Flexural Analysis of RC Beam Strengthened with Side Near Surface Mounted-CFRP Techniques

Mohd. Faisal Ameen Mohd. Ejaz[1], Prof. P.S. Lande [2]

[1]PG Student Department of Applied Mechanics, Government College of Engineering, Amravati, Maharashtra, India
[2] Associate Professor, Department of Applied Mechanics, Government College of Engineering, Amravati, Maharashtra, India

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Abstract - *In this paper an analytical and numerical study was conducted on RC beam strengthened with the side near surface mounted technique. Finite element-based software ANSYS was used to model the geometry of the beam. Thus, the result generated by the software is compared with manual hand calculations using mathematical and theoretical concepts given by Indian Standard and American standard codes. The results are validated by comparing analytical and experimental setups conducted by previous researchers. The result obtained shows a good agreement between the analytical and numerical results. This higher accuracy in the result is achieved by using Finite Element based software ANSYS. The result shows a significant reduction in the deflection of the RC beam strengthened with side near surface mounted CFRP rebar and strip. The comparative result of the SNSM and NSM methods is obtained and the flexural response of the beam is studied. Flexural strength, maximum shear, Strain energy, maximum stress, and strain are the parameters carried out in this study.*

Key Words**: Flexural strength, FRP, CFRP, SNSM, NSM, Stress, Strain energy, Shear.**

1.INTRODUCTION

Several factors might decrease the ultimate load-carrying capacity of concrete structures such as steel corrosion in an aggressive environment, design calculation errors, and poor mix design. Demolition and reconstructing deteriorated structures are uneconomical. Therefore, it is considered important to strengthen and improve the strength of deteriorated structures. Structural strengthening involves upgrading existing structures to enhance the strength of structural members, enabling them to carry additional loads or improving their performance under existing loads. There are various factors that can necessitate structural strengthening, including construction errors, changes in building codes, deterioration over time, modifications in building usage, or deficiencies in the original design. The near-surface mounted (NSM) fiber-reinforced polymer (FRP) technique is one of the methods used to strengthen reinforced concrete elements. The NSM technique involves bonding fiber-reinforced polymer materials, such as carbon or glass fibers, to the surface of existing concrete elements in order to enhance their structural capacity. The near-surface mounted (NSM) fiber-reinforced polymer (FRP) reinforcement technique has gained significant attention in both research and practical applications in recent years. Side near surface mounted fiber reinforced polymer technique is one of the several methods which are employed to improve reinforced concrete elements. The side near surface mounted (SNSM) technique has been proposed for strengthening RC beams. In SNSM method the CFRP rods were placed laterally, adjacent to the longitudinal steel bars inside precut grooves. CFRP; also called Carbon fiber-reinforced polymer, is a composite material made of a polymer matrix reinforced with fibres have been used. It is not prone to corrosion in hostile environment. The FRP bars are protected from detrimental mechanical impact due to their embedding within the concrete and the use of a binder agent. After the strengthening process is completed, the structural appearance of the elements is typically almost unchanged. With the development of fiber-reinforced polymer (FRP) composites, FRP reinforcement emerged as an innovative alternative to traditional steel reinforcement. FRP composites, embedded in a polymer matrix, possess high strength, low weight, and corrosion resistance. Research studies started to emerge, focusing on the application of these materials for the strengthening of concrete elements and structures. Due to high tensile strength FRP bars can resist larger loads. When it comes to designing strengthened elements, there may not be a specific code dedicated solely to this method. However, various models and guidelines have been developed by researchers and organizations to estimate the ultimate capacity and predict the failure behavior of strengthened elements. Some of the key data that should be collected during the inspection of deteriorated beams include:

- The main reinforcement ratio which plays a significant role in the effectiveness of strengthening measures, especially in reinforced concrete beams. If the existing element is already over-reinforced, the effectiveness of strengthening may be limited, as the failure mode may shift to compression failure rather than tension failure. According to the ACI (American Concrete Institute) Code, excessive reinforcement can lead to brittle failure modes and is generally not desirable.

- Determining the concrete cover thickness is essential to assess the feasibility of using the near-surface mounted (NSM) fiber-reinforced polymer (FRP) technique or any other reinforcement method. The concrete cover refers to the distance between the outer surface of the concrete element and the nearest layer of reinforcement. There are several methods to determine the concrete cover thickness Design calculations, Magnetic rebar locator (cover meter) test, Break-off test. By accurately determining the concrete cover thickness, we can ensure that there is sufficient cover to accommodate the NSM FRP reinforcement and meet the required design specifications for durability, fire resistance, and other structural considerations.

Several parameters can affect the design of near-surface mounted (NSM) fiber-reinforced polymer (FRP) reinforcement. These parameters play a crucial role in determining the effectiveness and performance of the strengthening system. Some of the key parameters include: Spacing between grooves, Concrete thickness between FRP and steel bars, Concrete compressive strength, , NSM FRP bars to groove perimeter, FRP to steel reinforcement ratio, Axial rigidity of fiber-reinforced polymer bars, The effect of the distance between beam edge and grooves. There are two major failures:

1. Failure by crushing of compressive concrete. Excessive loading can lead to concrete crushing failure, where the concrete in compression fails due to high compressive stresses.

2. Premature failure: the failure mode by debonding and concrete cover separation. Insufficient bond between the NSM FRP reinforcement and the surrounding concrete can lead to debonding failure, where the FRP reinforcement detaches from the concrete substrate.

The near-surface mounted (NSM) technique has been widely used for strengthening reinforced concrete (RC) beams and has shown improved resistance and ductility compared to traditional strengthening methods. However, to address certain limitations and further enhance the performance, the side near surface mounted (SNSM) technique has been proposed as an alternative approach for strengthening RC beams. The SNSM technique involves inserting fiber-reinforced polymer (FRP) reinforcement into the lateral sides of the beam, rather than the bottom part as in the NSM technique. The implementation process of SNSM is similar to NSM, with the difference being the placement of the FRP reinforcement.

This research aims to investigate the global behavior of reinforced concrete beams strengthened with CFRP rods circular in cross section compare with CFRP rectangular strips using the SNSM technique. The effects of the FRP cross sectional area and strengthening location CFRP rebar is to study.

CFRP strips, inserted in man-made groove, created at the tension sides of intact/degraded reinforced concrete beams, to improving/ recovering structural performance [18]. Inserting the CFRP strips of straight profile at the sides instead of the bottom surfaces of the strengthened beams.

RC beams strengthened by means of the SNSM technique using CFRP bars. Flexural strengthened beams are tested under four-point bending conditions. A different SNSM reinforcement type and ratio are used for the strengthening of the RC beams. The load carrying capacity, deflection and strain data are analyzed for the ductility, energy absorption capacity, failure modes and cracking behavior of the tested beams. The analytical models predict the flexural responses of the RC beams.

The nonlinear finite element analysis of reinforced concrete structural plays an important role on structure analysis. It can analyze the mechanical behavior of many complex configurations in engineering accurately, and describe crack formation and expansion, the appearance and process of structure breakage, and evaluate the ultimate bearing capacity and reliability of the structure, which are important in guiding the analysis, design and construction of practical engineering works. But the compilation of a more realistic three-dimensional finite element nonlinear analysis program of reinforced concrete is very complex, and the combination of reinforced concrete finite element theory and the relatively mature commercial finite element calculation software- ANSYS would be able to get twice the result with half the effort. ANSYS as a finite element based virtual stimulation software used as an analysis tool to determine desired parameters of RC beam. In modern structural engineering ANSYS structural analysis software is used to simulate computer models of structures, electronics, or machine components for analyzing the strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other attributes. The advanced nonlinear function of Structural module in ANSYS program can better simulate material and geometry nonlinear properties of large- scale complex structures, and its powerful functions before and after treatment for reinforced concrete structure model establishment bring great convenience. By using the methodology to generate model in ANSYS software we can obtain desire results for NSM technique. Various combination of NSM can be stimulated on ANSYS to get the optimum placement and orientation of NSM reinforcement. These results can be verified by analytical procedures given by standard codes. The comparative result of the SNSM and NSM methods is obtained and the flexural response of the beam is studied. Flexural strength, maximum shear, Strain energy, maximum stress, and strain are the parameters carried out in this study.

Literature Survey

Several researchers such as Al-Mahmoud F et al [5], Bilotta et al [6] and Sharaky et al [7], Mohammad Al-Zu'bi el et. [10], Saja Waleed Fathuldeen, Musab Aied Qissab [11], have studied the strengthening of concrete structures, bridges in particular, by using CFRP strengthening techniques Near-surface mounted carbon fiber polymer strengthening technique. Their experimental investigations have shown a significant increase in the bending capacity of RC beams. These studies have also proved that the most frequent failure mode for the NSM technique is failure by separation of the concrete covering.

On the other hand, Boulebd Adel, Ferhoune Noureddine et al [4], Mohammad Abdallah et al. [8], Md Akter Hosen et al [9],] studied the SNSM technique over NSM as an alternative one. Also, LI Xiaoran and Wang Yuanfeng et al. [16] First introduces finite element analysis theory of reinforced concrete by using ANSYS software. Peter Sabola,*, Sergej Priganca [1] calculated the Shear resistance with ACI 318-95 by superimposing the shear in concrete, shear in transverse steel stirrups and shear in FRP reinforcement, which according to formulation is limited by reaching the limit strain in the reinforcement which allows aggregate interlock or by possibility of occurrence debonding failure mode. Considers a limit condition of reaching the limit strain in the reinforcement which allows aggregate interlocking.

1.1 Objective of Study

This research aims to determine flexural response of RC beams using different cross section of CFRP as a reinforcement used in SNSM technique and to establish an analytical model and numerical simulation to compare the strengthening techniques. CFRP strips rectangular cross section and CFRP rod circular cross section are mounted at side and bottom of main reinforcement in tension zone of RC beam. Analysis results determined and compared parameters such as maximum deflection, maximum shear stress, equivalent elastic strain, strain energy and equivalent stress in RC beam.

2. SYSTEM DEVELOPEMENT

Five Under-reinforced concrete beams (125 × 250) are prepared and one of them is strengthened by inserting SNSM CFRP strips rectangular in cross section and another one with CFRP rod circular in cross section at straight profiles. They were created concrete covers of 25 mm for SNSM and 12mm for NSM. The comparative flexural response of beams was evaluated by applying four-point loading to the present beams. Strains and mid-span deflection of the beam is measured using (ANSYS FEM software). This software was chosen because of its precision when it comes to modeling strengthened RC beams. The dimensions of RC beams were as follows: 2300 mm long, a rectangular cross-section of 125 mm wide and 250 mm high, with a span between supports of 2000 mm. The reinforcement of a 2-12 mm steel bar in tensile and 2 -10 mm in compression is used. In order to avoid shear failure, a transverse reinforcement of 6 mm diameter spaced at 50 mm was placed along the RC beam. The five RC beams were reinforced according to Fig. 1, Fig-3 and Tab. 1, with CFRP rods 10 mm in diameter and a 15 x 5 mm strip of CFRP.

The total number of elements for the reference beam is 6033 with 26213 nodes. Element size is taken as 25mm for refinement of matrix mesh to achieve accuracy in output data. There are 740 nodes and 368 elements generated only for longitudinal steel reinforcement where as the stirrups steel takes 990 elements in meshing. The strengthening length of CFRP is considered throughout the length of the beam.

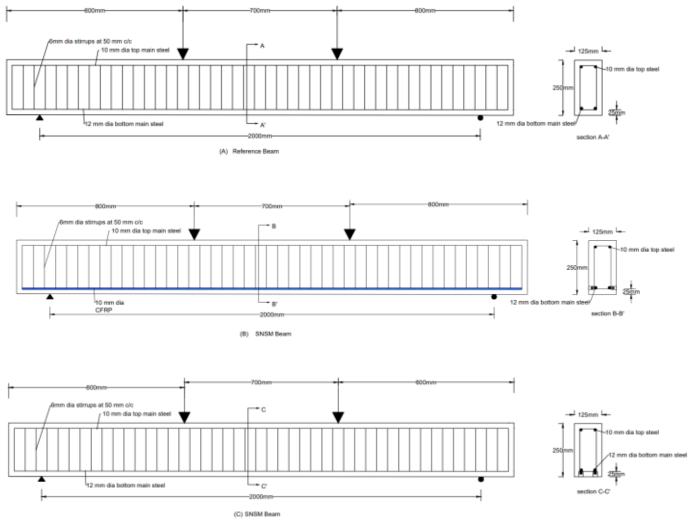

Fig -1: Test setup

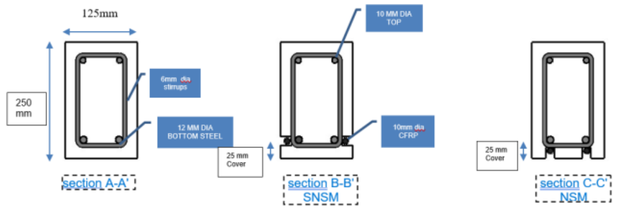

Fig -2: Cross Section of Test Beams

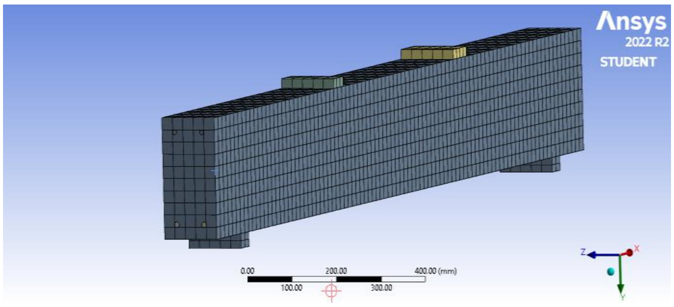

Fig -3: Beam model in ANSYS

Table -1: Details of the RC beams modeled

Details of RC beams modeled		
01	Referencing RC beam	REF
02	Strengthened RC beam using the SNSM technique with 10 mm diameter CFRP rods	SNSM - 10
03	Strengthened RC beam using the SNSM technique with 5 x 15 mm CFRP strip	SNSM - 5x15
04	Strengthened RC beam using the NSM technique with 10 mm diameter CFRP rods	NSM -10
05	Strengthened RC beam using the NSM technique with 5 x 15 mm CFRP strip	NSM - 5x15

Material properties:

The concrete has been modeled as a solid element having 41 MPa as a compressive Ultimate strength and 5 MPa as a Tensile Ultimate strength in ANSYS. Young's modules of concrete is considered to be 32 GPa , whereas the Poisson's Ratio is take as 0.18. In order to model the tension steel reinforcement material used as a HYSD steel having density 7850 Kg/m3 modulus of elasticity 200 GPa, Poisson's ratio 0.3,tensile yield strength of 550 MPa And compressive yield strength of 250 MPa. The stirrup steel having 300MPa as a tensile yield strength. CFRP has an elastic modulus of 290 GPa, and a tensile strength of 3100 MPa.

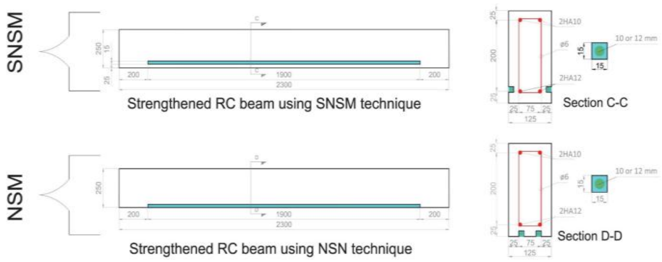

Fig -4: Reinforcement Details

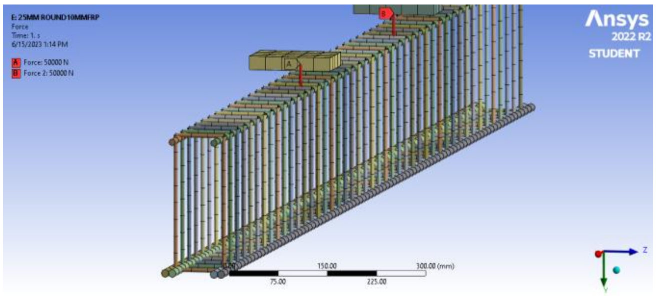

Fig -5: SNSM Reinforcement Detail

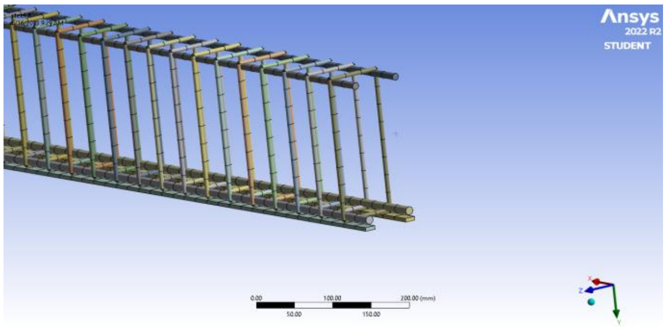

Fig -6: NSM reinforcement Detail

ANALYTICAL STUDY

Macaulay's Method, also known as the double integration method, is a mathematical technique used to determine the equation that describes the deflected shape of a beam. This method simplifies the process of finding the equation for beam deflection by enabling the use of a single equation for bending moment throughout the length of the beam.

Before Macaulay's paper in 1919, the equation for beam deflection could not be expressed in closed form, and different equations for bending moment were used in different regions of the beam. Macaulay's Method revolutionized this approach by providing a unified equation for bending moment along the entire length of the beam.

By applying Macaulay's Method in conjunction with the Euler-Bernoulli theory, the expression for bending moment can be integrated to obtain the equation for deflection. This integration process considers the properties of the beam, such as the flexural rigidity (EI), assuming it remains constant (i.e., the beam is prismatic).

If we assume the flexural member to be prismatic, then EI is constant and we can solve the general deflection equation as follows:

$$EI\frac{d^2y}{d_{x^2}} = M(x)$$

$$EI\frac{d_y}{d_x} = \int_0^L M(x)dx + C_\theta$$

$$EI\,y = \int_0^L\int_0^L M(x)dx + C_\theta x + C_\delta$$

- C_θ is the rotation (dy/dx) at $x = 0$ (i.e. the start of the flexural member);
- C_δ is the deflection, y, at $x = 0$.

principal stresses:

The value of maximum principal stress, also known as the major principal stress, occurs when the shear stress acting on one of the principal planes is zero. For biaxial (2D) stress conditions, there are two principal stresses: the maximum principal stress and the minimum principal stress.

The equation for the maximum principal stress, σ_1, can be expressed as follows:

$$\sigma 1= (\frac{\sigma x+\sigma y}{2})+ \sqrt{(\frac{\sigma x-\sigma y}{2})^2 - \tau xy^2}$$

Where:
σx and σy are the normal stresses in the x and y directions, respectively. τxy is the shear stress acting on the xy plane. This equation allows you to calculate the maximum principal stress when you know the normal stresses in the x and y directions and the shear stress on the xy plane.

The principal stresses represent the maximum and minimum values of normal stresses acting on the principal planes. They play a crucial role in analyzing the stress state of a material and understanding its failure behavior under different loading conditions.

Strain energy

Strain energy refers to the potential energy that is absorbed by a body as a result of deformation or strain. It is represented by the symbol "U". The strain energy absorbed by a material is equivalent to the work required to deform or strain the object. This relationship allows us to express the strain energy as the deformation work.

Mathematically, we can state:

Strain energy = Deformation work

In the case of a member with a constant cross-section and a gradually applied load, the strain energy can be calculated as the area under the load-extension curve. This area represents the work done or the energy absorbed by the material during the deformation process.

The specific equation for calculating the strain energy in such cases depends on the nature of the load and the material behavior. For linearly elastic materials, the strain energy can be calculated using the equation:

$$U = \frac{1}{2} \times P \times \delta L$$

or

$$U = \frac{P^2 L}{2AE}$$

Or

$$U = \frac{\sigma^2 V}{2E}$$

Where,
P = Load applied
δL = Change in length
A = Cross-sectional area
σ = Axial stress
L = Length of the component
V = Volume of component
E = Youngs modulus

For pure bending moment over the component with the constant cross-sectional area, the strain energy is given by,

$$U = \frac{M^2 L}{2EI}$$

Where,

M = Bending moment

L = Length of component

E = Modulus of elasticity

I = Moment of inertia

3. RESULTS AND DISCUSSIONS

The result of numerical study is illustrated in fig 6-10 which shows the force- maximum deflection, maximum shear stress, equivalent elastic strain , Strain Energy and Equivalent Stress

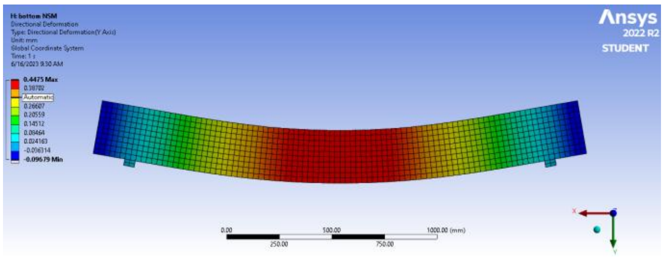

Fig -7: Deflection of Beam

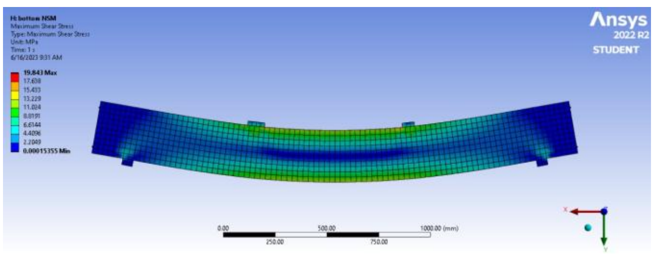

Fig -8: Maximum Shear Stress

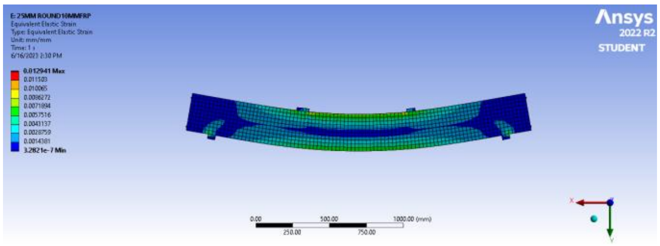

Fig -9: Equivalent Elastic Strain.

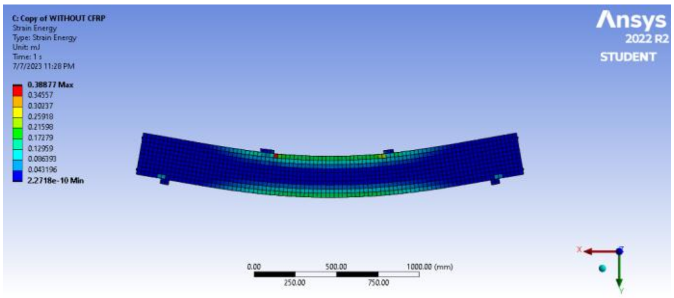

Fig -10: Strain Energy.

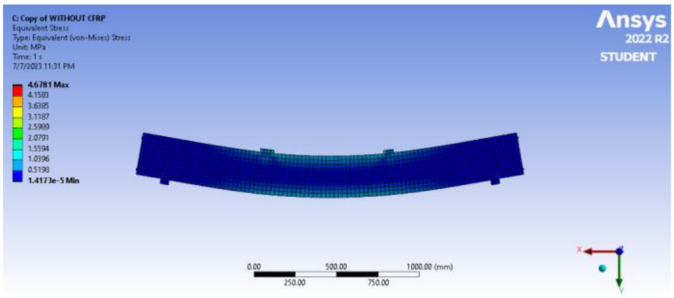

Fig -11: Equivalent Stress.

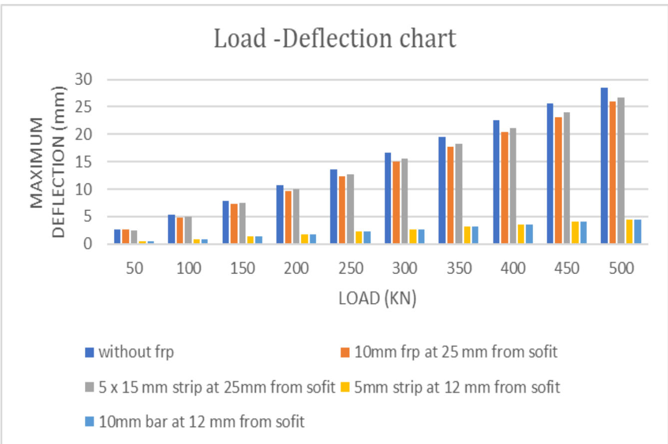

Chart -1: Load Deflection Graph

From the above load deflection chart, it is notice that the SNSM-10 technique resulted in a 27% reduction in deflection, while the NSM-10 technique achieved an 85% reduction. This indicates that both methods effectively increase the bending capacity of the RC beams.

The higher resistance to mid-span deflection observed in the NSM method is attributed to the increase in the internal lever arm of the tensile material in the reinforced section. The internal lever arm refers to the distance between the centroid of the tensile reinforcement and the neutral axis of the beam. By placing the reinforcement closer to the neutral axis, the NSM technique increases the lever arm, resulting in enhanced bending capacity and reduced deflection.

The impact of the strengthening rebar's cross-section on the deflection criteria is noted to be insignificant. This is because the same amount of tensile reinforcement area is applied for strengthening regardless of the cross-sectional shape of the rebar. The primary factor influencing deflection reduction is the change in lever arm resulting from the location of the strengthening reinforcement.

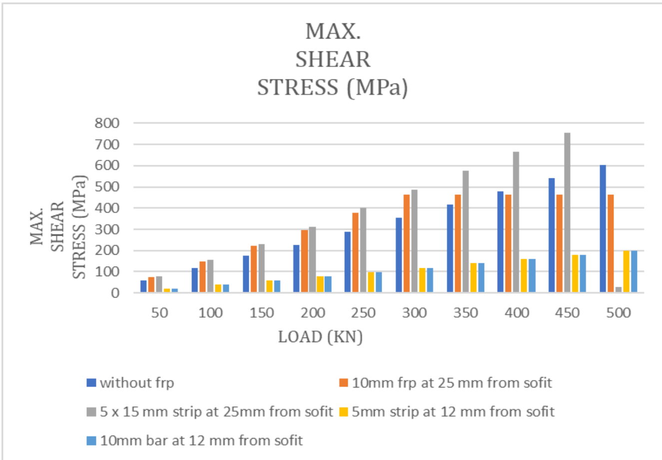

Chart -2: Comparison of Maximum Shear Stress

It is observed that the SNSM technique results in a significant increase in shear stress, with a 20% increase for SNSM-10 and a 25% increase for SNSM-5x15. On the other hand, the NSM method shows a reduction of 67% in shear stress for both NSM-10 and NSM-5x15.

The cross-sectional shape of the strengthening reinforcement has a notable impact on the shear capacity of the RC beam strengthened with the SNSM technique. The specific cross-sectional shape, such as the dimensions and configuration of the reinforcement, influences the shear resistance of the strengthened beam.

In the case of the SNSM technique, where the strengthening reinforcement is placed on the lateral sides of the beam, the geometry and distribution of the reinforcement play a significant role in enhancing the shear capacity. By increasing the cross-sectional area and optimizing the arrangement of the strengthening reinforcement, the SNSM technique effectively increases the shear resistance of the beam.

However, in the NSM method, where the strengthening reinforcement is placed on the bottom surface of the beam, the reduction of 67% in shear stress indicates that this method does not significantly contribute to the shear resistance capacity of the RC beam. The NSM technique primarily focuses on enhancing the flexural capacity and reducing deflection, but its impact on shear resistance is limited.

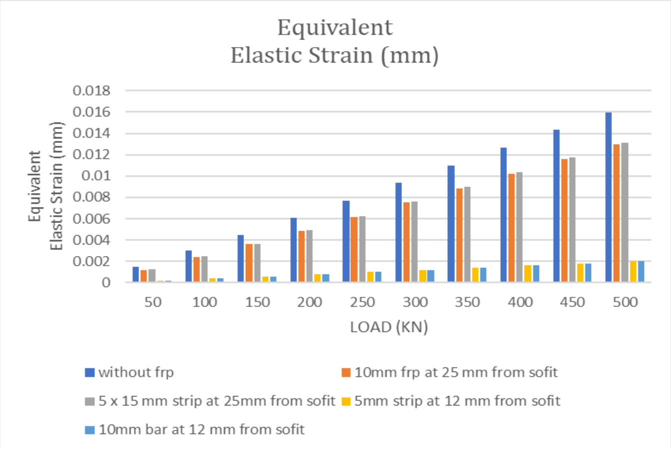

Chart -3: Equivalent Elastic Strain

A significant decrease in equivalent strain in reinforced concrete (RC) beams through the use of strengthening techniques, particularly the side near surface mounted (SNSM) and near surface mounted (NSM) methods.

Chart-3 indicates a 20% decrease in equivalent strain for SNSM-10 and SNSM 5X15 compared to the reference (REF) case. Additionally, there is an 86.5% decrease in strain for NSM-10 and NSM-5x15.

In the NSM method, the strengthening reinforcement is placed at the critical tensile location in the RC beam. This strategic placement significantly improves the tensile strength in flexure of the beam compared to the SNSM and REF cases. By introducing additional tensile reinforcement in the critical locations, the NSM method effectively reduces the equivalent strain and enhances the structural performance of the RC beam under flexural loads.

The decrease in equivalent strain reflects the improved resistance of the strengthened beams to deformation and indicates a more robust and stable structural response. Lower strain values suggest reduced material elongation and improved load distribution, resulting in enhanced structural integrity and performance.

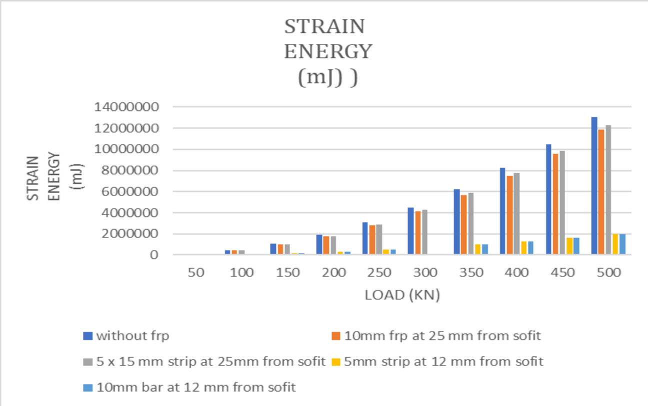

Chart -4: Strain Energy

Chart-4 indicates an exponential increase in strain energy. It shows a decrease of 7% to 8% in strain energy for SNSM-10 and SNSM-5x15 cases, while a significant reduction of 83% to 85% is observed for NSM-10 and NSM-5x15.

The decrease in strain energy in the SNSM-10 and SNSM-5x15 cases can be attributed to the decrease in ductility of the RC beam strengthened with CFRP reinforcement. The introduction of CFRP reinforcement increases the stiffness and strength of the beam, resulting in reduced ductility. As a result, less strain energy is absorbed by the beam during deformation.

On the other hand, the significant reduction in strain energy observed in the NSM-10 and NSM-5x15 cases can be attributed to the decrease in internal shear force. The presence of CFRP reinforcement in the NSM method reduces shear deformation in the beam, resulting in a decrease in strain energy.

It is important to note that strain energy is a measure of the energy absorbed by the structure during deformation. The decrease in strain energy suggests that the strengthened RC beam exhibits a more efficient and stiffer response, with less energy dissipated and absorbed by the structure.

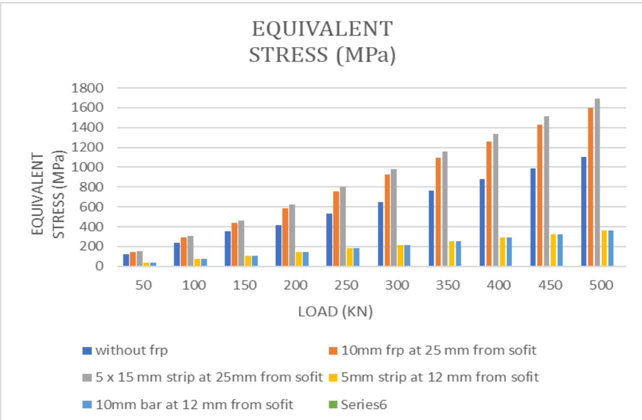

Chart -5: Equivalent Stress

The equivalent stress of the reinforced concrete (RC) beam is observed to increase by 43% for SNSM-10 and 52% for SNSM-5x15. This suggests a significant effect of the cross-sectional area of CFRP strengthening on the equivalent stress.

The increase in equivalent stress in the SNSM-10 and SNSM-5x15 cases can be attributed to the additional reinforcement provided by the CFRP strengthening. By increasing the cross-sectional area of the CFRP reinforcement, the beam's capacity to resist external loads is enhanced, resulting in higher equivalent stress.

In contrast, the NSM technique exhibits a highly reduced ductility, leading to a decrease in equivalent stress. The decreased ductility in the NSM technique causes a reduction of 67.3% compared to the reference (REF) case and 77.4% compared to the SNSM cases.

It is important to note that the effect of the cross-sectional area of CFRP reinforcement on the equivalent stress in the NSM technique is reported to be insignificant. This suggests that, in the NSM technique, other factors such as the placement of the reinforcement in critical tensile locations play a more dominant role in determining the equivalent stress.

The equivalent stress is a measure of the stress level experienced by the material and is an important consideration in assessing the structural behavior and performance. The changes in equivalent stress observed indicate the impact of strengthening techniques on the stress distribution and load-carrying capacity of the RC beam.

3. CONCLUSIONS

- Strengthening Effect: Both methods effectively enhance the strength and performance of reinforced concrete (RC) elements. The NSM method focuses on improving flexural strength and reducing deflection, while the SNSM method emphasizes flexural and shear capacity enhancements.

- Flexural Strength: The NSM method demonstrates higher resistance to mid-span deflection due to an increase in the internal lever arm of the tensile reinforcement. This leads to a significant improvement in the flexural strength of the RC beam.

- Shear Capacity: The SNSM method provides increased shear strength due to the strategic placement of the strengthening reinforcement on the lateral sides of the beam. This reinforcement configuration improves shear resistance and contributes to enhanced structural performance.

- Ductility: The NSM method exhibits reduced ductility, which can result in a decrease in strain energy and equivalent stress. This characteristic should be considered when evaluating the overall behavior and performance of the strengthened structure.

- Cross-Sectional Area: The cross-sectional area of the CFRP (Carbon Fiber-Reinforced Polymer) reinforcement in the SNSM method has a significant impact on the shear capacity and equivalent stress of the RC beam. Increasing the area can lead to improved performance and increased equivalent stress.

- Design Considerations: The choice between the NSM and SNSM methods depends on the specific structural requirements, load conditions, and design considerations of the project. Factors such as material properties, structural configuration, and the presence of critical locations (e.g., shear zones) should be carefully evaluated.

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