced concrete offers a viable solution for reconstructing traditional masonry constructions and aging concrete structures. Numerous scientific studies have explored its effectiveness in strengthening existing older buildings.

(Brückner *et al.*, 2006) state in the document using TRM to strengthening concrete members can be a useful method for improving RC members' flexural or shear capacity, axial deformation capacity, and compressive strength through confinement, as well as their ductility and energy dissipation for seismic retrofitting. This material is produced using fiber and mortar; the strength of each component and the bond between them have a fundamental impact on the beam's ultimate capacity.

2.1.1 Fiber materials

Fiber material made from a mass of raw materials. Fibers play a crucial role in manufacturing various materials, and some of the strongest engineering materials incorporate these fibers. Generally speaking, there are two primary categories or various types of fibers: natural and manmade. Natural fibers are made by geological processes, plants, and animals. Man-made fibers include glass, which is manufactured from inorganic materials, and synthetic fibers, which are made from petrochemicals, which are used to make polymers like polyvinyl alcohol (PVA), carbon, aramid, polyethylene (PE), polypropylene, and others.

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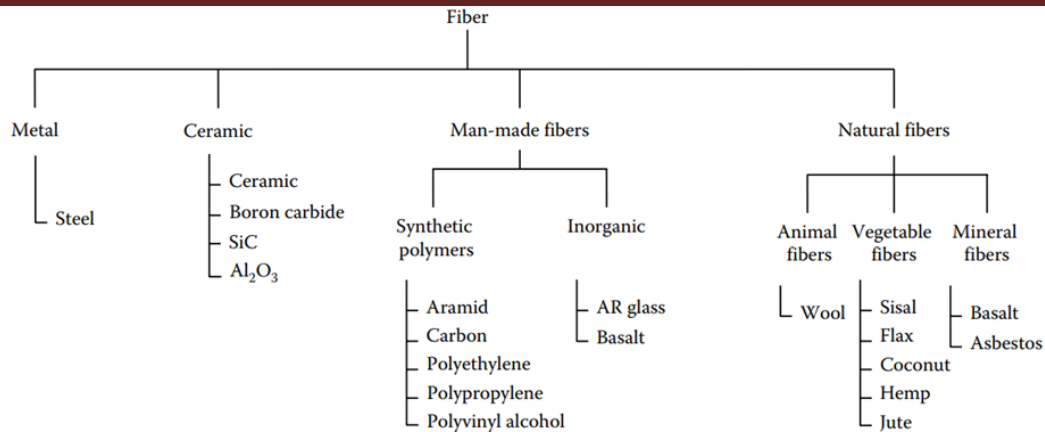


Figure 2-1 Fiber types. (Peled et al., 2017).

The most common fiber for strengthening is: -

- Carbon fibers
- AR glass fibers
- Aramid fibers

I. Carbon fibers

In the 1970s, carbon fibers first emerged for the aerospace sector, when cost was less important than quality. Carbon fibers' use in aircraft applications eventually expanded due to a notable decrease in cost in the 1980s. Heine and Fitzer 1988). High resistance to acid, alkaline, and organic solvents is a feature of carbon filaments that makes them useful in cement-based composites. Graphite fiber, another name for carbon fiber, is a polymer. It is an extremely lightweight and strong material. Carbon fiber is twice as stiff and five times stronger than steel. Carbon fiber is the perfect production material for many items because, although being lighter than steel, it is stiffer and stronger. To name just a few, carbon fiber is the material of choice for engineers and designers when it comes to manufacturing.

Carbon fiber is very popular in many industries because

- is high in tensile strength
- fiber has a low weight to strength ratio

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- is high in chemical resistance
- is temperature tolerant to excessive heat
- has low thermal expansion

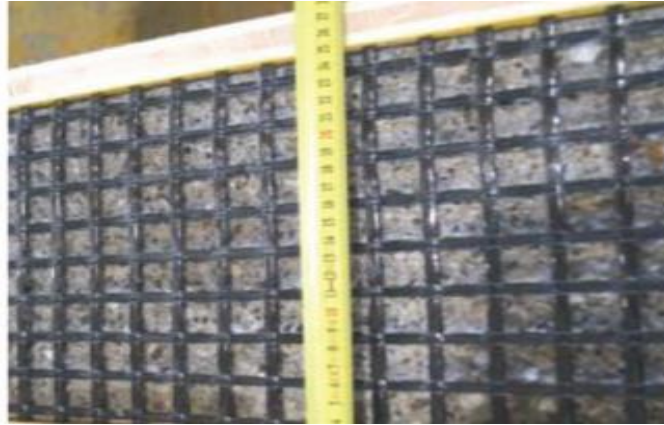


Figure 2-2 Textile carbon fiber used in experiment (Rossi *et al.*, 2021)

II. Glass fibers

Around 1940, glass fibers for composite materials started to be produced commercially (Gupta, 1988). Since then, glass fibers have proliferated as a common reinforcement element in polymer-based composite materials, for which there is growing demand. In cement-based matrices, glass fibers constitute a widely used reinforcing fiber. Glass fibers have a high specific strength (the ratio of tensile strength to density) and a high specific modulus for the price per unit. AR glass filaments are now the most widely utilized glass reinforcing material in TRC applications due to their strong adhesion with cement-based matrices and their reasonably inexpensive cost, which offers an excellent cost–performance ratio.

III. Aramid fibers

In 1967, DuPont introduced its meta-aramid fiber, branded as Nomex. The development of aramid fibers, also referred to as aromatic polyamides, had already commenced in the 1960s. Subsequently, in 1971, the same company launched Kevlar, a para-aramid fiber renowned for its exceptional modulus and strength. Subsequently, Twaron, a different para-aramid fiber, was created in the late 1980s (Twaron is a registered

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product of Teijin). In 1987, the more flexible and highly tenacious aromatic copolyamide fiber Technora come to the market.

The entire class of aromatic polyamides is known as an Aramids. These are synthetic fibers with exceptional chemical stability, a high tensile strength, low density, great abrasion resistance, and high elastic modulus. Aramid fibers are also appealing for applications of strengthening of structure because to their unique qualities of high strength and low weight. However, the chemical composition of aramid fibers restricts their use due to challenges in matrix adhesion. Additionally, their polymer structure is susceptible to moisture, which affects their performance.(Palola et al., 2020).

2.1.2 Mortar

Cement-matrix composites are important for the civil infrastructure. The cementitious mortar utilized in TRM composites is crucial because, when the textile is impregnated, it serves as a medium for the applied force to be transferred to the strong material. The mortar must possess the following qualities: it must not shrink, have good workability (so it can be applied with a trowel), high viscosity (for overhead or vertical surfaces), have a lower rate of workability loss (for successive layer application), and have strong shear resistance (to prevent early debonding). Cementitious mortars or cementitious mortars modified with polymers can be used as this inorganic matrix. Portland cement is often used in both forms, and in the second type, a little dosage of dry polymers less than 5% by weight of cement is added. The shear strength of mortar is increased, the workability and setting time are adjusted for this application, and the binding between the mortar and fibers is strengthened by the use of polymers. The strength of the bond that mortar creates with fabric and substrate determines the quality of the matrix; this bond cannot be precisely determined by the mortar's mechanical characteristics. Depending on the fabric, adhesion supplements, finer cement, additives, fly ash, micro aggregates, and inorganic nanoparticles can all be used to improve cementitious mortar.

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Table 2-1 Comparison of mortar and resins

Mortar	Resins
<ul style="list-style-type: none"> • It supplies water protection against erosion. • Can be applied in wet structure • Can be applied in any kind of temperature conditions • It's utilized to fill up the slits in the structure. • It's utilized to renovate cracks of any structure. • It is time-saving. • Better finishing surfaces can be often obtained. 	<ul style="list-style-type: none"> • Relatively expensive resins • The material exhibits inadequate performance at temperature ranges beyond the glass transition temperature • Potential risks for the workers • Difficulty in application on moist areas or at low temperature ranges • The challenge of irreversibility (the inability to reverse the repair without causing damage to the original structural element) • Non-compatibility between resins and substrates

Source (Al-Salloum et al., 2012)

2.2 Component of beam

2.2.1 Concrete

The most widely utilized manmade material in the world is concrete. It is a primary building material that is widely utilized in the construction of roads, bridges, dams, and buildings. The main ingredients of concrete are Portland cement, water, and aggregate, which can be either rock, sand, or gravel. After combining these materials, a workable paste is created that gradually becomes harder. It has its own set of advantages and disadvantages. Some benefits include being a long-lasting, reasonably priced material with low maintenance needs, being non-combustible, strong under compression, and a highly flexible material that is easy to mold before it solidifies. In comparison to other construction materials, concrete has a low tensile strength, is brittle, has a poor strength-to-weight ratio, and is easily cracked.

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Concrete under compression has a linear elastic stress-strain relationship up until the beginning of microcracks. This is when the behavior stops being linear and strain increases, the stress decreases beyond the ultimate compressive strength. Until the failure stress value is reached, the stress-strain response under uniaxial tension exhibits a linear elastic relationship. The start of microcracking in the concrete material is correlated with the failure stress. A softening stress-strain response is indicative of the growth of microcracks beyond the failure stress.

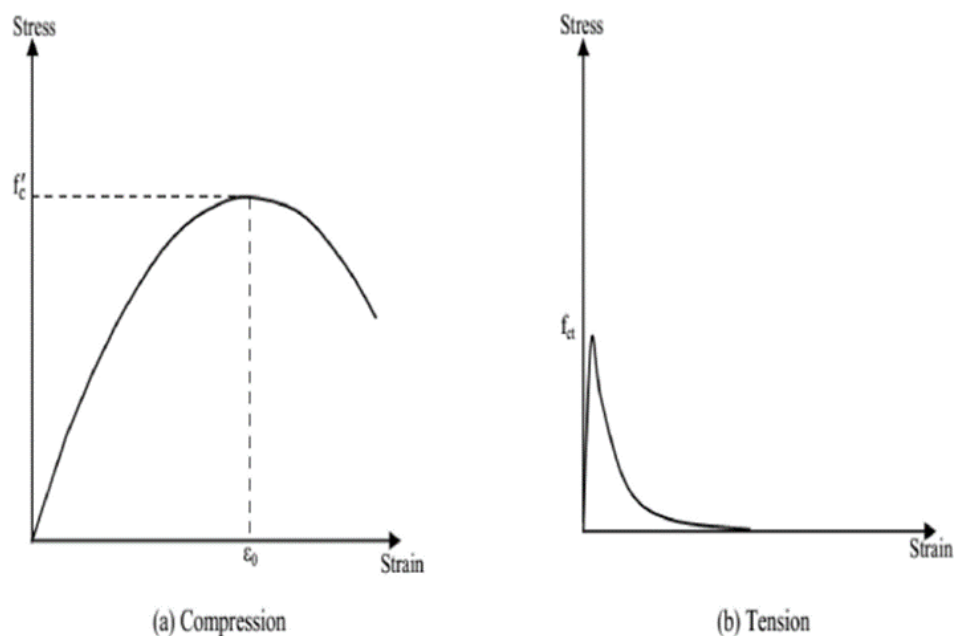


Figure 2-3 Uni-axial stress-strain curves of concrete (Ramin., 2016)

2.2.2 Reinforcement

Figure 2-4 shows a typical stress-strain relationship for reinforcing steel. Steel exhibits linear elastic properties at initial stress values lower than the initial yield stress. The reinforcement starts to neck and loses strength at the maximum tensile strain. According to ASTM A615, at maximum strain, the steel reinforcement fractures and the load capacity is lost. Figure 2-4 identifies several material characteristics that could determine this steel response. These include the strain at which peak strength is reached (ϵ_u), the elastic modulus (E_s), the yield strength (f_y), the strain at which fracture occurs (ϵ_{max}), the peak strength (f_u), and the capacity before steel fracture (f_s).

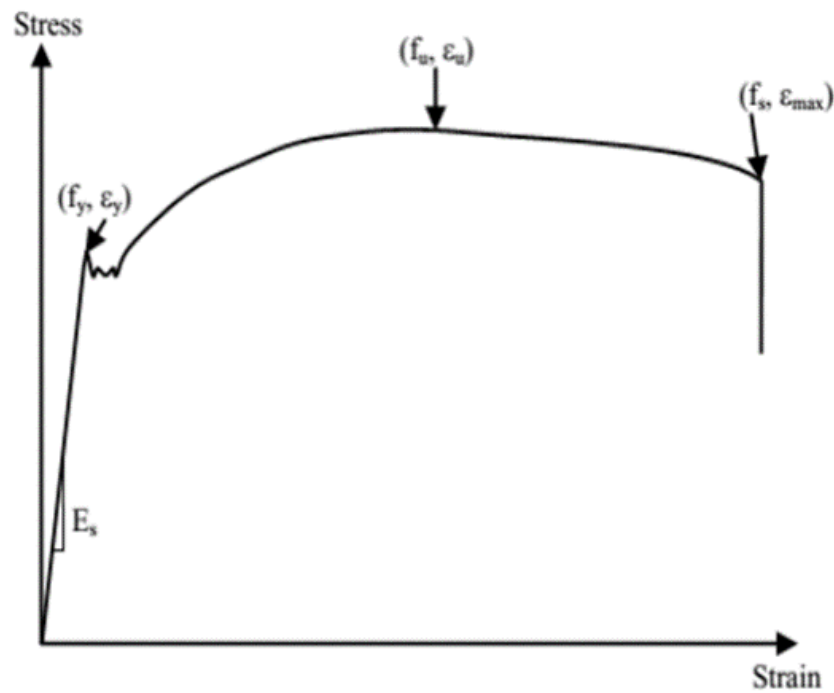


Figure 2-4 Tensile stress-strain curve for typical reinforcing steel bar (Ramin., 2016)

2.3 TRC as composite material

Composite materials as the name indicates are made by bringing together at least two separate fundamental materials, where one or more materials act as reinforcements, and the other one or more materials perform as the matrix. Textile-Reinforced Concrete (TRC): An Emerging Composite Material. Textile Reinforced Concrete (TRC) is produced by embedding a continuous textile fabric within a cementitious matrix. This matrix comprises a binder made from Portland cement and small-size aggregates.

When it comes to matrix performance, TRC is more durable than regular reinforced concrete since its matrix often falls between the 0.40–0.45 w/c ratio range. TRC offers a significant durability advantage because to its crack control, which is typified by repeated cracking upon loading and cracks less than 100 μm broad, often approximately 50 μm . When compared to ordinary concrete, where fracture widths are restricted to 0.1–0.3 mm, this offers improved durability performance. When cracks in a matrix are less than 50 μm in width, they tend to self-heal, therefore the penetrability of the cracked matrix is not significantly different from that of an uncracked matrix. Because of their high tensile strength and flexibility, this class of cement composites in particular, TRC paves the way

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for innovation in construction. TRC is better suited for structural and semi-structural applications. (Peled et al., 2017).

Current repair and retrofitting methods utilize high-quality textile materials, including glass and carbon yarns. These methods involve hand lay-up technology, where the necessary component is bound or wrapped with the textile and impregnated with polymer. Similar applications can be made of a cementitious matrix, which has some built-in benefits such improved compatibility with the concrete substrate. Numerous investigations have been conducted to ascertain the degree of performance improvement that can be attained with these kinds of systems. The enhanced performance comprises resistance against environmental factors that have triggered corrosion processes, mechanical strengthening to compensate for up for the resistance lost as a result of deterioration, or improvement of mechanical performance in non-deteriorated structures where retrofitting is necessary to satisfy new resistance standards or additional loading requirements, like earthquake effects.

2.4 TRC Installation Method

There are several methods for installing Textile Reinforced Concrete (TRC) for structural strengthening. which is hand lay-up, shotcrete and spray, stay-in-place precast TRC panel, precast TRC panel with grouting, and TRC overlay for concrete pavement. mostly used for repair or strengthening structures is hand lay-up installation method and the steps are first removing deteriorated concrete section then treat rebar from future corrosion, if necessary, finally place fresh concrete or mortar with textile grid.



Figure 2-5 Hand lay-up TRC method for strengthened structure

source (<https://www.youtube.com/watch?v=or48dYkjfZs&t=124s>)

2.5 Advantage of TRC

Textile-reinforced concrete boasts numerous advantages, making it suitable for diverse applications. The TRC is now used based on research findings that have been published in research journals. In Germany, textile-reinforced concrete has proven effective as a construction material for pedestrian bridges (Rempel et al., 2018). Textile reinforced concrete, on the other hand, is ideal for non-structural concrete components including formwork, sandwich panels, acoustic panels, and facade panels. Modern architecture also saw a rise in the use of facade panels. Textile reinforced concrete can be utilized in furniture design, architectural accessories, and a variety of other applications, including a concrete boat.

TRC is a complex material with the following major characteristics: A thin layer that can improve corrosion protection for current concrete reinforcement and has high tensile strength, low weight, and outstanding corrosion resistance. The strength of Textile Reinforced Concrete (TRC), which incorporates a reinforcement fiber grid, can enhance various performance aspects, including binding strength, flexural strength, shear strength,

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torsion resistance, stiffness, and axial torsional forces. The flexibility properties of TRC enable the creation of curved geometries, such as shell structures and columns. TRC structures are substantially smaller in size and magnitude than RC structures, providing a completely new possibility for the building industry. Because the reinforce material does not corrode in normal conditions, no cover is required for protection, allowing us to make our building more cost-effective. TRC may be used to create a very thin strengthening layer because no concrete cover is required. When used as reinforcement, fiber textiles have a significantly larger surface area than traditional steel-bar reinforcements. The fiber provides two indications of workability: first, it has a short anchoring length, and second, it has a very dense crack pattern. As a result, very high bond forces fiber can be added to the concrete. Compared to typical steel bar reinforcements, TRC produced from fiber textiles exhibits a direct increase in strength. (Peled et al., 2017).



Figure 2-6 TRC pedestrian bridge in Albstadt, Germany (Rempel et al., 2018).

2.6 Failure of strengthening elements located in the tensile zone

The literature has extensively documented various failure modes, highlighting the intricate mechanical behavior exhibited by the Textile Reinforced Mortar (TRM) strengthening system. In the majority of the research, failure modes other than those seen in FRP strengthening systems have also been reported. A graphical representation of all the documented failure modes that will be discussed later may be seen in Figure 2-7. Typically, the weakening of the strengthening effect or concrete failure can lead to the failure of an RC element that has been reinforced in flexure using TRM. The primary failure modes observed when strengthening a beam with textile-reinforced concrete (TRC) include slippage of textile fibers within the matrix, debonding at the concrete-matrix

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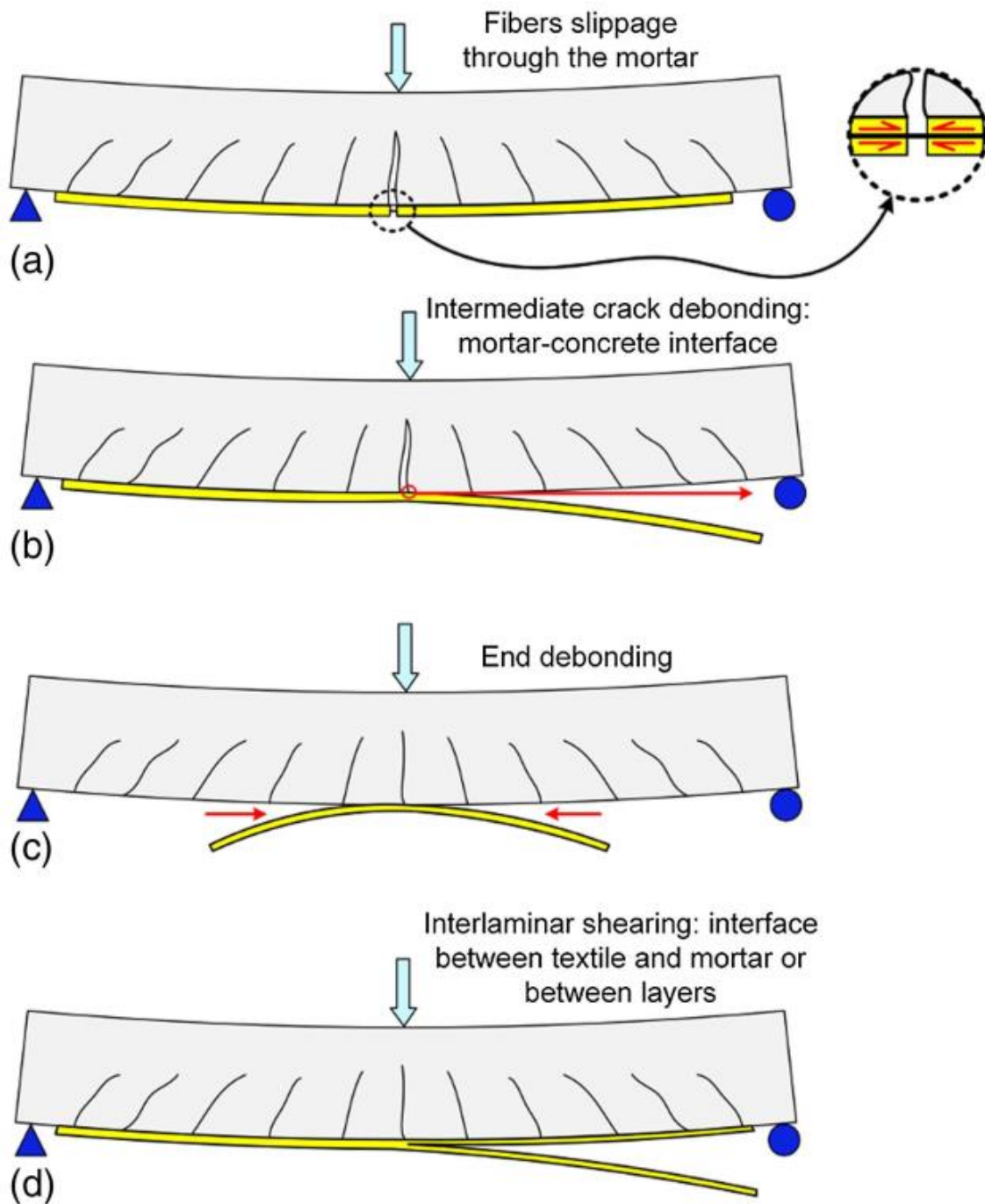
interface, interlaminar shearing, peeling of the concrete cover, and rupture of the textile fibers.

The failure modes can be categorized as follows:

- 1) Slippage of the textile fibers within the matrix; This failure mode is related to both a weak chemical bond at the fiber–matrix interface and low mortar impregnation of the fibers. Because the rovings' exterior fibers are more impregnated than the core fibers, there may be a partial rupture of those outer fibers. Slippage happens in the area of maximum moments, however in this instance, the load drop brought on by the lack of strengthening action is gradual and smooth.
- 2) Debonding of the concrete-matrix interface; This mechanism of failure is caused by the loss of the bond between the concrete and the matrix. The TRM layer may separate in two ways: either from the ends or from the area where flexural cracks are developing and causing the largest bending moments. The first case, which propagates debonding toward the support, is typically referred to as intermediate crack debonding Figure 2-7(b). The second case is commonly referred to as end debonding; as Figure 2-7(c) illustrates, the TRM detachment advances in the direction of the midspan. End debonding may occur if the TRM has a short anchoring length. The load drops in both cases are sudden, indicating the brittle nature of debonding.
- 3) Interlaminar shearing; This failure mode involves a fracture surface within the thickness of the Textile Reinforced Mortar (TRM), and/or shearing between layers of mortar and textile. Such shearing can occur when using high tensile strength textiles with small grid sizes. The use of coated textiles also exhibits this failure behavior.
- 4) Peeling of the concrete cover; in this case, debonding starts in a shear-flexural or intermediate flexural crack and moves all the way to the TRM reinforcement's end. A strong bond between the mortar and the concrete is demonstrated by the fact that a portion of the concrete cover is still attached to the composite material. When high-strength mortars are combined with many layers of high-strength textiles, this failure mode usually results in larger flexural capacities than the previously mentioned failure modes 1, 2, and 3.

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- 5) Rupture of the textile fiber; textile fibers rupture in a single piece when they are subjected to high tensile stresses at the region of maximum moment. There is a sudden decline in load because this system is brittle.



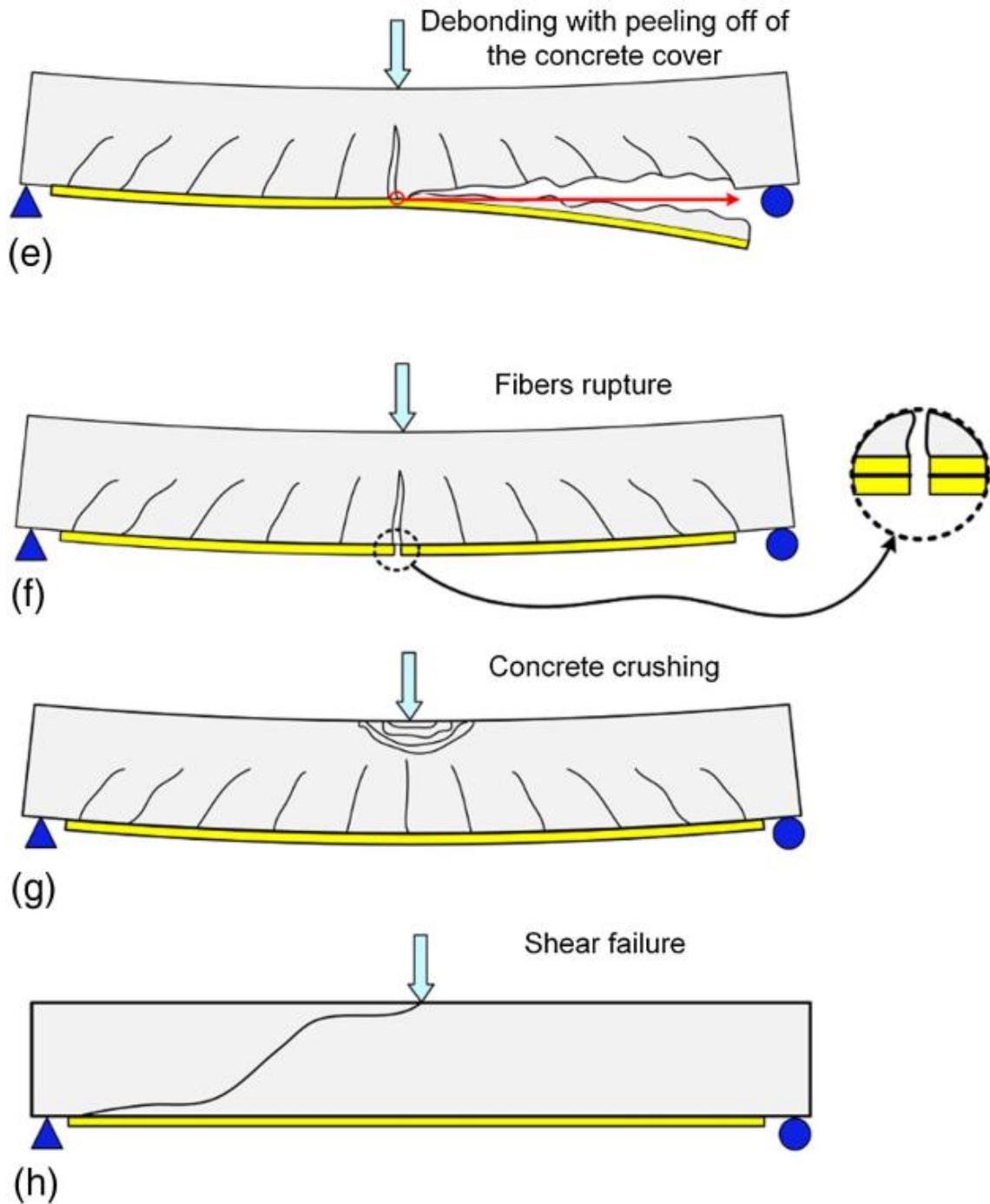


Figure 2-7 Schematic representation of failure modes (Rossi et al., 2021).

2.7 Structural applications of TRM

The important applications of textile-reinforced concrete are:

1. Bridge construction
2. Retrofitting old structures
3. To act as a protective layer for existing buildings

Reinforced and prestressed concrete is used in the construction of many bridges, both old and modern. The use of contemporary concrete materials in the construction of concrete bridges is growing in importance. They make it easier to strengthen and repair already-existing bridges, quickly replace damaged sections of existing bridges, and design new, difficult bridge projects. In the built environment, the development of advanced concrete materials and their structural uses are therefore crucial subjects of discussion.

There are several cutting-edge structural concrete materials available for strengthening already-existing bridges. Studies conducted on fiber-textile-reinforced concrete (F/TRC) and textile-reinforced concrete (TRC) enhanced reinforced concrete beams showed the benefits of this strengthening technique in both the serviceability limit state and the ultimate limit state (Rossi et al., 2021). Adam et al. (2020) have also addressed the application of TRC for strengthening, namely for bridge deck slabs. A high-performance mortar and a carbon-fiber-reinforced polymer reinforcement help compensate the proposed strengthening option, known as SMART-DECK. The TRC-strengthened slab segments' flexural and shear strengths were tested, and the results showed that applying the suggested strengthening strategy significantly increased the slab segments' bending and shear capacities. (Lantsoght., 2022)

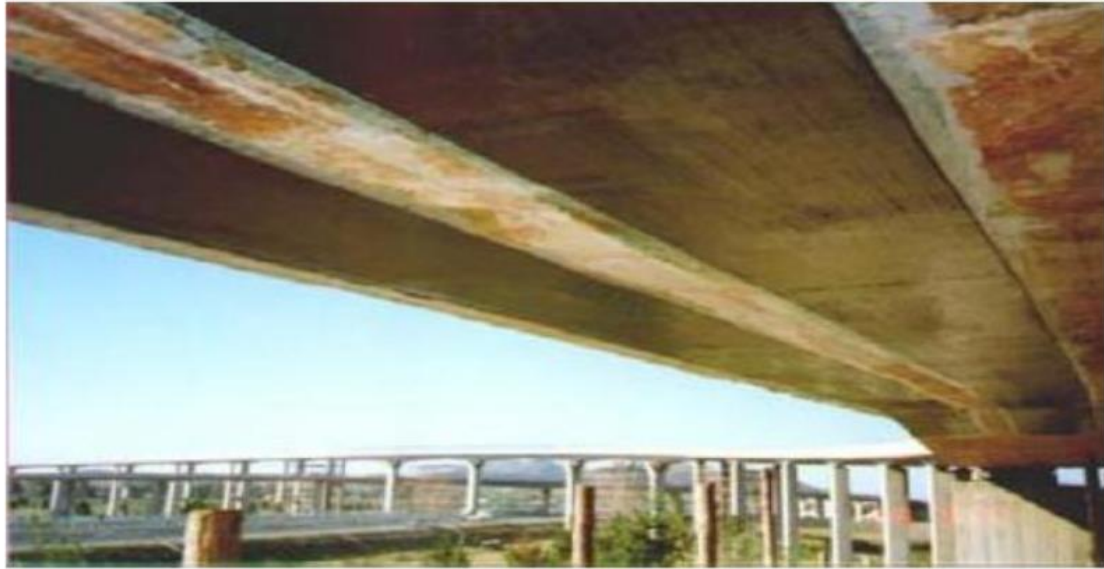


Figure 2-8 Flexural strengthening of a highway RC bridge slab in China.

It has also been studied how TRC can be used to enhance one-way and two-way RC slabs (Schladitz et al., 2012; Loreto et al., 2013; Koutas et al., 2017). The research showed that the fiber type, quantity of textile plies, and matrix strength were the design parameters that had an impact on TRC strengthening. The flexural capacity of an RC component generally rises with the number of textile plies; however, the quantity of textile reinforcement does not immediately correspond with this increase in flexural capacity. For flexural strengthening, it is more beneficial to use fibers having a greater elastic tensile modulus, like carbon fibers, rather than ones with a lower value, like glass fibers (Kim et al., 2020).

The strengthening design process should precisely calculate the increase of the flexural capacity utilizing the TRC system in order to prevent an undesired failure scenario. If not, depending on the shear span ratio and the degree of strengthening, reinforcing flexural elements using the TRC system may cause a shift in the failure mode from flexural to shear failure mode, or flexure-shear mode. This is because the TRC system acts as a tensile reinforcement in RC flexural components, raising the tensile reinforcement ratio as a result of the TRC flexural strengthening.

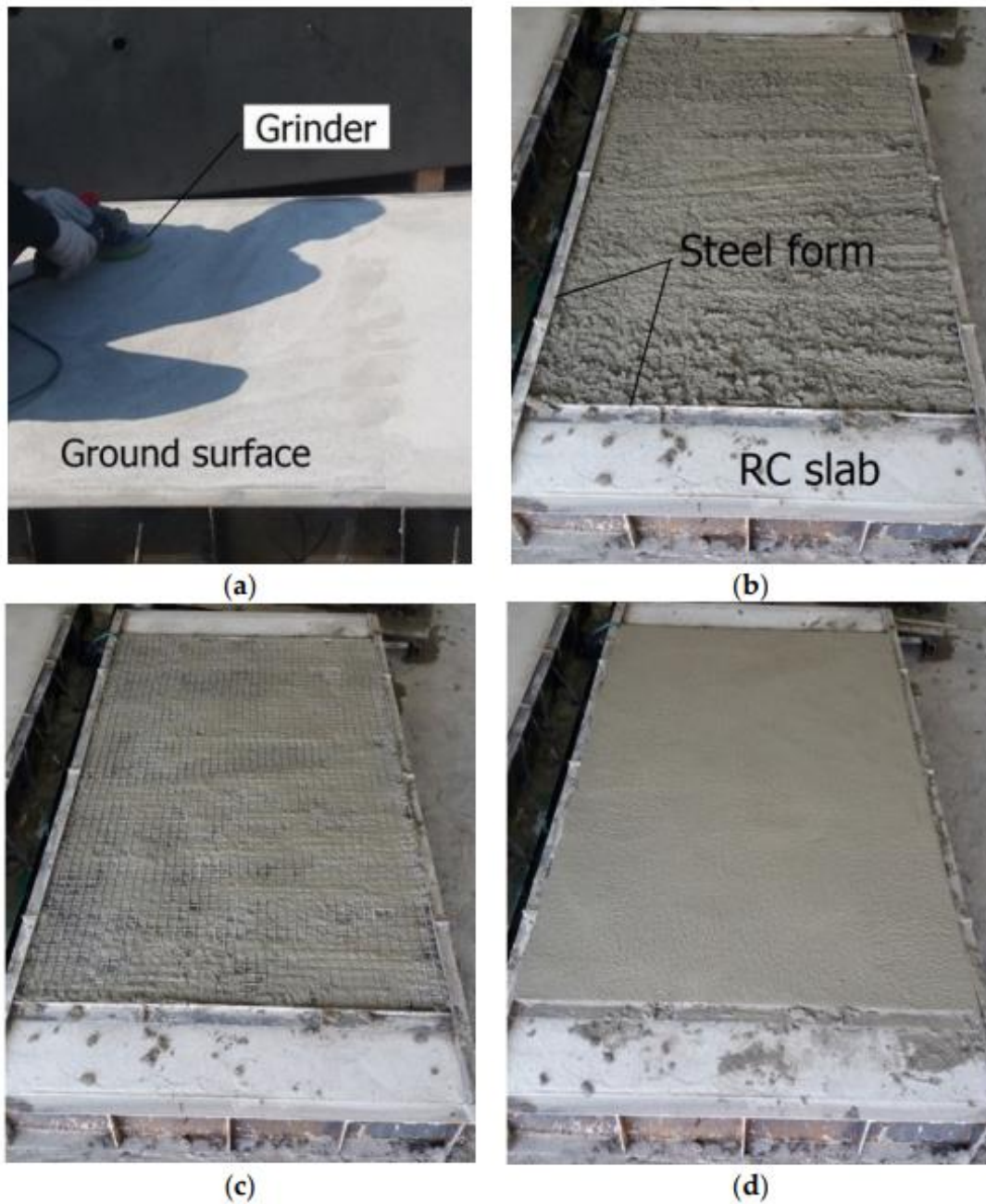


Figure 2-9 Application of TRC on strengthening slab steps a) Grinding of top surface; b) Placing of 1st mortar layer; c) Placing textile reinforcement; d) Placing of 2nd mortar layer.

(Kim et al., 2020).

2.8 TRC as shear strengthening

TRM can be a useful method for improving RC members' flexural or shear capacity, their axial deformation capacity and compressive strength through confinement, and their ductility and energy dissipation for seismic retrofitting. Carbon TRM U-jackets can achieve similar strengthening effectiveness as carbon FRP U-jackets in enhancing shear capacity of beams. The average increase in load carrying capacity of beams shear strengthened by TRM was 51% when compared to an unenhanced reference beam. The use of textile-mortar jacketing resulted in a significant increase in shear resistance, which is enough to change a beam's failure mode from shear to flexural. (Zhang *et al.*, 2019).

2.9 TRC as flexural strengthening

Numerous studies have demonstrated the effectiveness of Textile Reinforced Concrete (TRC) in providing flexural reinforcement. Among these, Volkova *et al.* (2016) conducted an empirical study to explore the bending performance of TRC. The main objective of the research was to assess the feasibility of employing robust reinforcing fabrics composed of glass and carbon roving in textile-reinforced concrete. The findings indicate that the use of reinforcing fabric results in a significant increase in flexural strength as well as an increase in bending stress because of carbon fibers' capacity for load bearing. However, flexural reinforcement was not much evaluated in dynamic conditions.

2.10 Review on related experimental research

The use of an AR fiberglass textiles made locally to improve reinforced concrete beams for flexural strength was investigated by (Giese *et al.*, 2021). They examined eighteen rectangular beams that were reinforced with TRM and put through a four-point bending test. The beams were 1500 mm long, 200 mm deep, and 120 mm wide. According to the study's findings, TRM reinforcement significantly raised the ultimate load, which increased linearly with number of layers. The ultimate load increased by 31%, 54%, and 72% for the beams reinforced with two, three, and four layers of textiles, respectively.

A research study by (Volkova *et al.*, 2016) presents two TRC samples consisting of carbon rovings and glass fibers with high strength reinforcement were created. In the longitudinal direction, the fabric contains glass or carbon rovings, but in the transverse

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direction, it exclusively contains glass rovings. A three-point bending test was used to evaluate the generated samples' flexural performance. The study's findings demonstrated the benefit of strengthened materials; reinforced concrete has a bending strength of 5.2 MPa. The application of reinforcing fabric results in a flexural strength enhancement. The specimens reinforced with carbon rovings have a strength of 9.5 MPa, while the specimens reinforced with AR-glass have a strength of 8.1 MPa.

(Yin and Xu, 2011) conducted an experiment to determine how anti-crack and bearing capacity are affected by mesh sizes, surface treatments, and TRC cover thickness. Hybrid fabrics composed of E-glass and carbon yarns were employed in the experiment. The sizes of the textiles mesh were 20 mm by 20 mm and 10 mm by 10 mm. The continuous bending moment zone of 100 mm and its span of 490 mm characterized the four-point loading fixture. They come to the conclusion that compared to textiles with 20mm×20mm mesh sizes, those with 10mm×10mm mesh sizes could be more suited for reinforcing concrete.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter describes the methodologies that used in Finite Element Analysis for strengthening beam with TRC.

It takes a lot of time and money to conduct experiments. So, for nonlinear evaluations of structural components, numerical modelling and simulation have emerged as strong and intriguing computational tools. The most reliable results come from experimental testing, which is also utilized to reflect loading resistance and failure processes as accurately as feasible. To precisely understand the features of strengthened beams and to improve load carrying capacity with various parameters, in-depth parametric evaluations are occasionally required. Despite the fact that experimental analysis is reliable, test expenses are considerable and they are challenging to undertake, finite element software offered the advantage of being able to run with different parameters based on the trial outcomes.

A variety of engineering issues can be approximately solved using the finite element method, a numerical analytical methodology. It was first intended to examine stresses in sophisticated aircraft structures, but it has since been expanded and used in a wider range of continuum mechanics applications. Due to its flexibility and adaptability as an analysis tool, it is becoming more and more well-liked in engineering schools as well as the industry (Ratheesh and Chacko, 2019).

The general-purpose finite element program ABAQUS/CAE software package (SIMULIA 2022) is used to execute the numerical simulations created in this research study.

3.2 Experimental detail for simulation

Because the simulation of a numerical model makes sense if it coincides with the validation done on the experimental data, all finite element modeling and simulations are based on the experimental data conducted by (Rossi *et al.*, 2021). Through an experimental campaign, the efficacy of TRC in strengthening reinforced concrete (RC) beams against bending was examined. A few of the variables were the number of textile layers, the type

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of cementitious material utilized, the mechanical anchorages, and the addition of steel fiber that was quickly distributed. This experimental program intends to analyze the effects of specific strengthening configurations on beam specimens with a cross section that is more likely to be found in actual constructions at the Ultimate Limit State. Additionally, several techniques were used to apply the strengthening solutions in an effort to mimic actual practical conditions. This experiment serves as the basis for the Abaqus model's execution and cyclic loading studies.

3.2.1 General Properties of Tested beam and set up

The research's experimental analysis takes use of 13 beams that were cast at Carinthia University of Applied Sciences (CUAS) for the experimental investigation. Each beam measured 2.5 meters in length and contained a 220 x 450mm cross section. The internal reinforcement consisted of four longitudinal reinforcing bars, two of which had a diameter of 20 mm in the tensile zone and two of which had a diameter of 10 mm in the compression zone. Twenty stirrups with a 10 mm diameter were placed 125 mm apart to prevent shear failure. Applying on the bottom in the tensile zone, the reinforcing layer measured 2.1 m, or 50 mm, from each support centering with regard to the beam. There was a 2.2-m span.

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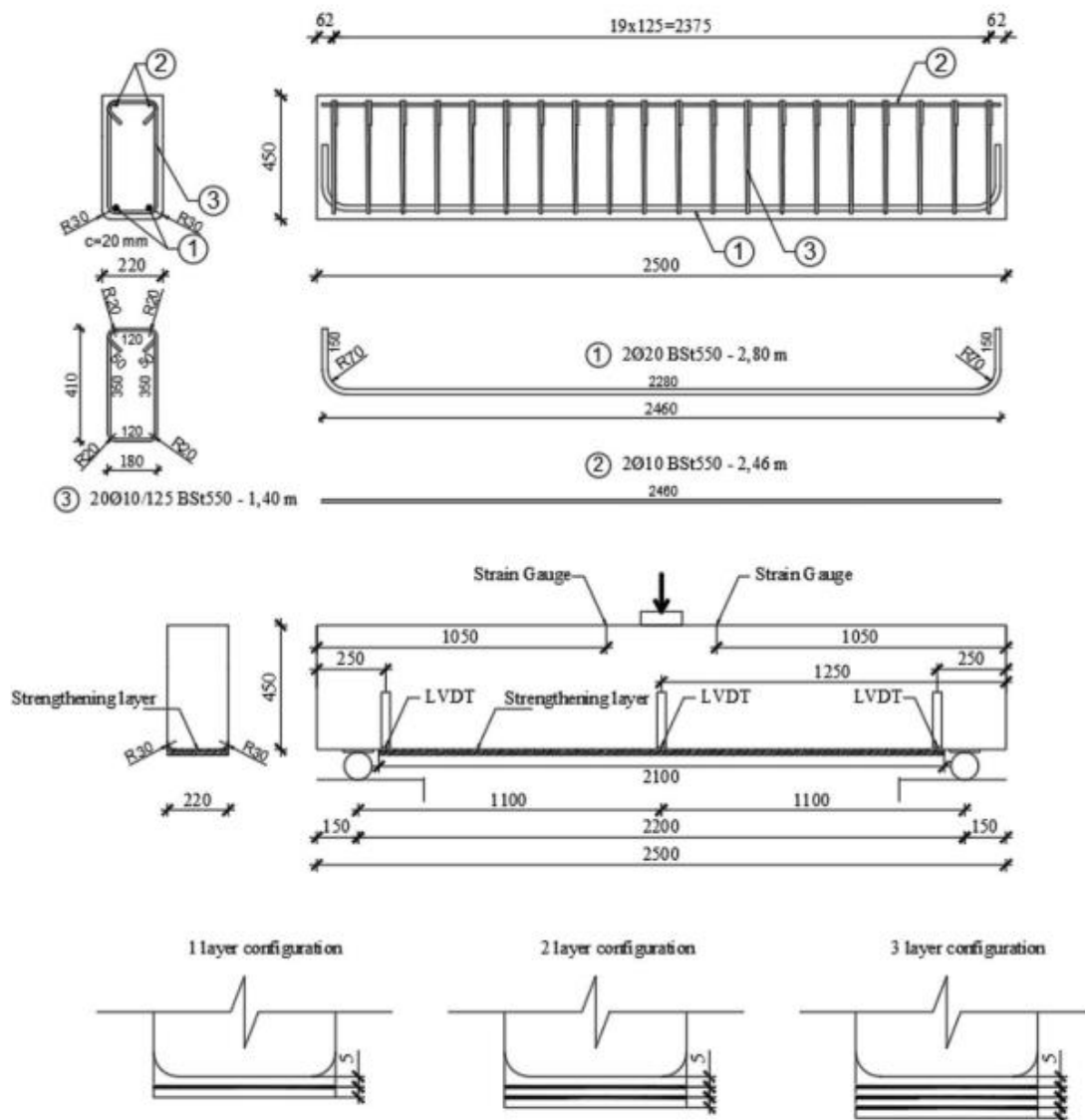


Figure 3-1 Geometric detail used in the experiment (Rossi *et al.*, 2021).



Figure 3-2 Loading detail used in the experiment (Rossi *et al.*, 2021).

3.2.2 Material Specification

Finite element modeling requires knowledge of the material properties. The materials for finite elements come from experimental research conducted by (Rossi *et al.*, 2021).

I. Material properties of steel rebar and concrete

The materials used to cast the beams were a C30/37 concrete and a 550Mpa capacity of steel reinforcement.

II. Material properties of textile

Table 3-1 Properties of textiles

	Longitudinal	Transversal
Roving axis distance, mm (in.)	25 (0.98)	25 (0.98)
Strand cross section, mm ² (in. ²)	3.62 (0.0056)	3.62 (0.0056)
Textile cross section, mm ² /m (in. ² /ft)	142 (0.067)	142 (0.067)
Average tensile strength, MPa (ksi)	3100 (449.62)	3300 (478.62)
Elastic modulus, GPa (ksi)	>220 (31,908)	>205 (29,733)

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III. Material properties of mortar

The mortar properties used in the experiment had a tensile strength of 4.8 MPa and a compressive strength of 88.7 MPa.

3.3 Finite Element Modelling

Most numerical investigations performed nowadays, especially on structural elements or even entire structures, employ finite element software. ABAQUS, ADINA, ANSYS, LISA, Vector, and other finite element software are the most effective and highly recommended programs. ABAQUS (Simulia 2022) was chosen for the non-linear finite element analysis of the current study because of its ability to model and analyze one-, two-, and three-dimensional elements, as well as the variety of material models that are available to it. Most importantly, though, is that it is a software that is widely used and dependable in structural engineering studies. FE modeling techniques were applied in order to simulate the RC beam strengthened with TRC. The procedure comprises element definition, material model, geometry, meshing, loading conditions, boundary conditions, and analysis.

3.3.1 Type of Finite Element

In Abaqus library different type of finite element are available which are truss elements, beam elements, shell elements, and solid elements.

Truss elements are one-dimensional elements that can resist only axial forces. They are useful for modeling slender structures such as bridges, towers, and cables. They have a cross-sectional area as a section property, and they are defined by two nodes. They are defined in Abaqus by the element type T2D21.

Beam elements are also one-dimensional elements, but they can resist axial, bending, and torsional forces. They are useful for modeling beams, columns, frames, and other structures that have a well-defined cross-section. They have a cross-sectional shape and orientation as section properties, and they are determined by two or three nodes. They are defined in Abaqus by the element type B312.

Shell elements are two-dimensional elements that can model thin or thick structures such as plates, shells, and membranes. They can resist in-plane and out-of-plane

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forces and moments. They are useful for modeling structures that have a large surface area compared to their thickness, such as aircraft wings, car bodies, and roofs. They have a thickness as a section property and are defined by three or four nodes. They are denoted in Abaqus by the element types S3, S4, S6, and S82.

Solid elements are three-dimensional elements that can model any shape and size of structures. They can resist any type of loading and deformation. They are useful for modeling structures that have complex geometries or material behaviors, such as rubber, plastic, metal, and composite materials. They no section properties and are defined by four to eight nodes. The element types C3D4, C3D6, C3D8, C3D10, and C3D202 are used in Abaqus to represent them.

The concrete and mortar part of RC beam was modelled by 3D-solid eight-node element which was called C3D8R element type. Two-node linear three-dimensional truss elements (T3D2) having three degrees of freedom in each node were used to model steel reinforcements and carbon fiber.

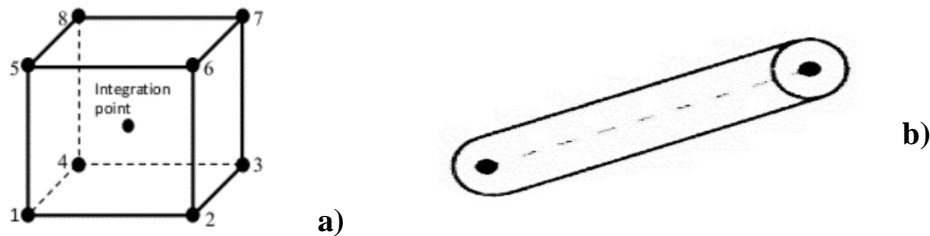


Figure 3-3 (a) Three-dimensional eight-node linear hexahedral (brick) element with reduced integration (C3D8R). (b) Two-node linear three-dimensional truss element (T3D2)

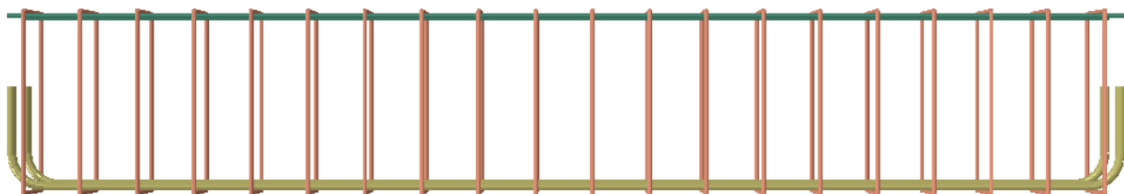


Figure 3-4 Finite element reinforcement detailing

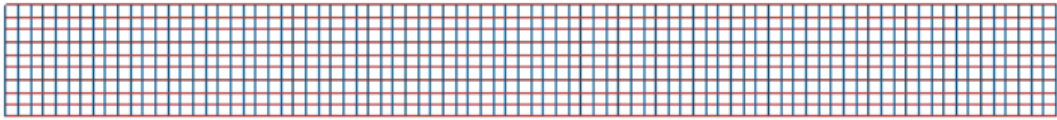


Figure 3-5 Finite element textile carbon mesh top view for 0° and 90°

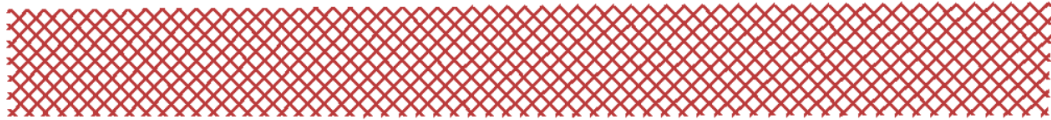


Figure 3-6 Finite element textile carbon mesh for 45° and -45°



Figure 3-7 Finite element mortar top view

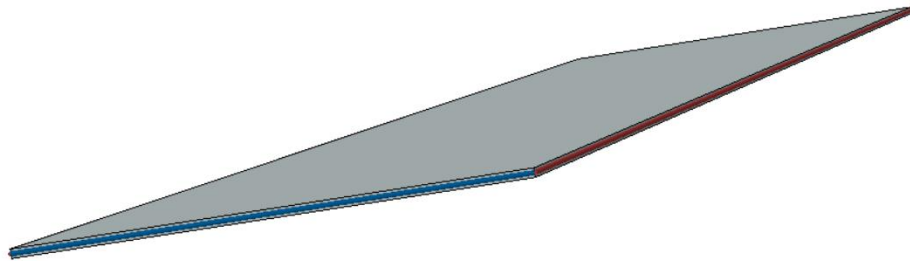


Figure 3-8 Assembled view of mortar with textile carbon mesh

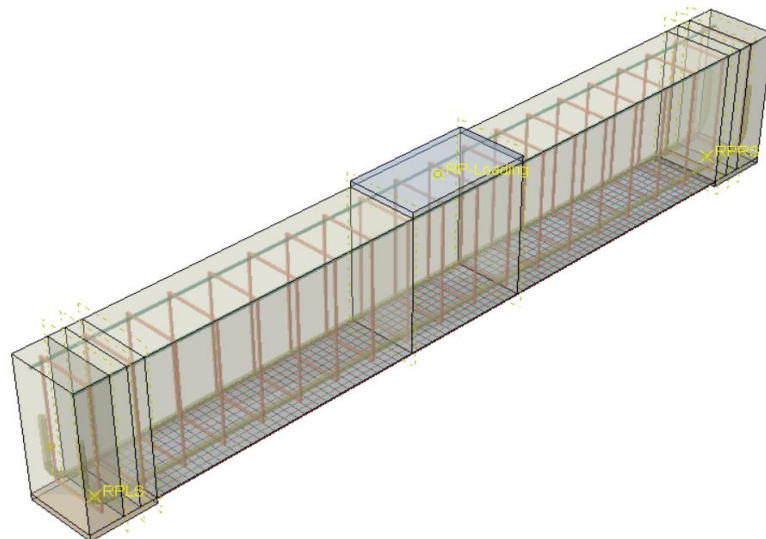


Figure 3-9 Assembly proposed model

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3.3.2 Material Modeling

The goal of ABAQUS's material library is to offer thorough coverage of isotropic and anisotropic, linear and nonlinear material behaviors. Certain mechanical behaviors provided cannot coexist in a single material specification; they are mutually exclusive. Some behaviors require the presence of other behaviors; for example, plasticity requires linear elasticity. The accuracy of the final outcome is significantly affected. The ABAQUS material library may be used to represent the majority of engineering materials, such as metals, polymers, rubbers, foams, composites, granular soils, rocks, plain concrete, and reinforced concrete.

3.3.2.1 Concrete

Concrete is a material that can be defined using different constitutive models, depending on the type of analysis and the expected behavior of the concrete. The program Abaqus states that there are three types of concrete cracking: smeared cracking, brittle cracking, and damaged plasticity (CDP). Every model has its own advantages and disadvantages, as well as different input parameters and assumptions.

The concrete smeared cracking model assumes that cracks are distributed uniformly over a finite region of the material. The model can capture the tensile behavior of concrete, including crack initiation, propagation, and closure. The model can also account for the effects of shear retention, tension stiffening, compression hardening, and cyclic loading. Nevertheless, the model is unable to account for the concrete's compressive failure or post-peak softening behavior.

The brittle cracking model assumes that cracks are localized in discrete regions of the material. The model can capture the tensile and compressive behavior of concrete, including crack initiation, propagation, branching, coalescence, and closure. The model can also account for the effects of shear retention, tension stiffening, compression hardening, softening, and cyclic loading. But in order to solve the crack route, the model needs a fine mesh, which could be difficult to solve.

According to the concrete damaged plasticity (CDP) model, the material experiences both damage and plasticity occur simultaneously. The concrete's tensile and compressive behavior, including crack initiation, propagation, closure, dilation, and compaction, can be represented by the model. The model can additionally take into account

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the effects of temperature, creep, shrinkage, confinement, and cyclic loading. Furthermore, ABAQUS's CDP model, when verified by the experimental test results, offers a more accurate and stable regime for modeling the nonlinear and post-peak behavior of quasi-brittle materials like concrete. Because of the above reason CDP model was selected.

In this investigation, examine the uniaxial compressive stress-strain response of conventional concrete. The approach aligns with the model proposed by the CDP Model (1990), which has found widespread use in nonlinear finite element analyses. Remarkably, this model demonstrates excellent agreement with experimental validation in this study. Specifically, the material properties of compressive strength of normal concrete (f_c') and its modulus of elasticity. These material properties, 30 MPa and 27137 MPa respectively, are derived from experimental tests. The compressive strength of 88.7 MPa and tensile strength of 4.8 MPa for the mortar were obtained from tests conducted on control specimens, as reported by Rossi et al. (2021).

3.3.2.2 Mortar

In this study, the numerical discretization of the 3D concrete components is achieved using the C3D8R element from the ABAQUS library. This element type is chosen for its ability to accurately capture the mechanical behavior of concrete under various loading conditions. To ensure a robust connection between the concrete beam and the fine-grained concrete layer, a surface-based tie constraint is employed. This method effectively simulates the strong bond observed in experimental tests, which indicated that delamination of the fine-grained concrete layer is unlikely. Consequently, the two parts are modeled as being perfectly bonded, with no relative motion allowed between them.

The mechanical properties of the mortar used in this study were determined through experimental testing on control specimens. The compressive strength of the mortar was found to be 88.7 MPa, while the tensile strength was measured at 4.8 MPa, as reported by Rossi et al. (2021). These values are critical for accurately modeling the behavior of the mortar in the numerical simulations.

3.3.2.3 Steel Reinforcement

Steel reinforcement is a term that refers to the use of steel bars, wires, or fibers to strength concrete structures. Steel reinforcement can improve the tensile, compressive,

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shear, and flexural strength of concrete, as well as its ductility and durability. Steel reinforcement can also reduce the cracking and shrinkage of concrete.

To model steel reinforcement in Abaqus different kind of method are available depending on the type and geometry of the reinforcement and the analysis objectives. Which is rebar layer, embedded element, discrete element.

Embedded element: This approach is used to define rebar layers, which are uniaxial reinforcement in membrane, shell, or surface components. The rebar layer, also known as a smeared layer, is measured by dividing the area of each reinforcing bar by the distance between the reinforcing bars. The material characteristics of the rebar layer are different from those of the supporting or host element. The reinforcement's tensile behavior, including crack initiation, propagation, and closure, can be captured by the rebar layer. The effects of shear retention, tension stiffening, compression hardening, and cyclic loading can also be taken into consideration by the rebar layer. The compressive failure of the reinforcement or the post-peak softening behavior, however, cannot be captured by the rebar layer.

Rebar layers in solid (continuum) elements are modeled using the embedded element approach, which involves embedding a set of surface or membrane elements with the previously described rebar layers in a set of host continuum elements. The interaction between the reinforcement and the concrete can be captured more precisely by the embedded element method than by the rebar layer method. The embedded element method, however, might need a finer mesh and more computing power.

In Abaqus/Standard, discrete axial reinforcement in beam elements is modeled using the discrete element approach. The discrete element method can capture the tensile and compressive behavior of the reinforcement, including crack initiation, propagation, branching, coalescence, and closure. The effects of shear retention, tension stiffening, compression hardening, softening, and cyclic loading can also be taken into consideration by the discrete element technique. The discrete element method, however, may be computationally expensive and needs a fine mesh to resolve the crack path.

3.3.3 Interaction Between Component

To guarantee strain compatibility between the various components, the kinematic relationship between them must be specified inside the finite element model. Stated

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differently, interactions must be defined in a way that causes one or more bodies to deform together as a function of loading applied between them. Depending on the type of analysis being done, ABAQUS offers many solutions for modeling the interface between the concrete body interactions and reinforcement

In this investigation, the embedding approach is used to ensure a perfect bond and displacement continuity between the reinforcement bars and the concrete, as well as between the mortar and carbon fiber. This method ensures that the stress transfer between the mortar and carbon fiber is accurately represented. This is crucial for evaluating the effectiveness of the strengthening technique and predicting the structural performance under cyclic load. The embedded interaction method simplifies the modeling process by assuming a perfect bond between the mortar and fiber. This assumption significantly reduces computational complexity and time without the added complexity of detailed interface modeling. This efficiency is crucial for conducting comprehensive parametric studies within a reasonable timeframe. The embedded model is practical for real-world applications where a strong bond between mortar and fiber is typically ensured through proper material selection and application techniques. In engineering practice, the embedded interaction method is widely used for its simplicity and effectiveness in capturing the composite action of reinforced materials. This practical relevance ensures that the findings of my study can be readily applied in the field, benefiting engineers and stakeholders involved in structural strengthening projects. Notably, (Abinezer., 2018) research on the enhancement of the flexural behavior of CFRP-strengthened RC beams in medium and low-grade concrete provides further support. In his study, Abinezer validated his experiments using ABAQUS with both cohesive and perfect bond models, finding that the results were more closely aligned with the perfect bond model. Furthermore Nguyen, H.C. and Ngo, D.Q. (2020) also validate experimental studies with Abaqus embedded model and get good agreement with investigated experiment result. This finding reinforces the validity of using the embedded interaction method, as it effectively captures the bond behavior in practical scenarios.

The other interaction is specified as a surface-based tie constraint, where a constraint is generated between a slave surface and a master surface on the model geometry. As a result, the interactions between the surfaces of the elastic and inelastic solid bodies that represent the steel plate and concrete at the loading point are defined by

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tie constraints and in order to connect the concrete beam with the fine grain concrete layer, the surface-based tie constraint is used. The reference point is constrained and connected to the plate's surface by a rigid body, which is the final interaction in this model. This will enable the plate to interact with other components of the assembly while moving as a rigid body.

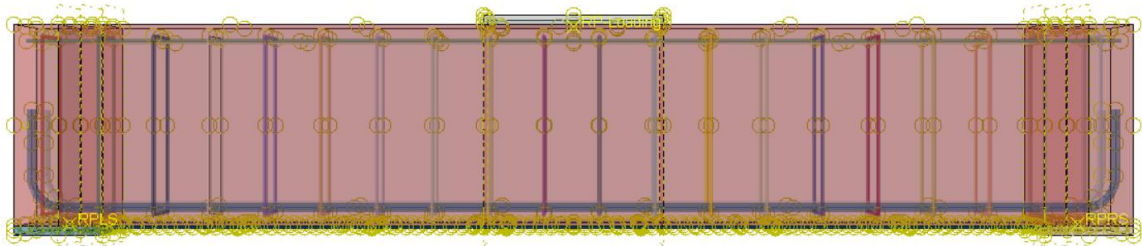


Figure 3-10 Interaction model between component

3.3.4 Boundary Conditions and Load Application

Loads can be applied either on solid models such as (key points, lines, hard points or areas) or finite element models (nodes and elements). Wherever the loads are applied to the model, the solver or the program automatically transfers to nodes and elements at the beginning of the solution. This research makes use of cyclic load and Abaqus' static general analysis. The static, monotonic load was applied in the center of the top of the beam using static general analysis, which is utilized for validation and solves for the equilibrium state of a structure under applied loads without taking into account any time-dependent effects. Furthermore, ramp amplitude loading, which involves gradually increasing the applied load over time until it reaches its maximum value. And cyclic load is used to study the behavior of beam strengthened for flexure using TRC, a cyclic load is applied at the center of the beam a rigid body plate as an amplitude. The cyclic displacements are repeated three times at each displacement, and the time interval between each cycle is decided to be 0.2 seconds due to the time-sensitivity analysis.

In ABAQUS, the constraints imposed on the model at its interfaces or boundaries are referred to as boundary conditions. Roller support, Pin support, and fixed support are a few examples of these restrictions. The actual environment of a structure or component is represented by boundary conditions, which are essential in determining how the model will respond and behave under different loading scenarios.

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A roller support boundary condition is a constraint that prevents a node or set of nodes from moving in vertical direction. It defined by setting the displacement values of the constrained nodes to zero in x and y direction. The roller support boundary condition has been chosen for this study after careful observation and simulation of the experimental data. The experimental data from (Rossi *et al.*, 2021), uses a roller type of support on the left and right side of beam.

Table 3-2 The boundary conditions of the beam

Direction	Restrain Condition	
	Left Support/Roller	Right Support/Roller
U1=X	0	0
U2=Y	0	0
U3=Z	-	-
UR1=X	-	-
UR2=Y	-	-
UR3=Z	-	-

3.4 Parameters Calibration

In finite element analysis, calibration studies are frequently conducted to assess how changing material parameters impact a numerical model. This is achieved by comparing experimental results with numerical predictions (Rossi *et al.*, 2021). Consequently, in order to guarantee the accuracy of the nonlinear finite element model of beam strengthening with TRC, it is imperative to calibrate the effect of the various geometric and material input parameters, such as mesh size, dilation angle, and viscosity parameter in constitutive equations of damaged plasticity model.

3.4.1 Mesh Sensitivity

In a numerical simulation, the components that are employed and the size of their mesh are important factors. The mesh is programmed with structural and material attributes that dictate the behavior of the structure under specific loading conditions. A finer mesh in finite element modeling usually yields a more accurate solution. However, the calculation time grows as the mesh gets finer and finer. Moreover, one of the key elements of TRC non-linear behavior is the controlled cracking of concrete. Convergence of the solution with appropriate mesh refinement is one of the finite element method's

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desirable features. Researchers employing numerical techniques for the nonlinear analysis of concrete structural elements have observed specific computational challenges resulting from mesh dependence impacts. When comparing the ultimate capacity to the experimental results, the 40mm mesh spacing shows a 0.7% difference, the 60mm mesh spacing shows a 0.4% difference, and the 50mm mesh spacing shows a 0.2% difference. Although all these differences fall within permissible limits, the 50mm mesh spacing demonstrates the closest match to the experimental results. This indicates that the 50mm mesh spacing not only meets the accuracy requirements but also offers a balance between precision and practical application, making it the most suitable choice for this investigation.

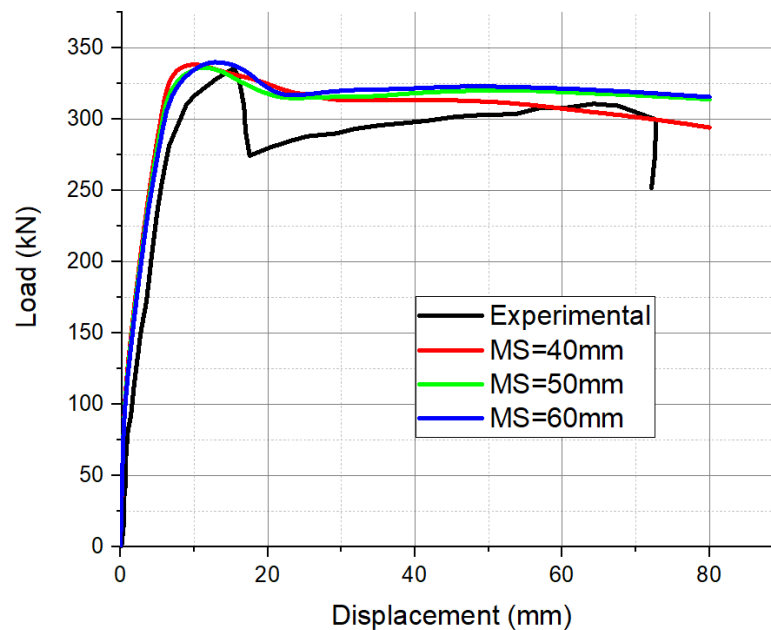


Figure 3-11 Calibration by different mesh sizes

3.4.2 Dilation Angle (ψ)

In the concrete damaged plasticity model, the dilation angle (ψ) represents the volume change that quasi-brittle materials undergo during compression. Concrete dilatancies, or expands, in response to triaxial tension and subsequent inelastic strain (Najafgholipour et al., 2017). Various studies by different authors (Lee and Fenves, 1998; Wu, Li and Faria, 2006; Malm, 2009; Voyiadjis and Taqieddin, 2009; Najafgholipour et al., 2017) recommend a dilation angle parameter range of 30° to 42° . When combining other plastic parameters such as viscosity and mesh size, the analysis revealed that a dilation angle of 38° resulted in a 1.74% difference from the experimental results, a dilation angle

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of 40 showed a 0.4% difference, and a dilation angle of 42 exhibited a 0.84% difference. Although all these differences fall within the acceptable range, the dilation angle of 40 demonstrated the closest match to the experimental results. The dilation angle of 40 was selected and consistently used throughout this investigation to ensure the most accurate and reliable outcomes. This choice underscores the importance of selecting parameters that not only meet theoretical criteria but also align closely with empirical data, thereby enhancing the validity.

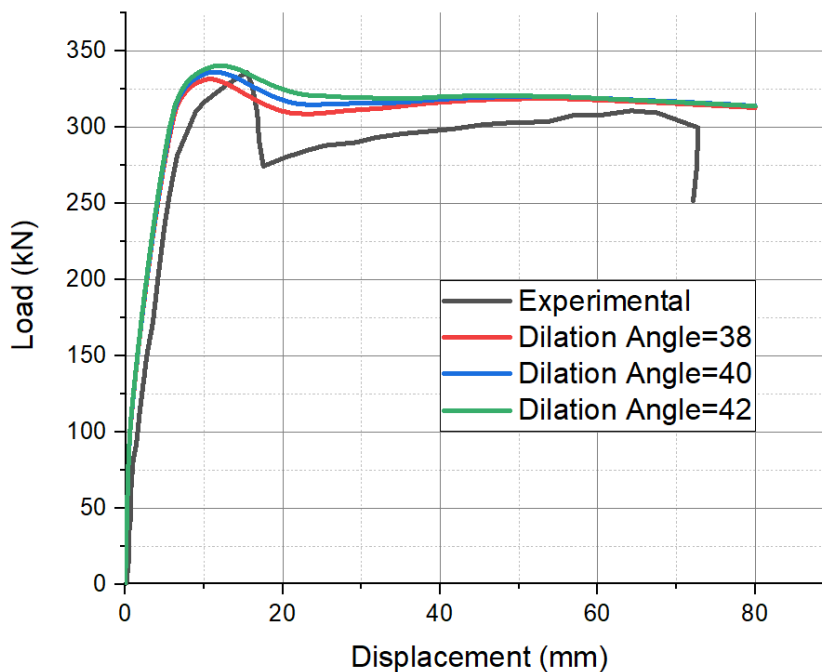


Figure 3-12 Calibration by different dilation angle

3.4.3 Shape Factor of The Yield Surface (K_c)

The yield surface's form is determined in large part by the parameter K_c , as per the concrete damaged plasticity model in ABAQUS. Its default value is 0.667 and it ranges from 0.5 to 1. (Simulia, 2022). Different authors have accepted different values for K_c , depending on the calibration research, while studying reinforced concrete structures using finite element studies.

3.4.4 Visco-plastic Regularization

Adjusting the viscosity parameter (μ) enables the material to momentarily exceed the plastic potential surface, hence mitigating convergence problems and enhancing solution stability. Setting this value in close proximity of 15% of the time increment step is suggested (Simulia, 2022). However, the time increment step was set automatically

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rather than fixed due to the strong nonlinearity associated with modeling joints. Since ABAQUS/Standard uses zero as the default value of μ , no viscoplastic regularization is applied. However, it is advised to input a material model with a very small value for the viscosity parameter rather than zero to increase the convergence rate in the softening zone.

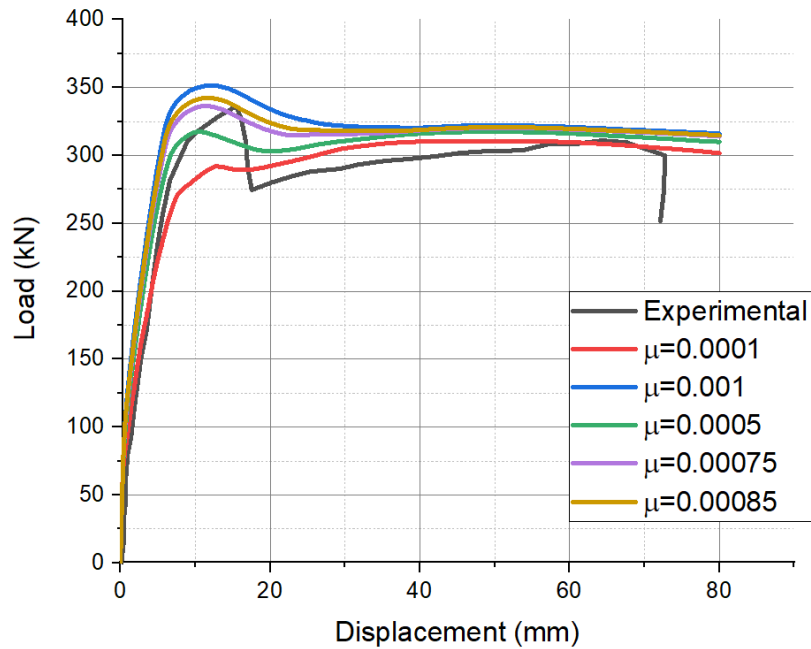


Figure 3-13 Calibration by different viscosity

For this study the above parametric calibration as shown in the table below

Table 3-3 Concrete plasticity parameters used for ABAQUS

No	Plasticity parameters	Values
1	Viscosity parameter (μ)	0.00075
2	Dilation Angle (ψ)	40^0
3	Shape Factor (Kc)	0.73
4	Stress ratio (σ_{bo}/σ_{co})	0.16, default value
5	Eccentricity (ϵ)	0.1, default value

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3.5 Validation Result

The load-displacement curve was developed by taking a node at the bottom center of the beam where maximum displacement was observed. The load-displacement curve developed from the FE analysis showed good agreement with the experimentally developed curve throughout the loading processes. Peak point was occurred at the maximum load resistance of 338.41kN and 337.68kN from FE analysis and experimental result respectively.

$$\text{Error (\%)} = \frac{\text{Experiment result} - \text{FEA result}}{\text{Experiment result}} * 100\% \quad (3.1)$$

The percentage difference between the FE analysis and experimental results were used to check the accuracy of the FE result. This percentage difference was determined by taking the absolute value of the discrepancy between the experimental result and the finite element (FE) result, divided by the experimental result. So, the maximum load resisted by the beam during the FE analysis and experimental result were 338.41kN and 337.68kN respectively. The percentage difference was 0.2% which was within the acceptable accuracy.

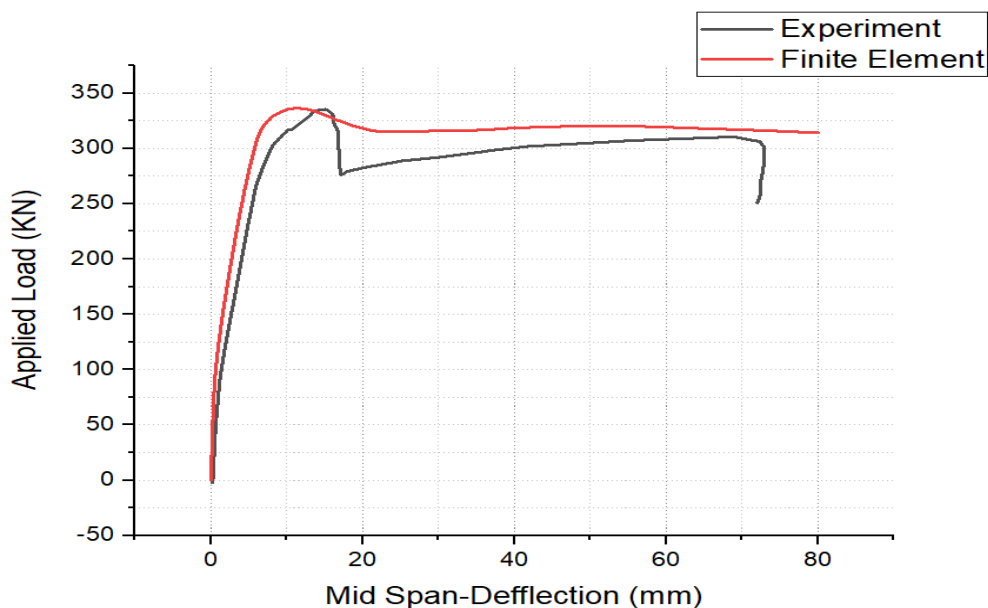
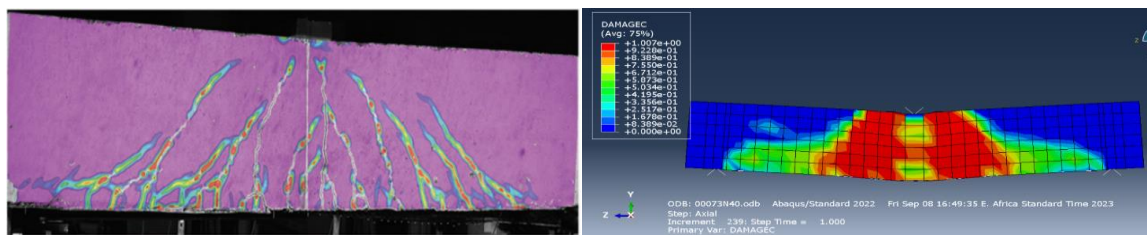


Figure 3-14 Comparison of load Vs mid span-deflection

The comparison between the crack patterns observed in the specimen obtained through nonlinear finite element analysis (NLFEA) and those reported in the experimental

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study reveals good agreement. More precisely, the Nonlinear Finite Element Analysis (NLFEA) anticipates a crack pattern marked by vertical bending cracks near the point of load application, as well as multiple inclined cracks extending across the remaining span. These inclined cracks gradually decrease in steepness as they approach the support. Additionally, horizontal or sub-horizontal fractures that are generally aligned with the height of the bottom longitudinal reinforcing bars are indicative of separation in the substrate concrete cover. The accuracy of the finite element model is further validated by this alignment. In conclusion, the nonlinear finite element model shows a strong capacity for anticipating the specimens' failure behavior.



a. damage in experiment result

b. damage in ABAQUS result

Figure 3-15 Damage in ABAQUS result and damage in experiment result

3.5.1 Empirical or Analytical Validation

- Flexural capacity by ACI318-05. A rectangular section with compression reinforcement, the flexural moment capacity calculated as:

$$M_n = M_1 + M_2$$

$$M_1 = K_n b d^2 \tag{3.2}$$

$$K_n = \left[1 - \frac{\rho f_y}{1.7 f_c'} \right] \rho f_y$$

$$\rho = \frac{A_s}{b d}$$

$$M_2 = K_n' b d^2$$

$$K_n' = \rho' f_y \left(1 - \frac{d'}{d} \right)$$

$$\rho' = \frac{A_s'}{b d}$$

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Where M_n is flexural moment capacity, M_1 is flexural moment due to tension reinforcement, M_2 is flexural moment due to compression reinforcement, b is the width of beam, d is the effective depth of beam, f_y is yield strength of reinforcement, f_c' is compressive strength of concrete.

To compare the Finite Element Analysis (FEA) with the empirical formula provided by the American Concrete Institute (ACI), the control specimen without any strengthening was analyzed. The results showed that the flexural capacity was 167.1 kN-m according to FEA and 164.47 kN-m based on the ACI analytical method. These results are in good agreement, indicating the reliability of both approaches.

- Flexural capacity of strengthened beam with TRC increased by M_{tex} based on (Rossi *et al.*, 2021).

$$M_{\text{tex}} = A_{\text{fib}} f_{\text{fib}} d_{\text{tex}} \quad (3.3)$$

Where M_{tex} is flexural moment due to TRC, A_{fib} is area of textile fiber, f_{fib} is tensile strength of textile fiber and d_{tex} is depth of textile fiber.

3.6 Parametric Study

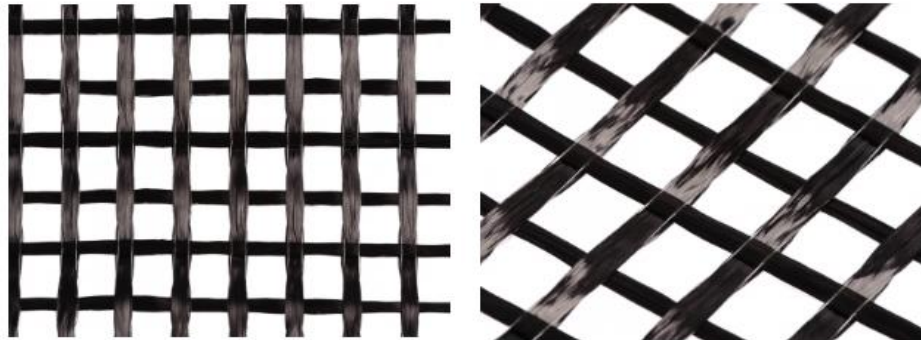
The primary goal of this research is to examine the maximum flexural strength of beam strengthened with textile-reinforced concrete for cyclic loading. To do this, first simulate the experimental beam study by (Rossi *et al.*, 2021) on an ACI paper to validate the material properties, and then the study continues for various parameters to increase the ultimate load capacity for flexure under cyclic loading after validation, which is finite element and experimental research are in good agreement. These parameters are mesh arrangement, number of mesh layers, TRC applied region, and mesh spacing.

3.6.1 Mesh arrangement

This parameter is modeled with fibers arranged diagonally at a 45° angle to the beam's longitudinal axis. The fibers are uniformly spaced within the mesh to provide consistent reinforcement throughout the beam. This orientation aids in evenly distributing stresses across the concrete matrix. Orthogonal Arrangement is the most common setup where the textile fibers are aligned at 0° and 90° to each other on the other hand 45° inclined mesh arrangement can help in better distributing stresses. The inclined fibers can

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bridge cracks more effectively in certain loading conditions, potentially improving the overall durability of the structure.



a. 0° and 90° direction mesh arrangement b. 45° direction diagonal mesh arrangement

Figure 3-16 Carbon Fiber Mesh Arrangement

3.6.2 Mesh spacing

Mesh spacing refers to the distance between the fibers or yarns in the mesh. This parameter is crucial as it influences the mechanical properties and ultimate capacity of the composite material. Commonly used mesh sizes are 5 mm × 5 mm to 25 mm × 25 mm. Bonding a TRC layer to the tension surface, often the soffit of a beam, enhances the flexural strength of beams or slabs. Textile reinforcement is provided in areas requiring increased moment capacity, and sufficient anchorage length should be ensured. Not all fibers in the textile contribute to carrying tensile stresses during flexural strengthening of beams. The effectiveness of this technique is debated because, in a typical bidirectional textile (with fibers oriented in two perpendicular directions), only the fibers parallel to the main axis are subjected to tension, while the other fibers mainly aid in forming the mechanical interlock mechanism.

3.6.3 TRC applied region

The mesh is strategically positioned to strengthen the beam in the maximum stress region rather than across the entire beam. This targeted approach is anticipated to be more economical, as it aims to achieve nearly the same ultimate capacity as full beam strengthening while using fewer materials.

After validation the cyclic load was applied based on cyclic load application criteria on (ACI374.2R-13)

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$$\text{Drift ratio (\%)} = \frac{\Delta l}{lb} * 100 \quad (3.4)$$

Where: -

Δl : and are the applied displacement at the beam mid

lb : Length of the beam from support condition to the application point of the cyclic displacement

As per the ACI 374 (ACI 374.2R-13) report, the loading is described in terms of drift ratio, and the cycles must adhere to predetermined drift ratios as specified in the following conditions.

1. Three fully reversed cycles shall be applied at each drift ratio.
2. The initial drift ratio must fall within the essentially linear elastic response range for the module. Subsequent drift ratio values should be no less than one and one-quarter times, and no more than one and one-half times, the previous drift ratio.

(The subsequent drift ratios are chosen within the range of 1.25 to 1.5 times the previous drift ratio.)

3. Testing or simulation will proceed with incrementally increasing drift ratios until the drift ratio reaches or surpasses 0.035

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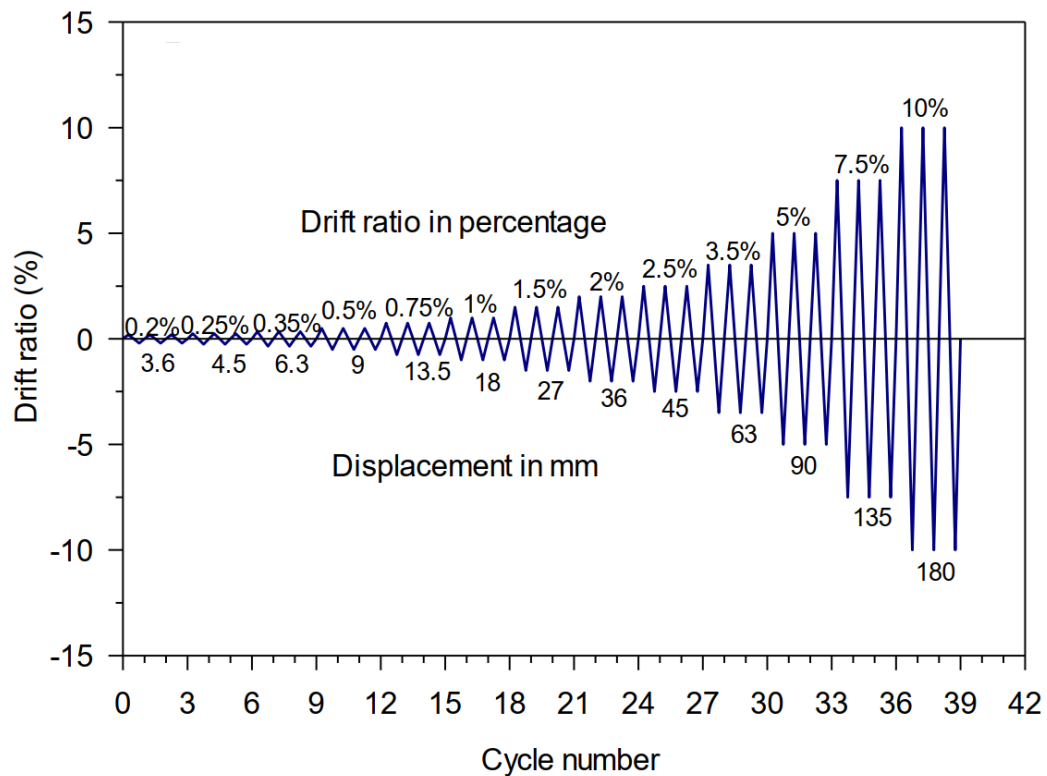


Figure 3-17 Reversal cyclic loading history recommended by (ACI 374.2R-13).

- L1, L2, and L3 indicate the number of layers of TRC layer one, layer two and layer three respectively, while the numbers represent the mesh spacing.

Table 3-4 Description of specimen

Specimen	Description for Specimen
MTL	Mesh for longitudinal and transverse direction
B1L1-ML-25-20	25mm Mesh spacing for Longitudinal and 20mm Mesh spacing for Transversal direction
B1L2-ML-25-20	25mm Mesh spacing for Longitudinal and 20mm Mesh spacing for Transversal direction
B1L3-ML-25-20	25mm Mesh spacing for Longitudinal and 20mm Mesh spacing for Transversal direction with Three Layer
B2L1-ML-25-15	25mm Mesh spacing for Longitudinal and 15mm Mesh spacing for Transversal direction with one Layer
B2L2-ML-25-15	25mm Mesh spacing for Longitudinal and 15mm Mesh spacing for Transversal direction with two Layer

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B2L3-ML-25-15	25mm Mesh spacing for Longitudinal and 15mm Mesh spacing for Transversal direction with three Layer
B3L1-MT-20-25	20mm mesh spacing for transverse and 25mm mesh spacing for longitudinal direction with one layer
B3L2-MT-20-25	20mm mesh spacing for transverse and 25mm mesh spacing for longitudinal direction with two layers
B3L3-MT-20-25	20mm mesh spacing for transverse and 25mm mesh spacing for longitudinal direction with three layers
MAR	Inclined with 45-degree mesh arrangement
MDR	Mesh applied on maximum deflection region

Table 3-5 Summary of parameters used

Specimen	Mesh Spacing	Layer	Mesh type
B1L1-MTL-25-25	25*25	1	Mesh spacing for longitudinal and transverse
B1L2-MTL-25-25	25*25	2	
B1L3-MTL-25-25	25*25	3	
B2L1-MTL-20-20	20*20	1	
B2L2-MTL-20-20	20*20	2	
B2L3-MTL-20-20	20*20	3	
B3L1-MTL-15-15	15*15	1	
B3L2-MTL-15-15	15*15	2	
B3L3-MTL-15-15	15*15	3	
B1L1-ML-25-20	25*20	1	Mesh spacing for longitudinal
B1L2-ML-25-20	25*20	2	
B1L3-MT-25-20	25*20	3	
B2L1-ML-25-15	25*15	1	
B2L2-ML-25-15	25*15	2	
B2L3-ML-25-15	25*15	3	
B3L1-MT-20-25	20*25	1	Mesh spacing for transverse
B3L2-MT-20-25	20*25	2	
B3L3-MT-20-25	20*25	3	
B1L1-MAR-25-25	25*25	1	Mesh spacing and mesh arrangement
B1L2-MAR-25-25	25*25	2	
B1L3-MAR-25-25	25*25	3	

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B2L1-MAR-20-20	20*20	1		
B2L2-MAR-20-20	20*20	2		
B2L3-MAR-20-20	20*20	3		
B3L1-MAR-15-15	15*15	1		
B3L2-MAR-15-15	15*15	2		
B3L3-MAR-15-15	15*15	3		
B1L1-MDR-25-25	25*25	1		Mesh spacing and mesh arrangement on maximum stress region
B1L2-MDR-25-25	25*25	2		
B1L3-MDR-25-25	25*25	3		
B2L1-MDR-20-20	20*20	1		
B2L2-MDR-20-20	20*20	2		
B2L3-MDR-20-20	20*20	3		
B3L1-MDR-15-15	15*15	1		
B3L2-MDR-15-15	15*15	2		
B3L3-MDR-15-15	15*15	3		

4.1 Result and Discussion on Parametric Study

After verifying the finite element analysis model, the study continues the investigations on reinforced concrete (RC) beams. These studies involved varying fiber mesh spacing and arrangements, as well as different layer configurations and application locations. The study investigates how these parameters impact the ultimate load-carrying capacity and failure mechanisms of reinforced concrete (RC) beams. As a reference or control specimen, this investigation employed an RC beam that had not undergone strengthening with textile-reinforced concrete (TRC).

4.1.1 Effect of Textile Fiber Mesh Spacing

A. Ultimate load capacity

The investigation utilized textile fiber mesh sizes of 25x25, 20x20, and 15x15. The ultimate load capacity improved dramatically as the space between consecutive fiber strands in the mesh was reduced. The control specimen's maximum load bearing capacity is 286kN. Table 4-1 below illustrates that with a mesh size of 25x25, the layer has an impact; however, when the mesh size is reduced, the layer's influence on the ultimate load capacity is negligible. For 25x25, 20x20, and 15x15, the ultimate load capacity increased with a single layer by 24.86 %, 28.15 %, and 40.31 % respectively, compared to the control specimen.

Increased layers have an impact on large mesh sizes, such as 25x25 mesh, and result in increases in ultimate load capacity of 24.86 %, 51.4 %, and 81.2 % for one, two, and three layers, respectively. However, layers precisely have no effect on 20x20 and 15x15 mesh sizes. For almost all sample three lay is not much difference from layer two.

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Table 4-1 Ultimate load capacity of different mesh spacing with varying layer

Sample	Mesh Spacing	Layer	Ultimate Load Capacity in (KN)	Increased Ultimate Load in (%)	Ultimate flexural capacity $M_{u,FEA}$ (kN-m)	Predicted ultimate flexural capacity $M_{u,ACI}$	Comparison $\left(\frac{M_{u,FEA}}{M_{u,ACI}}\right)$
B1L1-MTL-25-25	25x25	1	357.1	24.86	196.405	175.13	1.12
B1L2-MTL-25-25	25x25	2	433	51.4	238.15	196.453	1.21
B1L3-MTL-25-25	25x25	3	518	81.2	284.9	228.44	1.25
B2L1-MTL-20-20	20x20	1	366.5	28.15	201.575	177.712	1.13
B2L2-MTL-20-20	20x20	2	467.3	63.39	257.015	184.33	1.39
B2L3-MTL-20-20	20x20	3	467.3	63.39	257.015	190.95	1.35
B3L1-MTL-15-15	15x15	1	401.3	40.31	220.715	182.09	1.21
B3L2-MTL-15-15	15x15	2	401.4	40.35	220.77	217.33	1.02
B3L3-MTL-15-15	15x15	3	403	40.91	221.65	270.18	0.82

B. Load-displacement curve

Figure 4-2 shows the ultimate load carrying capacity of different textile carbon mesh spacing. As it was expected, the presence of the strengthening system significantly increases the flexural strength of beams, in terms of ultimate load. In every specimen, the one with smaller spacing (15x15) has a higher load-carrying capacity than the one with larger spacing (25x25). S-curve are constructed for only one layer for each spacing and sample B3L1-MTL-15-15 was more than the specimen B2L1-MTL-20-20, and B1L1-MTL-25-25, approximately by 12.16% and 15.45% respectively. Beyond the ultimate capacity, the beam experiences a sudden drop in load-carrying capacity. This drop occurs due to various factors, including cracking, fiber debonding, or material failure.

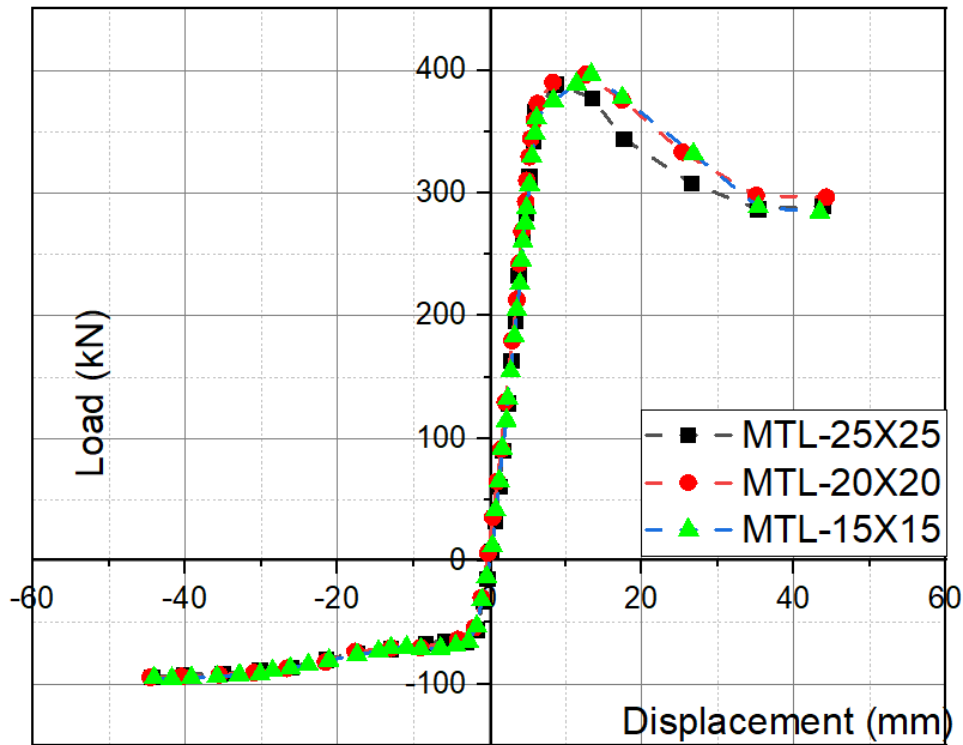
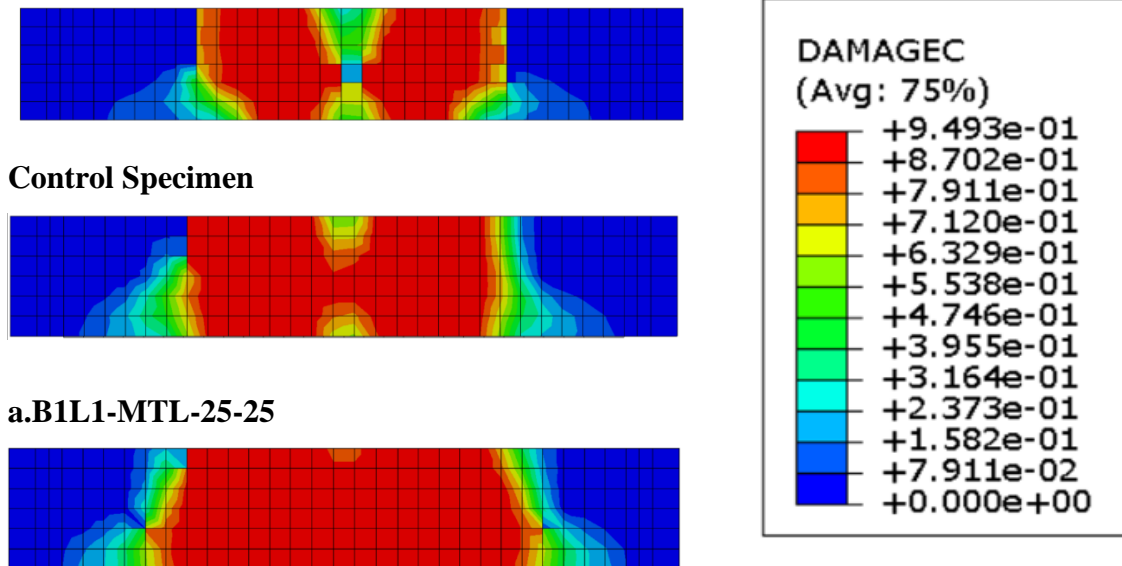


Figure 4-1 Load-displacement envelope curve for different mesh spacing

C. Failure modes

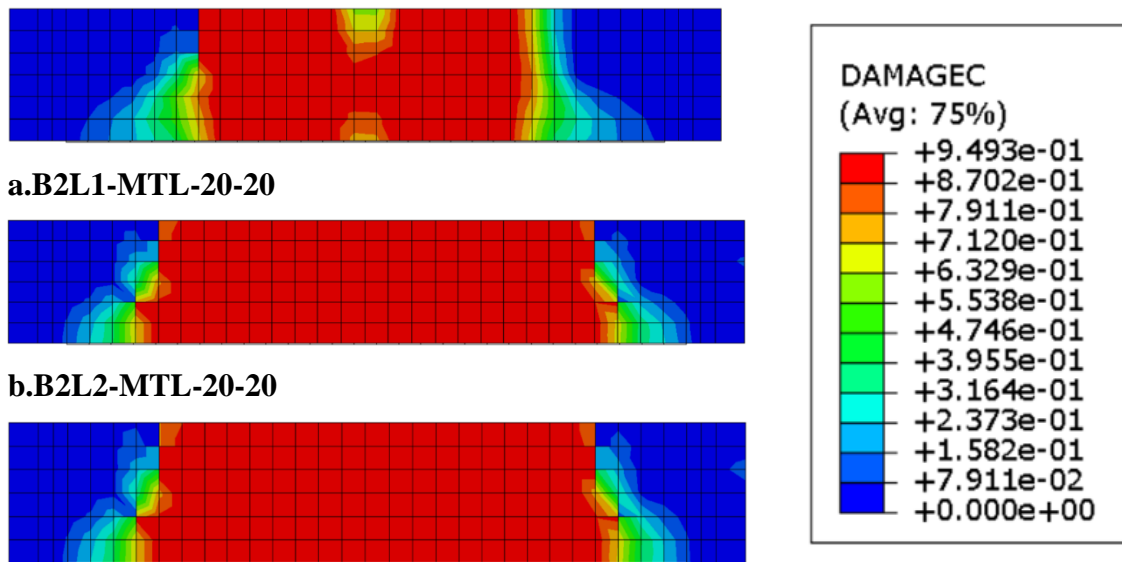
At the ending of the test, the damage pattern grows when increase the layer due to large cross-sectional area. This means that the layer's improved ultimate load capacity and stress distribute and with a 25x25 mesh has not lowered the damage pattern, it has been greatly impacted by the reduction in mesh size spacing from 25x25 to 15x15. Increasing the layer also lowered the intensity of the damage pattern for small spacing mesh sizes (15x15). Even while the damage intensity varies from one textile mesh to the next, it however increases from B1L1 to B1L3. When using 25x25 instead of 15x15, the analysis for B1L3 shows significantly more severe damage at the end.

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b.B1L2-MTL-25

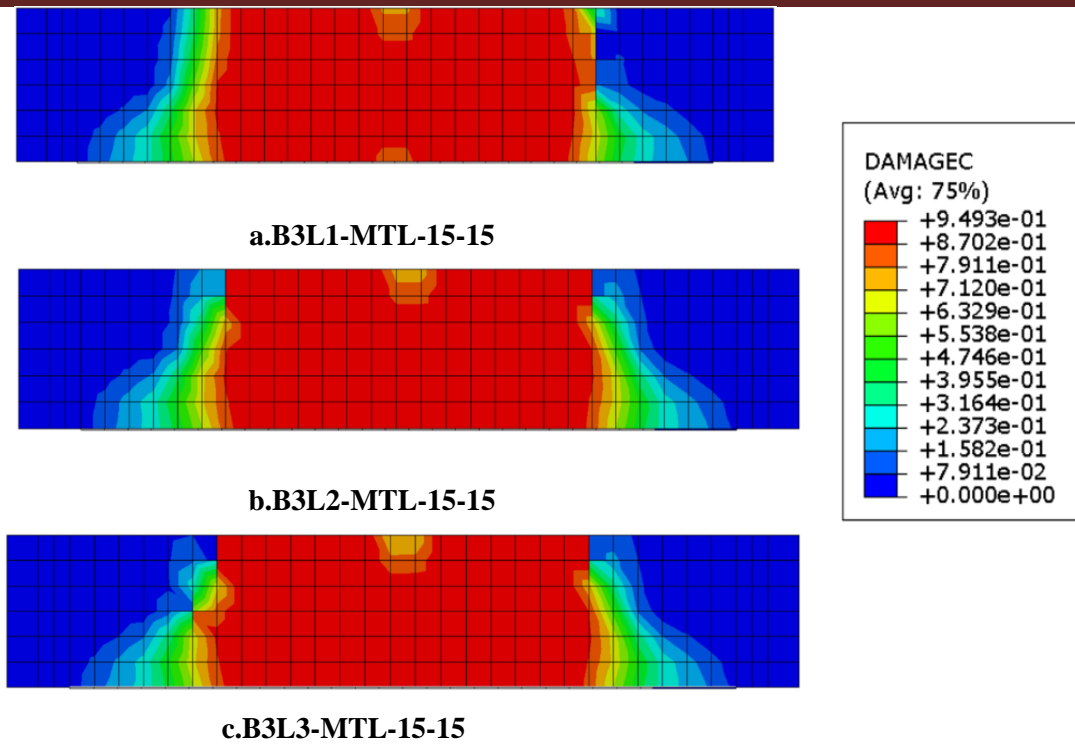
1. 25x25 Mesh spacing for one, two and three layers respectively



c.B2L3-MTL-20-20

2. 20x20 Mesh spacing for one, two and three layers respectively

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3. 15x15 Mesh spacing for one, two and three layers respectively

Figure 4-2 Mesh spacing effect at the end of the test

4.1.2 Effect of TRC applied region

First, a beam measuring 2100 mm in length was covered in textile mesh which is beam length to TRC ratio is $\frac{lb}{ltrc} = 1.19$. This parametric research is used to determine whether it is more cost-effective to apply to the largest deflection region 1500 mm rather than the entire length which is beam length to TRC length ratio $\frac{lb}{ltrc} = 1.67$ is if the value is about comparable. All three-layer 25x25, 20x20, and 15x15 meshes are evaluated for ultimate lateral load capacity, flexural capacity, deformation capacity, and failure mechanisms in order to configure the result. When applied largest ratio which is 1500mm, similar result shows as smallest ratio 2100mm on the failure mechanism and load displacement relationship.

A. Ultimate load capacity

The ultimate load capacity of a beam strengthened with TRC on its maximum deflection area is nearly identical to that of a beam strengthened with TRC along its whole length. As can be seen in table 4.2 below, the full region performs slightly better with a three-layer applied in a 25x25 mesh size; however, the maximum deflected region performs much better with a 15x15 mesh size applied in two and three layers; otherwise,

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their results are comparable, indicating that it is more cost-effective to apply on the maximum deflected region rather than its entire length.

Table 4-2 Ultimate load capacity of different mesh size with varying layer on maximum deflected region

Sample	Mesh Spacing	Layer	Ultimate Load Capacity in (KN)	Increased Ultimate Load in (%)	Ultimate flexural capacity $M_{u,FEA}$ (kN-m)	Predicted ultimate flexural capacity $M_{u,ACI}$	Comparison $\left(\frac{M_{u,FEA}}{M_{u,ACI}}\right)$
B1L1-MDR-25-25	25x25	1	356.7	24.72	196.185	172.44	1.14
B1L2-MDR-25-25	25x25	2	432.8	51.33	238.04	188.37	1.26
B1L3-MDR-25-25	25x25	3	507	77.27	278.85	212.28	1.31
B2L1-MDR-20-20	20x20	1	366.7	28.22	201.685	174.34	1.16
B2L2-MDR-20-20	20x20	2	467.4	63.43	257.07	194.09	1.32
B2L3-MDR-20-20	20x20	3	467.4	63.43	257.07	223.72	1.15
B3L1-MDR-15-15	15x15	1	401.1	40.24	220.605	177.56	1.24
B3L2-MDR-15-15	15x15	2	401.3	40.31	220.715	203.86	1.08
B3L3-MDR-15-15	15x15	3	402.8	40.84	221.54	243.25	0.91

B. Load-displacement curve

Figure 4-4 This shows as the above S-curve discussed on figure 4-2 but strengthening was applied on the maximum deflection region and S-curve are constructed similar to the above discussion for specimen with spacing (15x15), (20x20), and (25x25) and the result shows the smaller spacing (15x15) is higher load carrying capacity than from both (20x20) and (25x25). Which is B3L1-MDR-15-15 being more than the specimen B2L1-MDR-20-20, and B1L1-MDR-25-25, approximately by 12.02% and 15.52% respectively. it shows no difference on ultimate load capacity to apply strengthening material on maximum deflection region or full length.

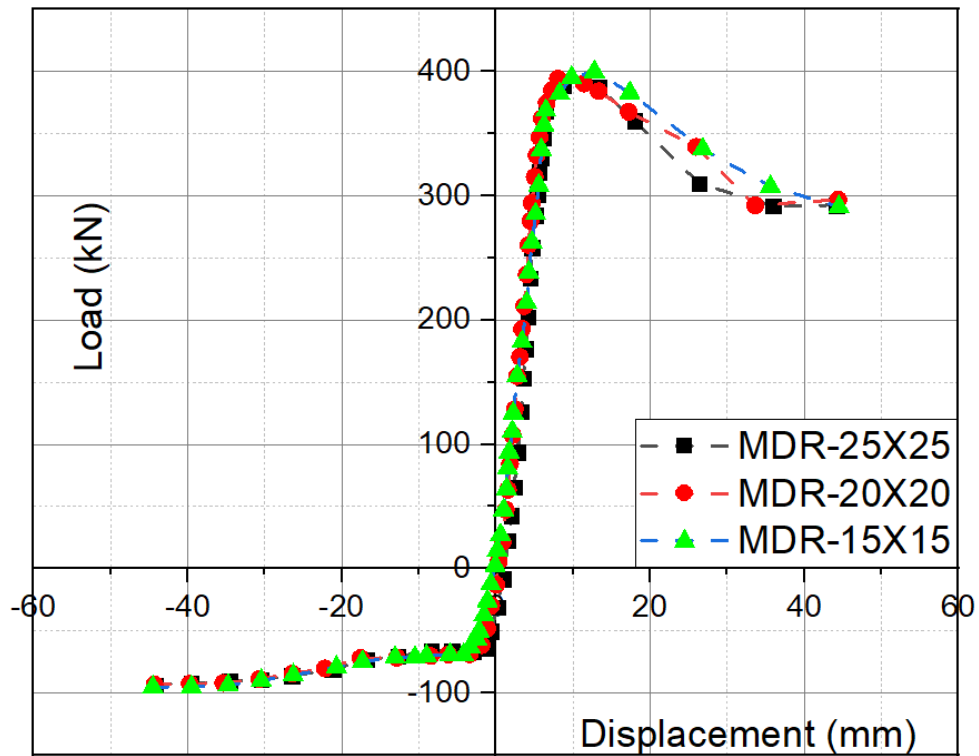
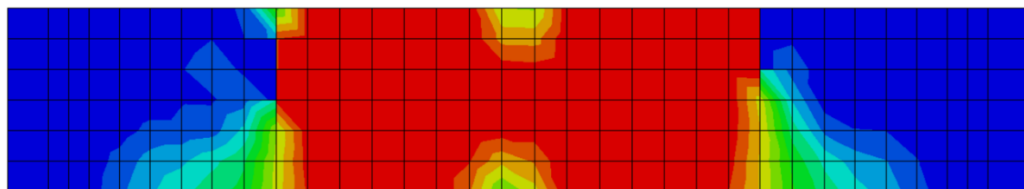


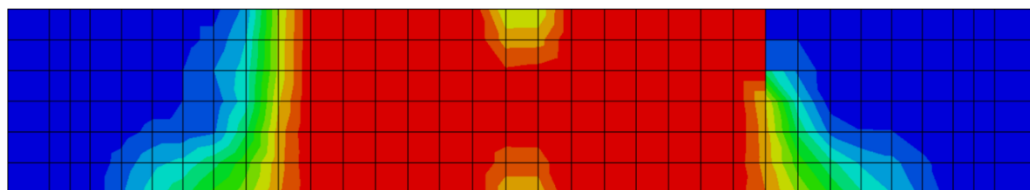
Figure 4-3 Load-displacement envelop curve for maximum deflection region different mesh size

C. Failure modes

From Figure 4-4, for all spacing of TRC the damage of the specimens exhibits almost identical damage patterns; this is due to the close vicinity of the cross-sectional area of TRC.

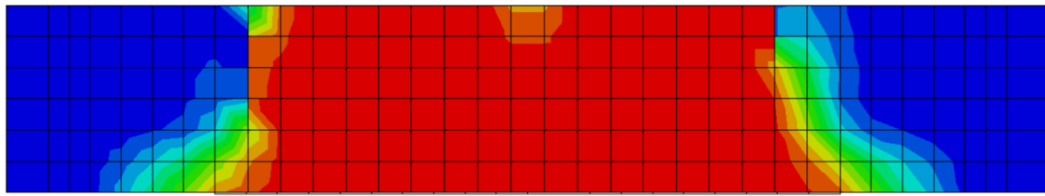


a.B1L1-MDR-25-25



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b.B1L1-MTL-20-20



c.B1L1-MTL-15-15

Figure 4-4 Shows TRC applied on the maximum deflection region for one layer

4.1.3 Effect of fiber mesh arrangement

A. Ultimate load capacity

Fiber strand with -45° and 45° to model fiber mesh arrangement parameter. As shown in table 4.3 below the result demonstrates higher ultimate load capacity compared with control specimen. However, the performance is slightly less when compared to the 0° and 90° model results discussed in item 4.1.1. The maximal load capacity for a 25x25 three-layer mesh size was enhanced by 67.73% when compared to a control specimen. Additionally, the ultimate load capacity increased by 31.5% using a single-layer 15x15 mesh size. It serves alternative for strengthened beams

Table 4-3 Ultimate load capacity of different mesh arrangement

Sample	Mesh Spacing	Layer	Ultimate Load Capacity in (KN)	Increased Ultimate Load in (%)	Ultimate flexural capacity $M_{u,FEA}$ (kN-m)	Predicted ultimate flexural capacity $M_{u,ACI}$	Comparison $\left(\frac{M_{u,FEA}}{M_{u,ACI}}\right)$
B1L1-MAR-25-25	25x25	1	333	16.43	183.15	177.94	1.03
B1L2-MAR-25-25	25x25	2	402.7	40.8	221.485	204.87	1.08
B1L3-MAR-25-25	25x25	3	479.7	67.73	263.835	245.27	1.08
B2L1-MAR-20-20	20x20	1	349	22.03	191.95	181.3	1.06
B2L2-MAR-20-20	20x20	2	439.6	53.71	241.78	214.97	1.12
B2L3-MAR-20-20	20x20	3	439.6	53.71	241.78	265.47	0.91
B3L1-MAR-15-15	15x15	1	374.8	31.05	206.14	186.91	1.10
B3L2-MAR-15-15	15x15	2	377.2	31.89	207.46	231.8	0.89
B3L3-MAR-15-15	15x15	3	378.3	32.27	208.065	299.13	0.70

B. Load-displacement curve

S-curve are constructed as shown in figure 4-5 for diagonal fiber mesh arrangement model. The result shows after ultimate load the graph not decrease rapidly as horizontal and vertical model shows on figure 4-3. But similarly, the smaller spacing (15x15) is higher load carrying capacity than from both (20x20) and (25x25). The percentage

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difference is B3L1-MAR-15-15 was more than the specimen B2L1-MAR-20-20, and B1L1-MAR-25-25, approximately by 9.02% and 14.62% respectively. It shows no difference on ultimate capacity. After ultimate capacity the beam continues to carry load but in a gradually decreasing manner. This gradual failure shows the material experiences progressive damage, such as fiber pullout, concrete crushing, or delamination.

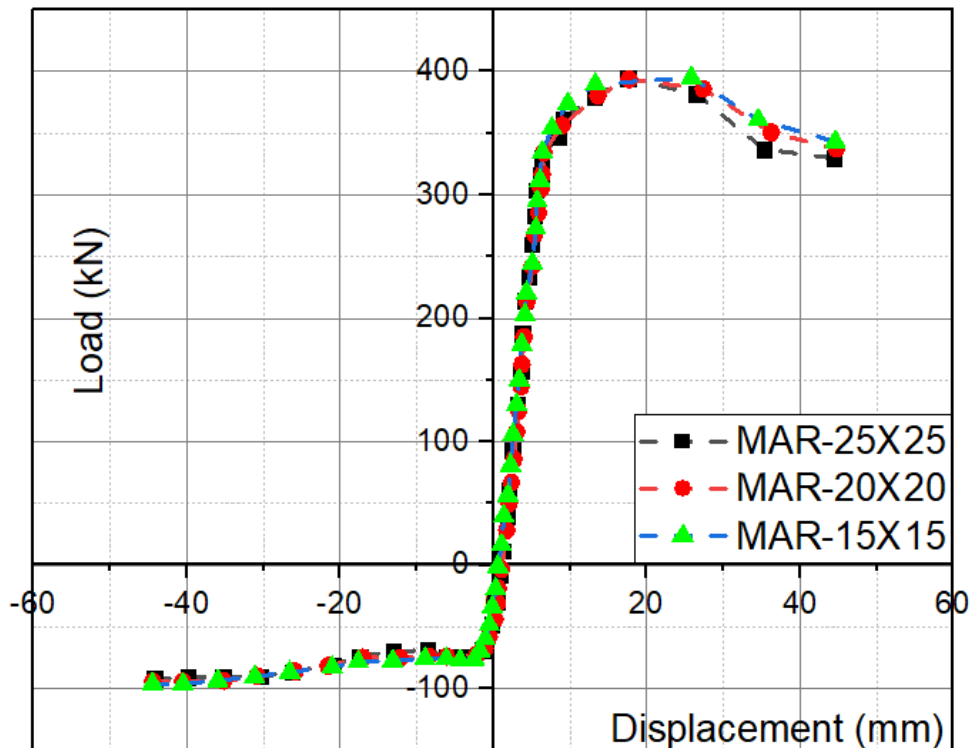
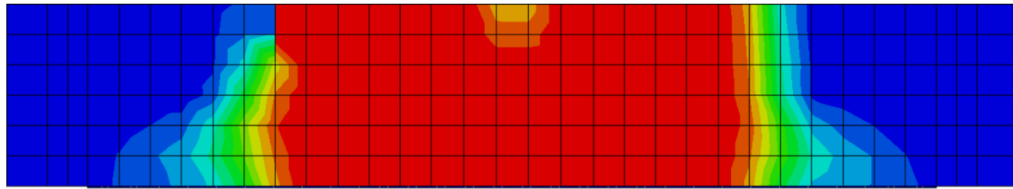


Figure 4-5 Load-displacement envelop curve for mesh arrangement modeled in 45°

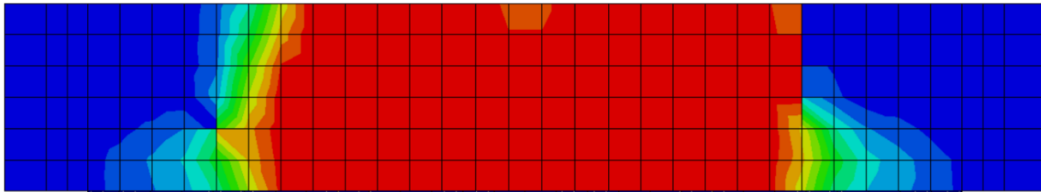
C. Failure modes

The effect of spacing on damage status can be determined in Figure 4-12. Three types of TRC spacing are presented and modeled with diagonal arrangement with 45° are presented. The damage intensity in each of the specimens nearly similar but slightly increases from specimens with higher spacing to specimens with lower spacing. When the spacing decrease the ability to withstand damage decreases. This is due to the cross-sectional area of TRC

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a.B1L1-MAR-25-25



b.B1L1-MAR-20-20



c.B1L1-MAR-15-15

Figure 4-6 Shows the damage of TRC applied on the entire region modelled with 45°

4.1.4 Effect of reduced spacing between transverse and longitudinal direction

It is all known fact that longitudinal reinforcement resists beam flexure based on this fact parameter is analysis on the effect of TRC spacing 20x25, which is 20 mm spacing for transverse direction and 25 mm spacing for longitudinal direction, and is compared with 25x20, which is 25 mm spacing for transverse direction and 20 mm spacing for longitudinal direction. Figure 4-7 illustrates how decreasing the spacing along the longitudinal direction influence the result of ultimate load.

As shown in the figure the ultimate capacity of 25x20 mesh size is 4.22% increase than 20x25 mesh size and almost equal ultimate capacity with 20x20 mesh size.

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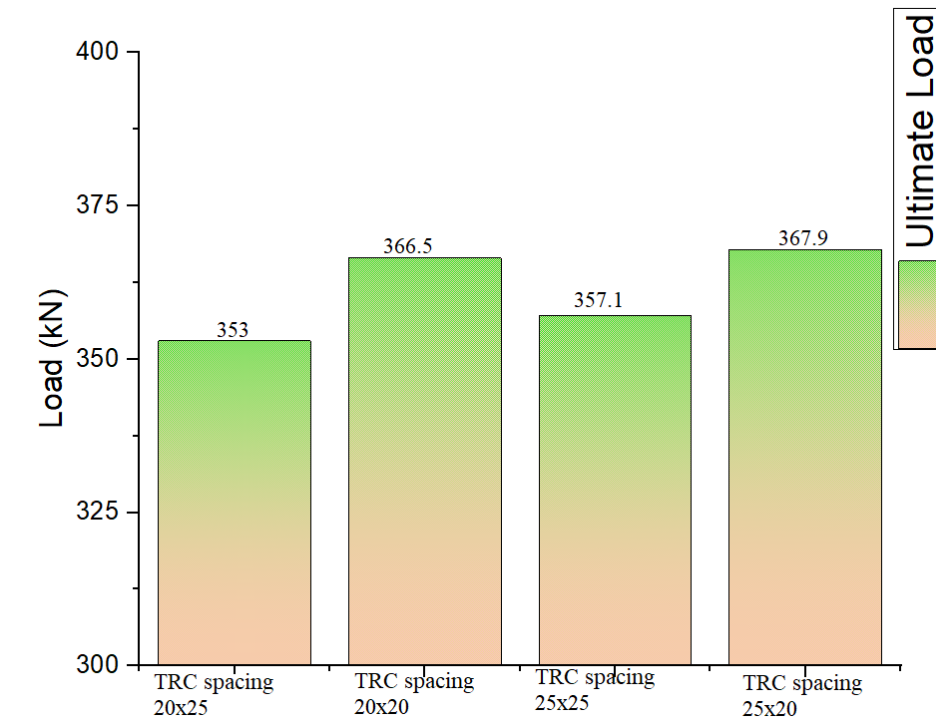


Figure 4-7 Ultimate load of different type of TRC spacing configuration

4.1.5 Comparison of TRC for location of applied region and arrangement

Figures 4-9, 4-10, and 4-11 illustrate the comparison analysis for 25x25, 20x20, and 15x15 mesh spacing, respectively, using the same TRC meshing spacing. The compared specimens are B1L1-MDR-25X25, B1L1-MTL-25X25, and B1L1-MAR-25X25, as shown in Figure 4-9. The results are as follows: specimen B1L1-MDR-25X25 has the same result as specimen B1L1-MTL-25X25, but specimen B1L1-MAR-25X25 has a 7.24 % decrease in ultimate load capacity.

The same procedure is repeated on Figures 4-10 and 4-11, but with 20x20 and 15x15 mesh spacing. The results are similar for Specimens B1L1-MDR-20X20 and B1L1-MTL-20X20, as well as for Specimens B1L1-MDR-15X15 and B1L1-MTL-15X15. However, the ultimate capacity decreased by 5.01 % and 7.07 %, respectively, for Specimens B1L1-MAR-20X20 and B1L1-MAR-15X15.

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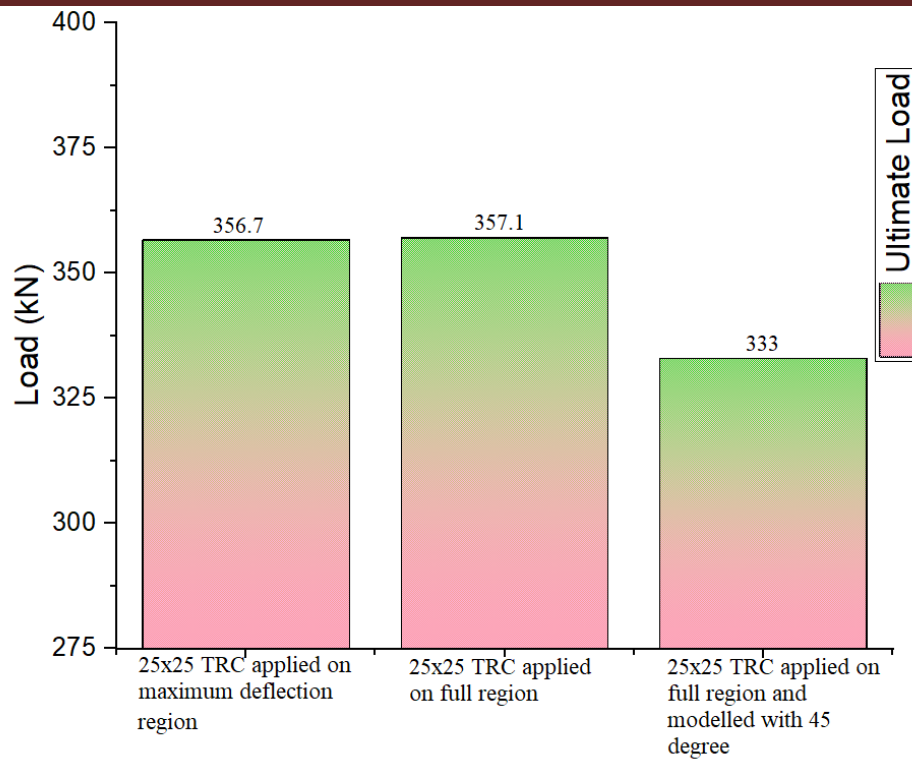


Figure 4-8 Ultimate load of different application region and different arrangement of TRC with 25x25 spacing

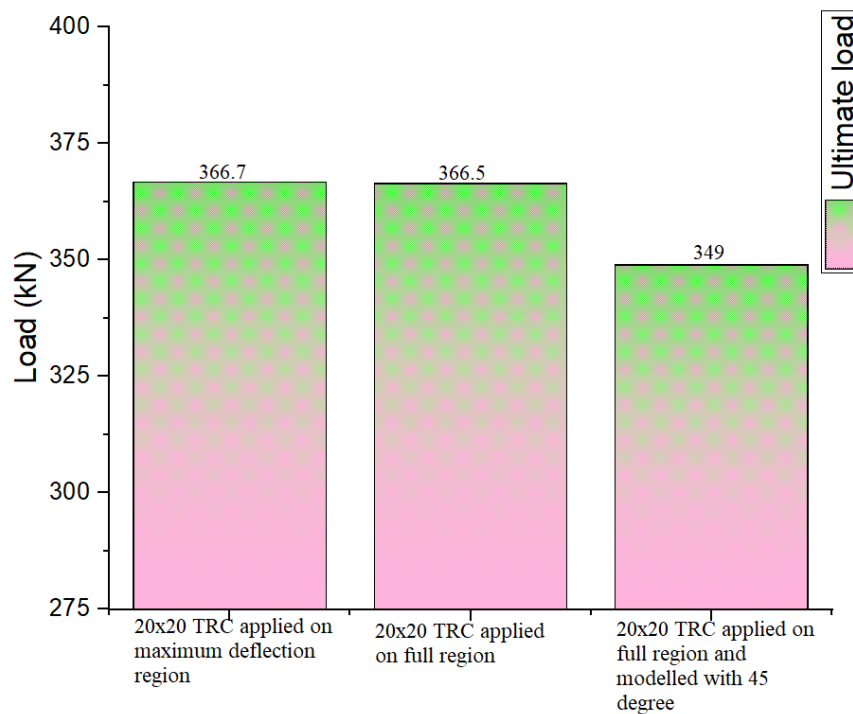


Figure 4-9 Ultimate load of different application region and different arrangement of TRC with 20x20 spacing

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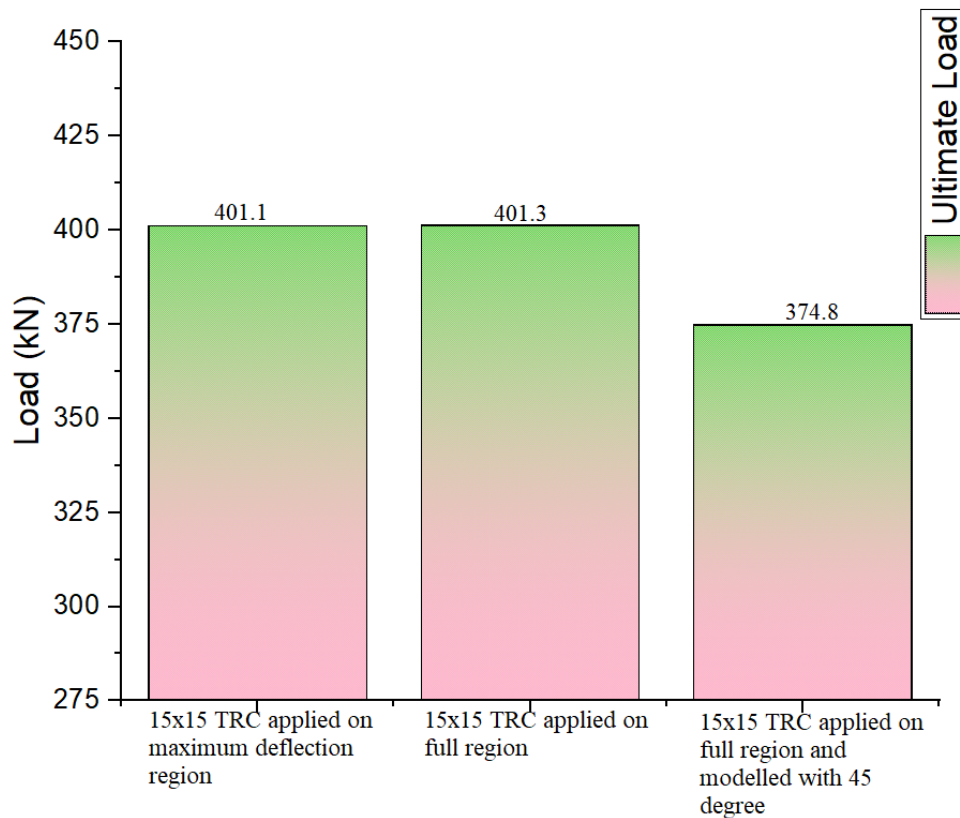


Figure 4-10 Ultimate load of different application region and different arrangement of TRC with 15x15 spacing

4.1.6 Comparative Analysis of Previous Studies

Nguyen and Ngo (2020) investigated the flexural capacity of beams strengthened with carbon textile reinforced concrete (TRC). The research focused on beams with a 25x25 mesh spacing, utilizing either one or two layers of TRC. For static loads, the strengthening led to a minimum enhancement of 25% and a maximum improvement of 43% compared to reference beams. Similarly, Giese et al. (2021) explored TRM-strengthened beams for static loads. Their findings revealed significant increases in ultimate load capacity: ranging from 30% to 62% for one, two, three, and four layers of TRM. This underscores TRC as an effective material for enhancing beam flexural capacity. Furthermore, from the result of this study TRC is also resilient against cyclic loads, exhibiting a remarkable 24% to 50% increase in ultimate capacity.

In summary, TRC demonstrate promise in structural strengthening material for static and cyclic load, making them valuable materials for civil engineering applications.

5.1 Conclusion

This study covered failure modes and the maximum load carrying capacity of a beam strengthened with TRC for cyclic loads. Using the FEA program ABAQUS, the model accuracy is calibrated and validated to provide a close match between the experimental data and the finite element model (Simulia 2022). Furthermore, a range of significant variables are taken into account, including textile fiber mesh layer, carbon textile mesh spacing, and textile carbon mesh arrangement. The following is the conclusion of the prepared result and discussions on these parameters:

When the mesh spacing is large, increasing the number of layers enhances the ultimate capacity of the structure. However, as the mesh spacing decreases, the influence of additional layers decreases. This is because closer mesh spacing reduces the interaction between layers, thereby limiting the distribution of load across them. Additionally, inclined mesh spacing alters the failure mode from sudden to gradual by effectively distributing stress throughout the structure. This gradual failure mode is beneficial as it provides more warning and reduces the risk of catastrophic collapse.

- Utilizing textile-reinforced concrete (TRC) to enhance beams subjected to cyclic loads proves to be an efficient and feasible approach, resulting in a substantial increase in load-carrying capacity up to 50% based on this investigation.
- It is more cost-effective to use MDR for the maximum deflection region rather than the entire region, as it exhibits behavior similar to that of MTL.
- For the MAR, MDR, and MTL one-layer parameters, a 15mm by 15mm mesh spacing increases load capacity by 40.24% compared to the control specimen. Similarly, a 25mm by 25mm mesh spacing increases load capacity by 24.72%, and a 20mm by 20mm mesh spacing increases it by 28.22%.

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- For the two spacing types, longitudinal and transverse, reducing the spacing along the longitudinal direction from 25mm to 20mm increases the load capacity from 24.86% to 28.15%. However, reducing the spacing in the transverse direction from 25mm to 20mm does not change the ultimate capacity.
- Although diagonal mesh arrangements (MAR) do not increase the ultimate capacity as much as MDR and MLT, they excel in promoting gradual failure. Unlike other configurations that tend to fail suddenly, diagonal mesh arrangements provide early warning signs before complete failure, enhancing safety. This gradual failure is highly recommended for its ability to offer these crucial safety indicators.

5.2 Recommendation

- Future research in this field should prioritize enhancing textile reinforcement to its maximum potential, investigating the durability of the strengthening system even under high-temperature conditions, and formulating design guidelines within the context of existing design frameworks.
- Since this study can only examine one type of material strength for both steel and concrete, more research on different grades of both materials is required.
- In order to fully understand the potential of TRC for strengthening construction, more research on many parameters is required.

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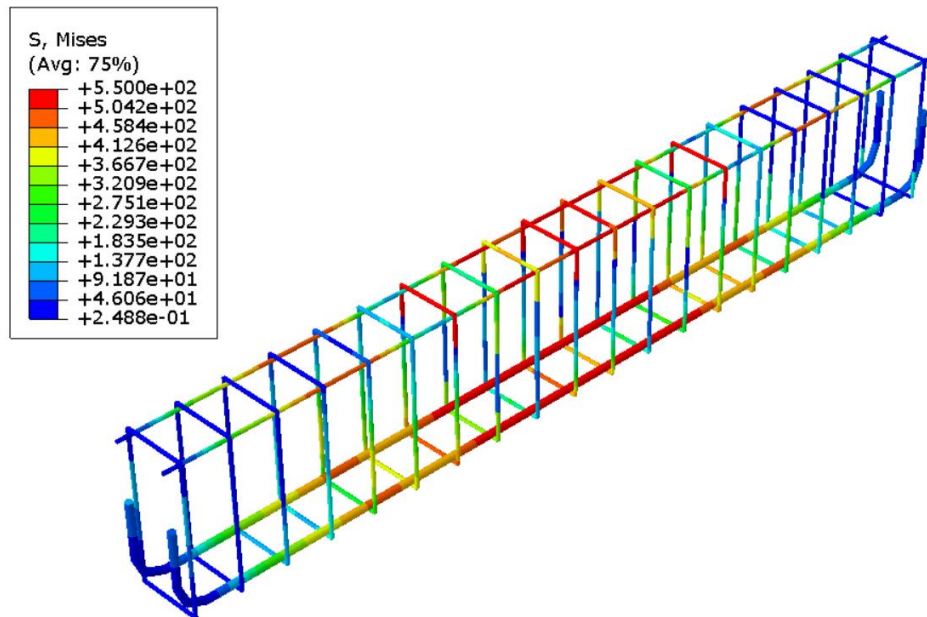
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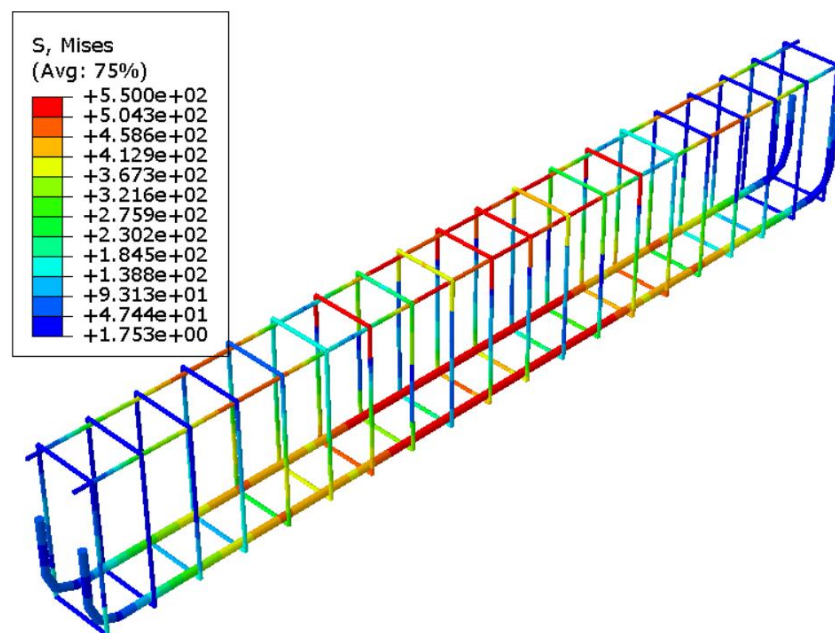
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APPENDIX

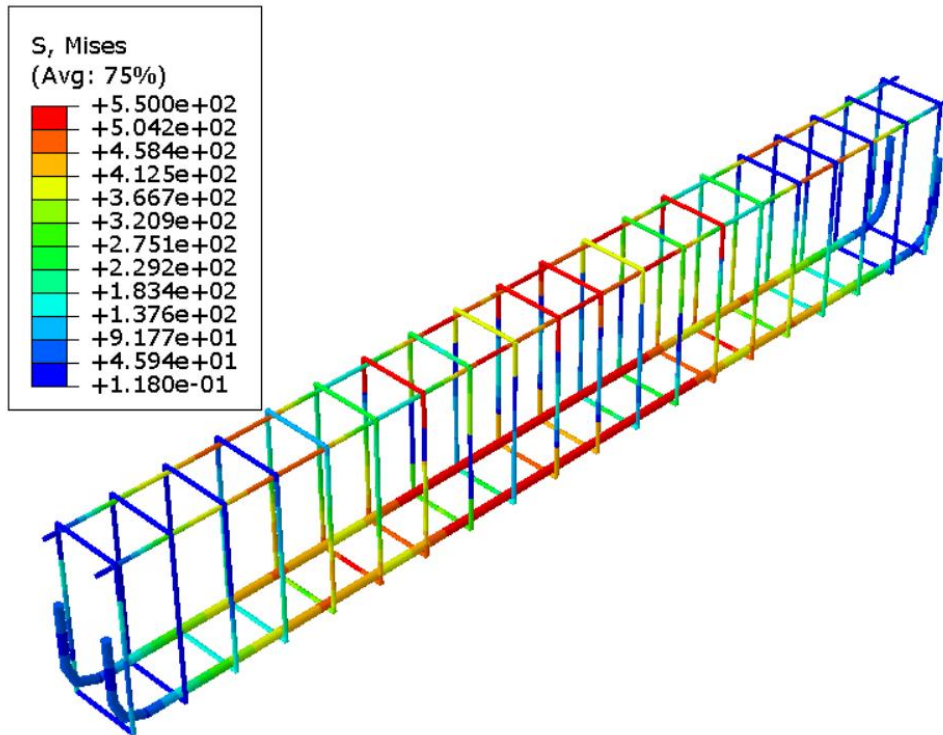


B1L1-MTL-25X25

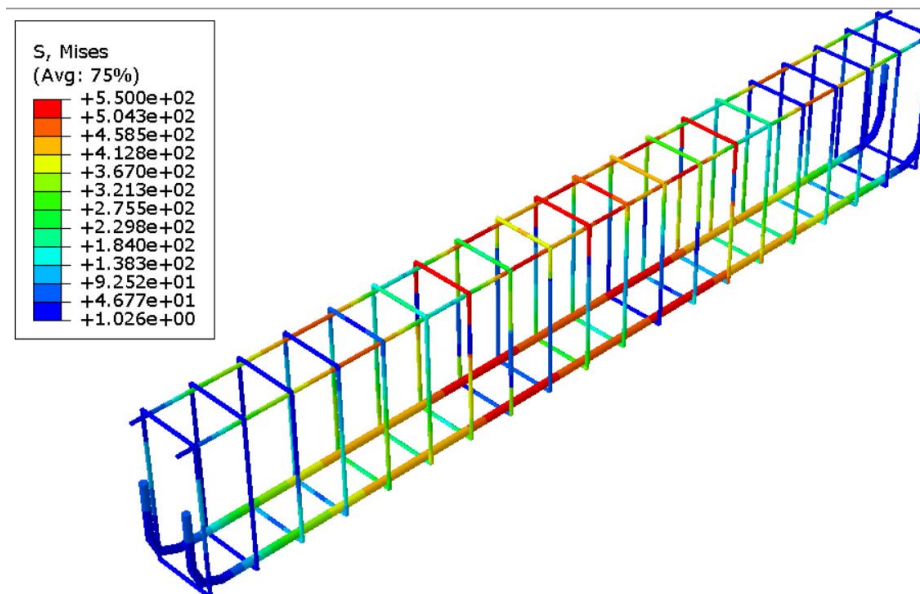


B1L1-MTL-20X20

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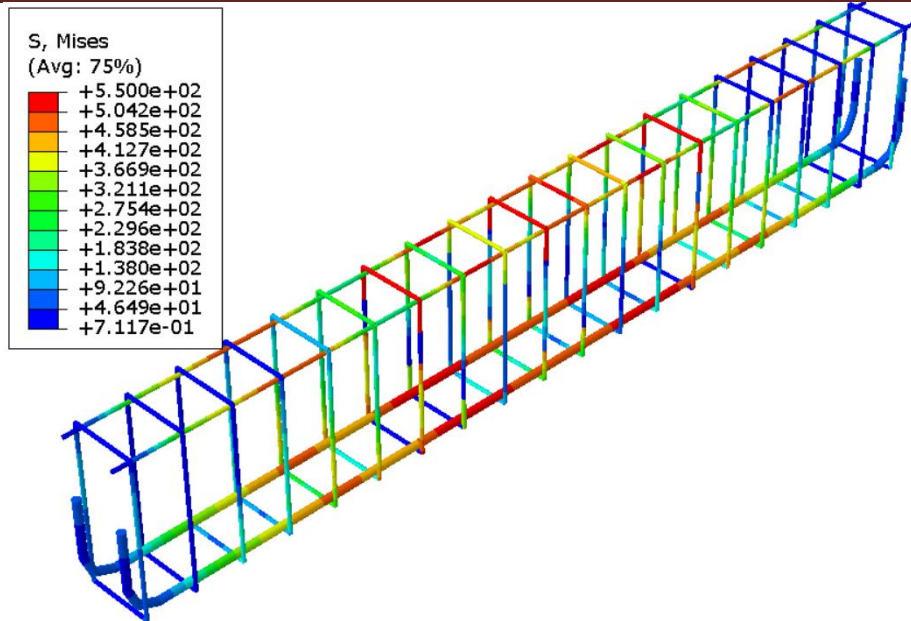


B1L1-MTL-15X15

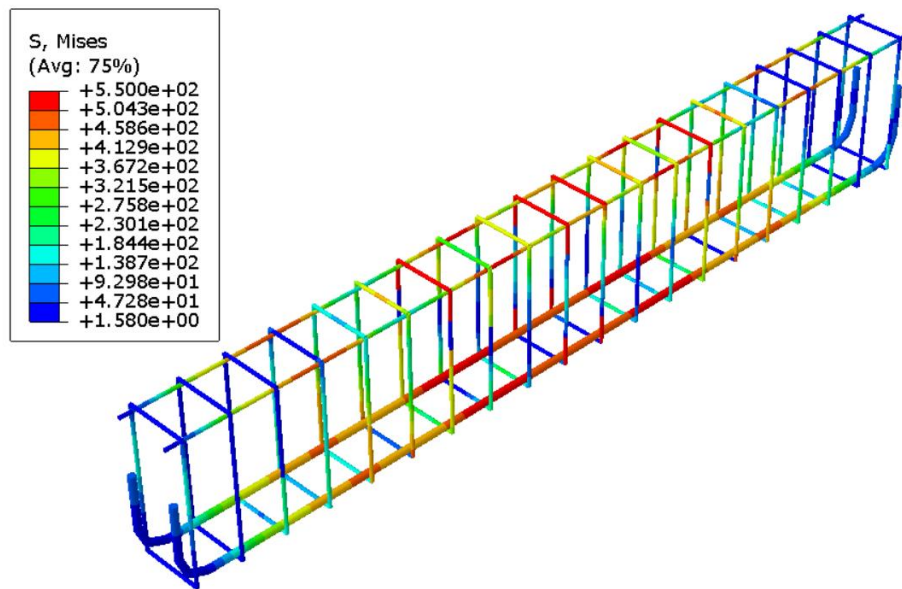


B1L1-MAR-25X25

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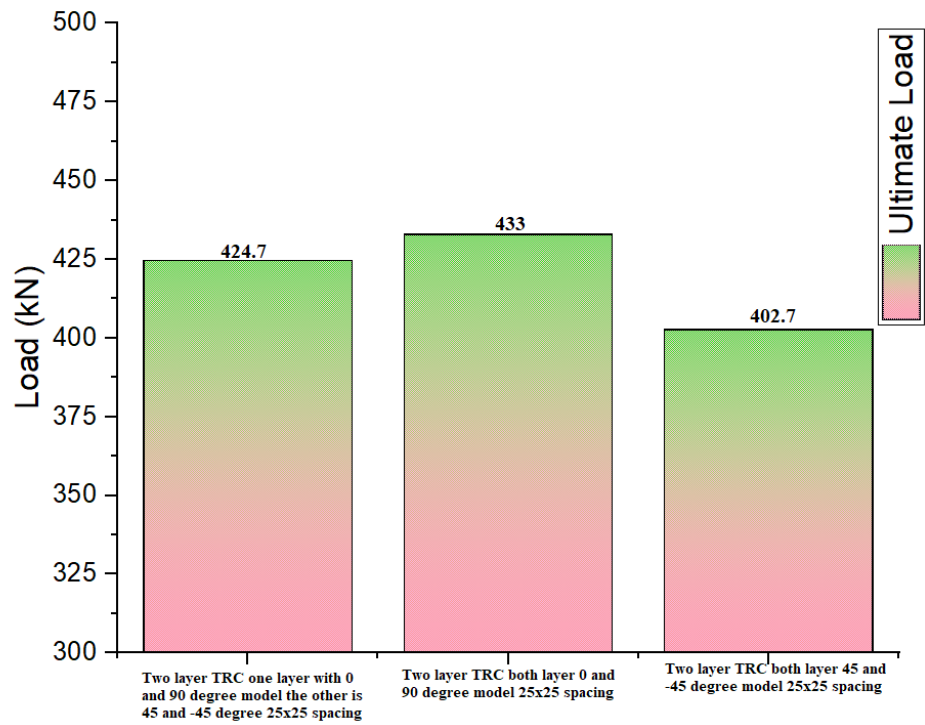
BIL1-MAR-20X20



BIL1-MAR-15X15

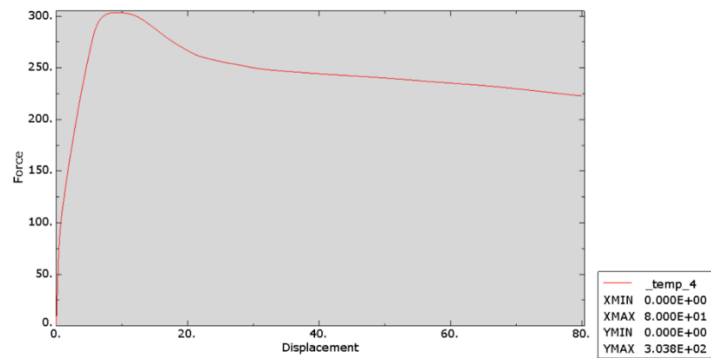
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Load vs displacement graph for two layers with different angle modeled with the same TRC mesh spacing



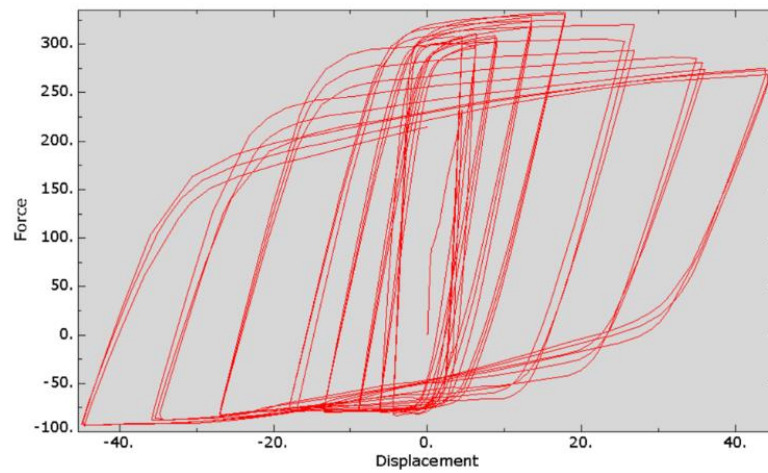
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Result for non-strength beam for validation with ACI formula

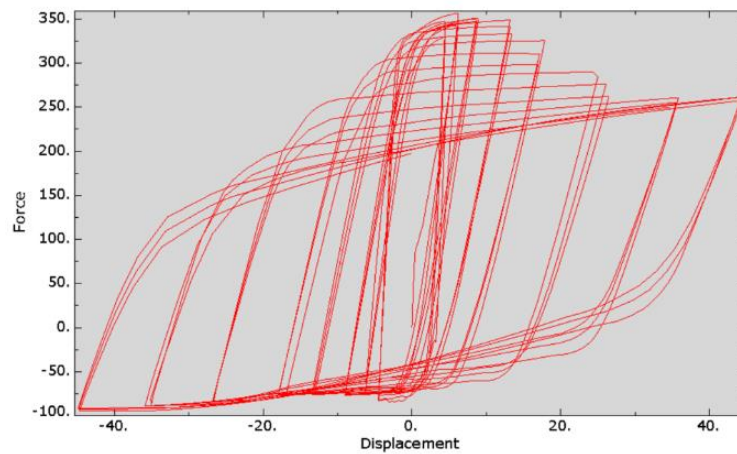


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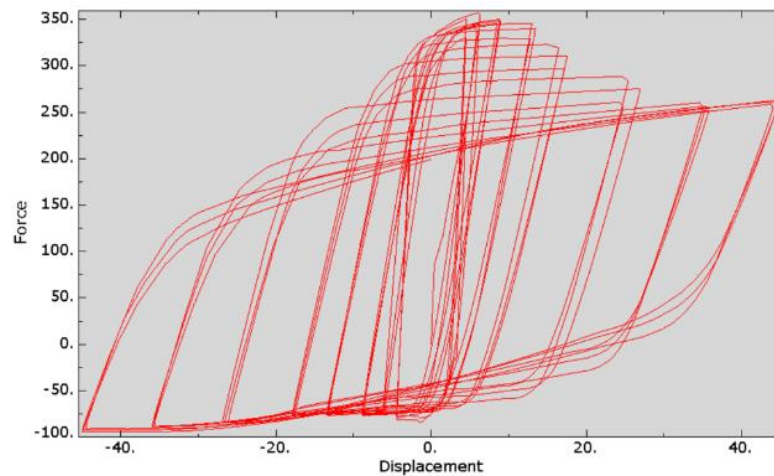
Hysteretic Behavior and Load-Carrying Capacities Sample



(a) B1L1-MAR-25-25



(b) B1L1-MDR-25-25



(c)

(c) B1L1-MTL-25-25

Sample load-displacement simulation path

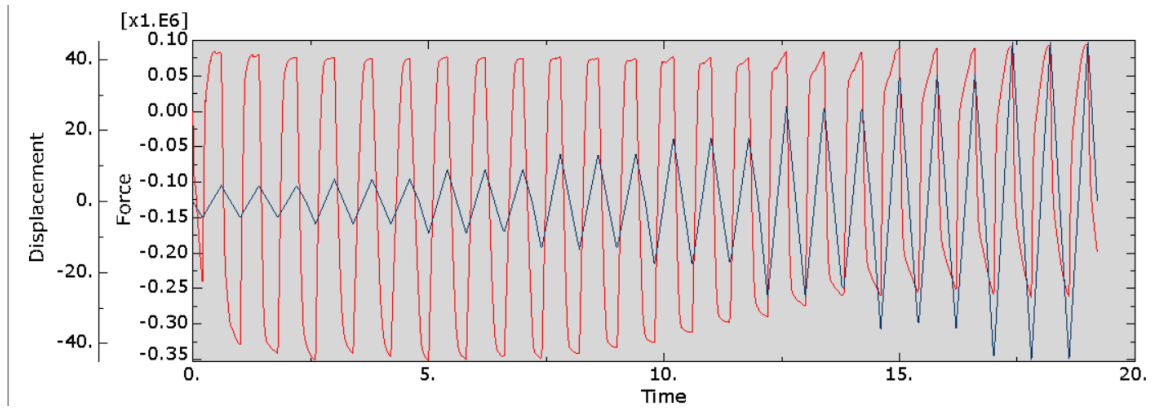


Figure 5-1 Sample load-displacement simulation path B1L1-MTL-25-25