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# NUMERICAL MODELLING OF FLEXURAL BEHAVIOUR OF TEXTILE REINFORCED CONCRETE

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**Key words:** Non-linear finite element analysis, Monolithic bar, Matrix reinforcement interface,Bond-slip behavior

**Abstract.** Textile Reinforced Concrete (TRC) is an advanced composite material comprising of fine-grained concrete strengthened with continuous textile fibers. Due to its good load-bearing capacity and non-corrosive characteristics, TRC has gained significant attention for its sustainability and long-lasting properties. In this study, flexural behavior of TRC reinforced with 4 layers of textile is studied through numerical simulation using non-linear finite element framework. A total strain rotating crack model (smeared crack approach) is employed for matrix, multi-linear bond-slip relationship is used for matrix-textile interface and linear elastic constitutive model is used to simulate the flexure behaviour of TRC panels in the model. Numerical model accurately predicts the first crack load and the post crack hardening behavior due to textile reinforcement. Further parametric analysis have been performed by varying the number of layers of textile reinforcement.

## 1 INTRODUCTION

The building construction industry is witnessing a paradigm shift towards sustainable development. In this regard, new materials and technologies are emerging which can strengthen structural elements without creating sustainability issues. These advancements aim to foster an environmentally friendly and sustainable industry [1].

Textile reinforced concrete has been emerged as a sought-after material due to its exceptional sustainability and durability. Comprising fine-grained concrete and multi-axial textile fibers, Textile Reinforced Concrete (TRC) boasts a sophisticated composition. The textile used in TRC composed of filaments, adding complexity to its structure.

Researchers have performed several studies to understand the mechanical behavior of TRC [2-3]. Based on several experimental flexural, tensile and pull-out tests non-linearity of TRC has become evident. [4]. Simplified numerical models have been developed to have proper understanding of this non-linear behavior of TRC. Bond behavior between textile and fine grained concrete has been found to be the most significant factor influencing the mechanical performance of TRC in structural applications. It has been observed that, mortar cannot fully penetrate into the inner filaments of a yarn, leading to an uneven bond stress distribution in the composite [5]. To understand the bond-slip relationship between textile fabric and the matrix, researchers have developed various numerical and analytical models. Macro-scale models simplify the analysis by ignoring inhomogeneity inside the yarns and simulate the overall bond-behavior [6-7]. Complex numerical models such as meso [8-9], micro[10-11], and multiscale [12] approaches can describe the relative slip between inner and outer filaments in a yarn and quantify the bond-slip relationship more accurately.However, these numerical models are too iterative and computationally expensive to be used extensively.

In this present study, Textile reinforced concrete panel is numerically modeled to simulate it's flexural response in three point bending test. Different constitutive relationships for fine-grained concrete and textile reinforcements are used. Bond-slip relationship has been used to model the slip between the concrete and the textile reinforcement. Once the numerical model is validated with the experimental results, parametric analysis is performed to study the effect of variation of number of textile layers.

## 2 FINITE ELEMENT MODEL

Non-linear 2D finite element model is used for macro-scale numerical modelling. The commercial software DIANA is used to perform all the analysis [7]. The experimental results from three point bending test are used to validate the numerical results. The non-linear FEM is discussed in the following sections.

### 2.1 Model domain specifications

To simulate flexural response under three-point bending configuration, TRC panel of dimension $200 \times 400 \times 35$ mm is modeled in DIANA as shown in Figure 1. To avoid an early stage localized failure due to stress concentration below the load point as well as near the supports, a steel plate of dimension $50 \times 2 \times 200$ mm is used. Interface with high normal stiffness has been created between the load plate and the panel to avoid punching failure at the compression face of the textile reinforced concrete panel.

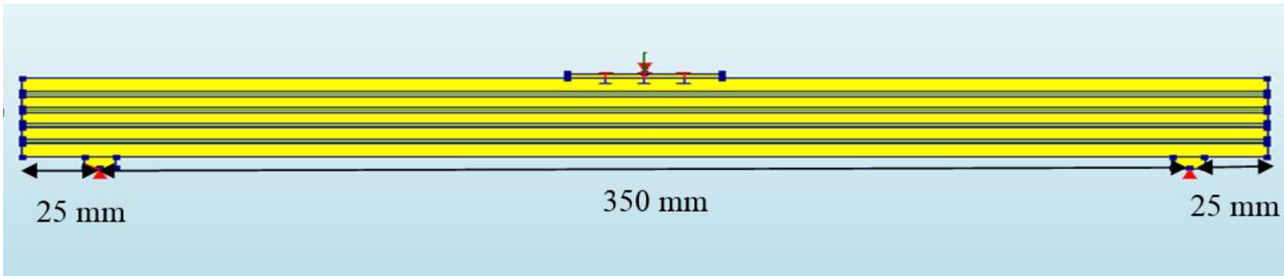



**Figure 1:** TRC under three point bending model in DIANA

### 2.2 Input material properties

In order to conduct a numerical simulation of the flexural behavior of TRC, various material properties must be provided as inputs in the finite element model. These properties encompass fine-grained concrete, textiles and the interface between the matrix and textile, and are detailed in Table 1.

Table 1: Properties of Fine-grained concrete

| **Material properties** | **Values** |
|---|---|
| Modulus of Elasticity | $30GPa$ |
| Poisson Ratio | 0.15 |
| 28 day Compressive strength | $50MPa$ |
| 28 day Tensile strength | $4.5MPa$ |
| Fracture Energy | $0.0828N/mm$ |
| 28 day flexural strength | $6.9Mpa$ |

The matrix has been reinforced with four layers of E-glass textile, and the specific properties of the textile have been outlined in Table 2. These essential inputs are crucial for accurately capturing and analyzing the flexural response of the TRC material in the simulation.

Table 2: Properties of E-glass textile

| **Properties of textile** | **Inputs** |
|---|---|
| Type of fibre | E-glass |
| No. Of textile layer | 4 |
| Type of weaving | Lenoweave |
| Grid Size | $16mm \times 16mm$ |
| Modulus of Elasticity | $70GPa$ |
| Diameter of textile | $0.9mm$ |
| Yield Stress | $1650Mpa$ |

### 2.3 Loading and boundary conditions

TRC panel under three-point bending configuration is modeled as shown in Figure 1. The entire panel has been considered along with the end supports i.e. hinge support at one end and roller support at another end. Self weight of the panel has been ignored as it is negligible. The loading was applied under displacement-control at the center in the top face of the panel until failure.

The total displacement of $5\ mm$ is applied in $500$ load-steps and secant method is used for iteration. The tolerances used are $0.01$ for force, $0.01$ for displacement and $0.001$ for energy[13]. Numerical solutions within these value are considered to be accurate and analysis reaches the next step. If the numerical solution does not converge, the analysis terminates.

### 2.4 Element types in the finite element model

After setting up the entire geometry the whole structure is meshed. The mesh size of $2.5mm$ with $4$ noded 2-D plane stress elements (Q8MEM) is used in the model for concrete as shown in Figure 2 [14].

For textile reinforcement, bond-slip reinforcement is chosen which creates an interface between matrix and textile and quantifies slip between them. 1-D bar elements is used to model the textile reinforcement. To introduce the relative slip between reinforcement and matrix, the bondslip reinforcement type is chosen in DIANA where the reinforcement bar is internally modeled as a truss or beam elements which is connected to matrix through interface element[14]. Four noded 2-D interface element L8IF (Figure 3) is chosen for the interface between the load plate and matrix . The finite elements used for different material in TRC composite is given in Table 3.

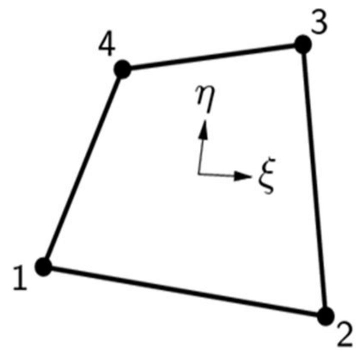
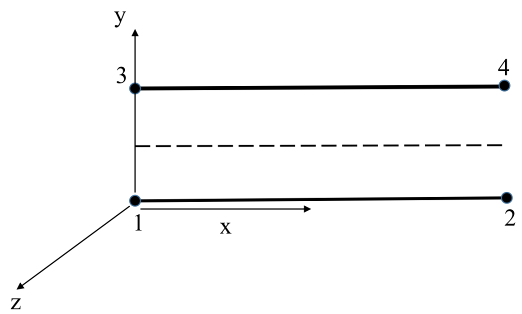


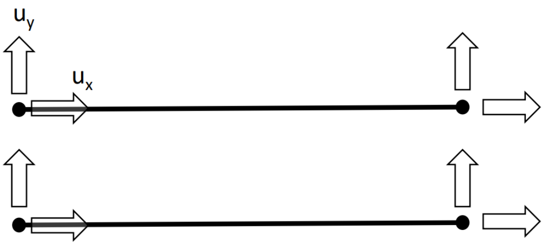

**Figure 2:** Element type-Q8MEM[14]

Table 3: Type of Elements

| **Geometry** | **Type of Element** |
|---|---|
| Panel | 2240 no of Q8MEM elements |
| Load plate | 20 no of Q8MEM elements |
| Support plate | 16 no of Q8MEM elements |
| Interface b/w load plate and panel | 20 no of L8IF elements |
| Textile Reinforcement | 640 no of Bar elements |




**(a)** Topology




**(b)** Displacement

**Figure 3:** Element type-L8IF

### 2.5 Material Models

#### 2.5.1 Fine grained concrete matrix

Total strain based rotating crack model (smeared crack approach) is considered to simulate the crack pattern of fine-grained concrete. In this material model crack direction continuously rotates with the principal directions of the strain vector [14]. The model includes tension softening and compressive behavior. Tension softening is modeled by non-linear Hordijk tension softening curve (Figure 4) available in DIANA and the compressive behavior is modeled by Thorenfeldt curve (Figure 5).

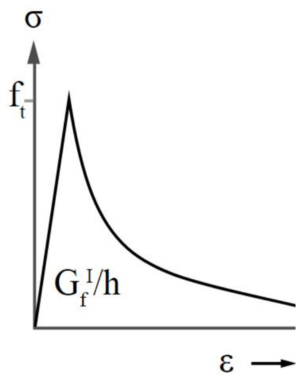



**Figure 4:** Hordijk curve for tension softening[14]

Tensile strength, compressive strength and young's modulus of matrix of concrete are used as per the experimental outcomes (given in Table 1). Mode-1 tensile fracture energy is calculated from an empirical formula given in Fib model code, 2010 [15]. The poisson ratio of concrete is taken as $0.15$. Crack band width is taken as the size of one element according to the crack band model [16].

At the lateral yarn location, there will be stress concentration which can cause crack formation in the interface zone between textile layers and matrix. To include this effect, the stiffness of the interface zone of $2\ mm$ thickness was reduced by $15\%$ and damage-based reduction mode is included to simulate the crack formations in this zone. The tensile strength of the matrix surrounding textile reinforcement is reduced to $3.825\ N/mm^2$ and mode-I tensile fracture energy of $0.07\ N/mm$ is considered in this zone.

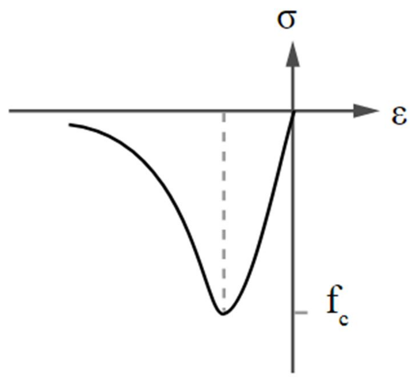



**Figure 5:** Thorenfeld curve for compressive behavior[14]

#### 2.5.2 Textile reinforcement

The textile fabric made of leno weave is used in this study. The textile fabric is in general made of yarns which are composed of a bunch of filaments stacked together as shown in Figure 6. To model the textile reinforcement macroscopically in the numerical framework, each layer of textile fabric is assumed to be bundled in a monolithic bar. This simplification is based on Aveston-Cooper-Kelly (ACK) analytical model [17] and it was adopted by Djmai et al. [18] for modelling TRC panel sandwich panels. The monolithic textile bar is considered to be homogeneous and the bond strength between the matrix and the bar is considered through the bond-slip relationship. The stress-strain curve for the monolithic bar is shown in figure 7.

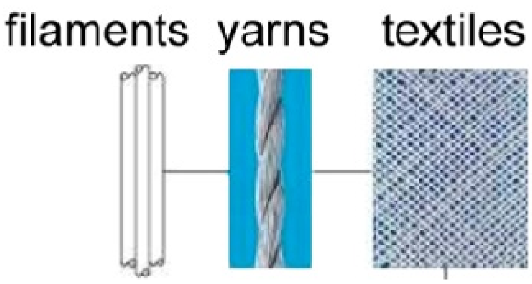



**Figure 6:** Filaments and yarns in textile[19]

In the monolithic textile bar, only the effect of longitudinal yarns is considered and the cross-sectional area of the bar is taken as the combined cross-sectional area of all the longitudinal yarns in particular textile layer of the TRC panel. Since we have four layers of textile reinforcement, four monolithic textile bars are used to model the TRC panel. In Figure 8 (a) the schematic of cross-section of TRC panel of width $dx$ with a single layer of the longitudinal textile fabric is shown and Figure 8 (b) shows the idealization of the textile layer into a monolithic bar with an equivalent contact perimeter, $C_{t,b}$ and cross-sectional area, $A_{t,b}$.

Both these parameters $C_{t,b}$ and $A_{t,b}$ are computed by multiplying the circular contact perimeter ( $C_f$) and cross-sectional area ($A_f$) respectively with the number of individual longitudinal yarns in one layer of the TRC panel. In our case, twelve numbers of longitudinal yarns per textile layer are present.

It should be noted that the effect of only longitudinal yarns is considered in the modeling as the panels are subjected to flexure and it has been reported in previous studies that the effect of cross-yarns is negligible [7]. Textile reinforcements are modeled with bond-slip reinforcements in DIANA to quantify the relative slip between the textile and matrix. The monolithic bar is assigned with linear elastic constitutive law with no limiting tensile strength to examine the appropriate failure mechanism.

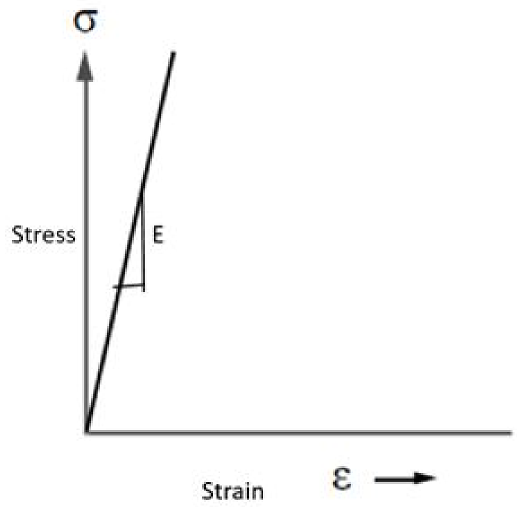



**Figure 7:** Constitutive law for textile

### 2.6 Bond-slip behavior

The bond behavior between matrix and yarn majorly governs the post-cracking strength of textile composites. The bond stress distribution depends on the extent of impregnation of concrete mortar into the textile.


**(a)** Schematic of a multi-yarn layer

**(b)** schematic of monolithic bar

**Figure 8:** Depiction of Monolithic bar

To model the bond-slip relation between the textile and concrete, a multi-linear model as shown in Figure 9 is considered. To acquire the multi-linear model parameters, the pullout test results of AR-glass from the literature are considered. While the AR glass has better resistivity toward alkali attack, it's mechanical response is similar to E-glass. Since there was no data available in the literature for E-glass, the bond-slip relation of AR-glass [20] is used and it is calibrated based on the experimental load-deflection response of TRC panel. The best-fit bond-slip curve after calibration that is used in the finite element model is shown in Figure 10.

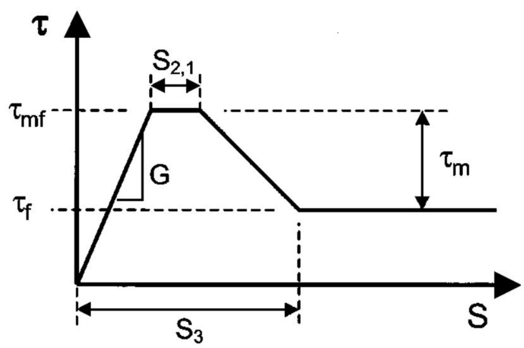



**Figure 9:** Bond slip behavior from literature[20]

## 3 FEA RESULTS

### 3.1 Model validation

The load-deflection response of TRC panels subjected to a three-point bending from numerical analysis is shown in Figure 11. Three distinct zones can be observed in the load-deflection response. In Zone 1, both concrete and textile take the load simultaneously through composite action. Between point O and $60\%$ of point A, the TRC composite shows linear-elastic behavior, thereafter nonlinearilty sets in. At point A, concrete matrix cracks and sudden drop is observed from point A to point B which is designated by zone 2. This drop is attributed to the softening in the concrete due to microcracking. In Zone 3, from point B to C, strain hardening is observed. In this zone, load is effectively transferred from concrete to textile reinforcement. Beyond point C, the textile gradually ruptures and the specimen fails. The comparison of the load-deflection curve from numerical analysis and experiment is shown in Figure 12. The initial stiffness of model and experimental curve exactly coincided and the first crack load at $A_1$ and $A$ matches well with $87\%$ accuracy. The drop after the first crack load and the subsequent strain-hardening is well captured by the model as per the experimental trend. The load and deflection values at the first crack load, the deflection at $0.8$ mm and the difference( in $\%$ ) is shown in Table 4.

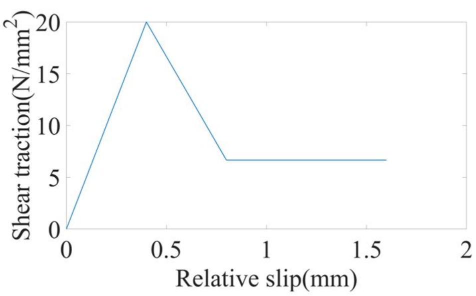



**Figure 10:** Calibrated Bond-slip

The finite element model predicts well upto 0.8 mm deflection. Some undulations are observed after that. However, from the design perspective, the model prediction holds good.

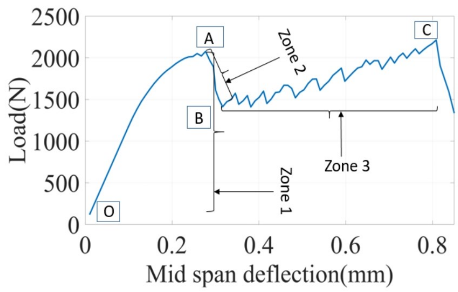



**Figure 11:** Load vs Deflection curve for simulation

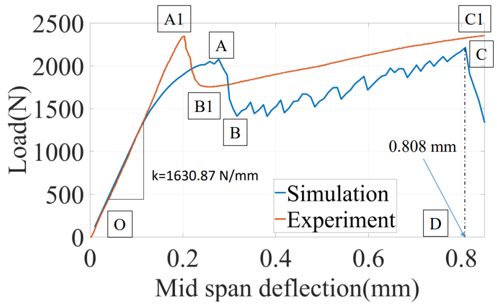



**Figure 12:** Experimental vs Simulation Results

Table 4: Comparison between results

| Results | Experimental | Numerical | Difference(%) |
|---|---|---|---|
| $1^{st}$ crack load (N) | 2273.47 | 2076.70 | 8.65 |
| Deflection at $1^{st}$ crack (mm) | 0.20 | 0.28 | 39.30 |
| load at $0.8mm$ deflection (N) | 2321.70 | 2213.49 | 4.66 |

### 3.2 Stress, strain contours at different stages

Non-linear analysis has been performed and the stress, strain contours at different stages of the load-deflection curve have been observed. At initial stage, concrete takes the major portion of the load hence load-deflection is linear in this region. At load $2076.70kN$, tensile stress gets localized near the bottom face and first crack occurs. Reinforcement stress and strain of concrete before and after first crack have been shown in the form of contours in Figure 13

After first crack stresses in the concrete around the crack is released and stress in textile gets increased gradually. Textile stress and the principal strain in concrete have been shown in the Figure 13. at the deflection of $0.808mm$.

## 4 PARAMETRIC ANALYSIS

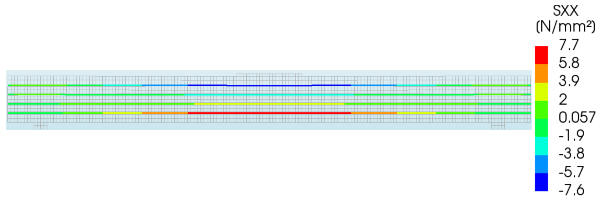
The parametric analysis is perfomed to understand the effect of number of textile layers on the flexural response of TRC panel.

### 4.1 Number of textile layers

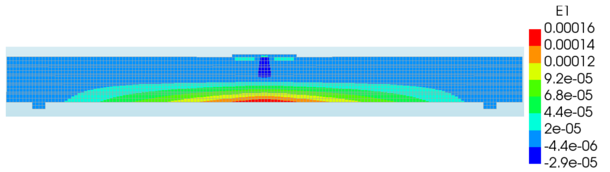
The TRC panel is initially modelled with four layers of textile fibre and the model is validated the experimental results. The number of textile layers governs the loading carrying capacity of TRC. The parameteric analysis is performed by reducing the number of layers from 4 to 1. The load-deflection response is shown in Figure 14. We observe that from 4 layer to 1 layer, the load carrying capacity drops to $43.05\%$ in the strain hardening peak load, while the initial first peak load remains the same. As the inital stiffness of load-deflection curve and the first crack load are nearly same, it can be concluded that there is hardly any effect of textile reinforcement in this zone as the major portion of the load is carried by the concrete itself.

As we decrease the number of layers, the drop from the first crack load decreases. Further the stiffness of the strain-hardening zone and the corresponding peak load also decreases. From 4-layer to 1-layer drop load decreases by $63\%$. Figure 15 illustrate the effect of textile layers at point A, B and C which corresponds to first crack load, drop load and peak load in strain hardening zone as described earlier.

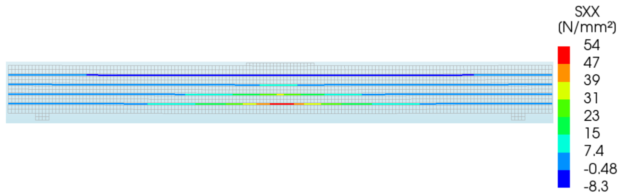
Strain hardening part in zone 3 is largely affected by the variation of textile layers. As we



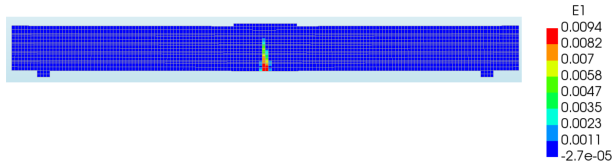

**(a)** Reinforcement stress at initial state



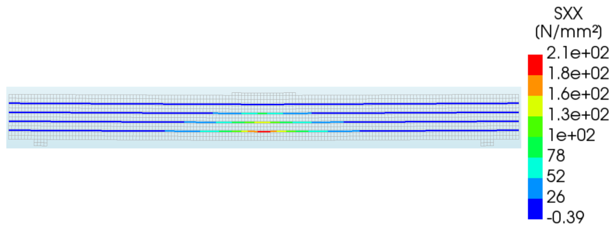

**(b)** Principal Strain of concrete at initial state



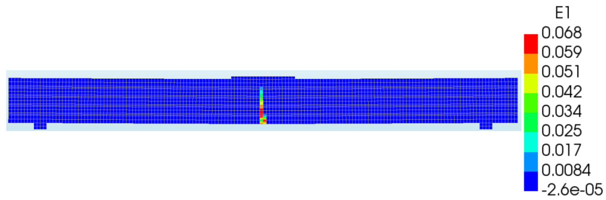

**(c)** Reinforcement stress after first crack




**(d)** Principal Strain of concrete after first crack




**(e)** Reinforcement stress at 0.808 mm deflection




**(f)** Principal Strain of concrete at 0.808 mm deflection

**Figure 13:** Stress, strain contours at different stages

increase the number of layers, the stiffness of the strain-hardening portion of the curve gets increased from k=$540.25 N/mm$ for 1 layer to k=$1630.87 N/mm$ for 4 layers.

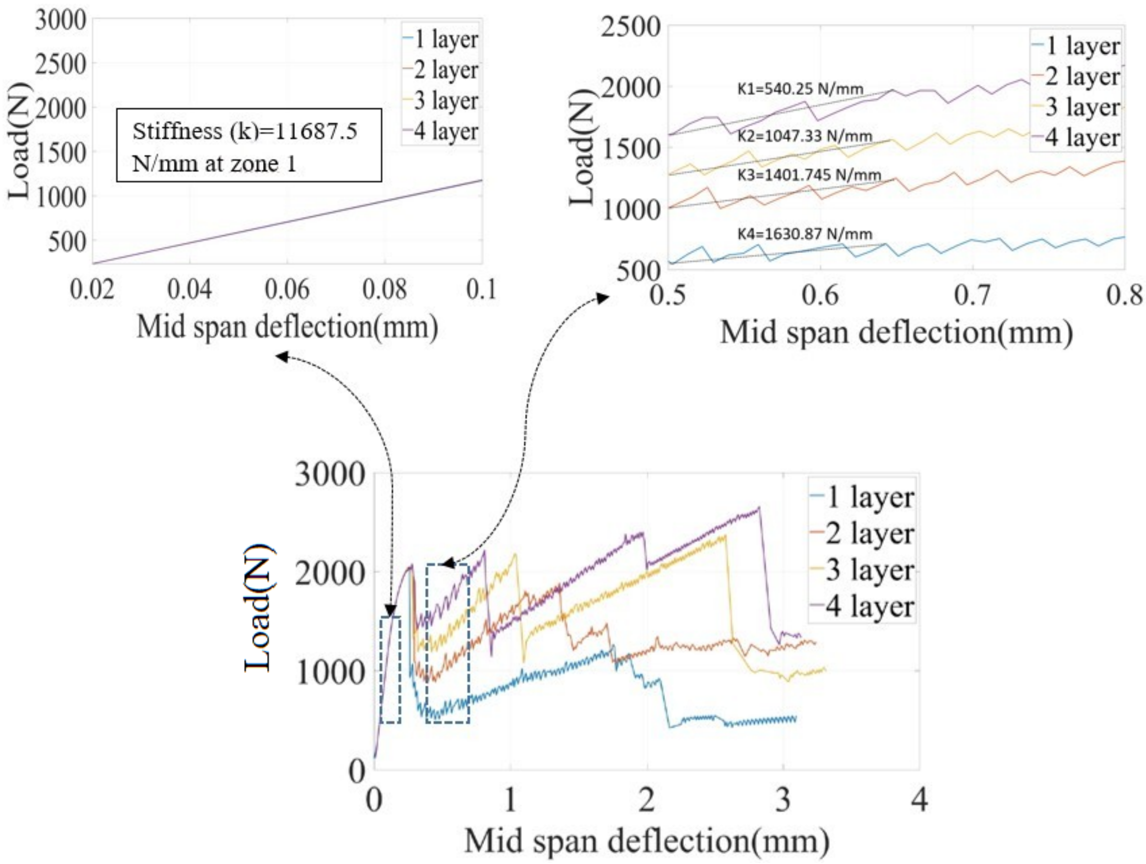



**Figure 14:** Load-deflection results for different layers

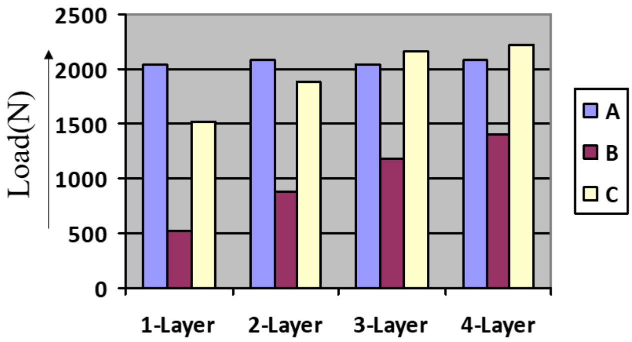



**Figure 15:** Load carrying capacity for different layers

## 5 CONCLUSION

In this study, a 2D macro-scale finite element model has been developed to demonstrate the flexure behavior of textile reinforced concrete. Experimentally obtained material properties are used as inputs in our model. To take into the effect of interaction between textile and matrix, bond-slip behavior has been incorporated as a model input from literature. Numerically obtained results found to be matching with the experimental results with an adequate degree of accuracy until the mid-span deflection of 0.808 mm. The Bond-slip relation found to be the most significant parameter which influences bond-behavior as well as the load-deflection response of Textile reinforced concrete .

To take into the effect of individual yarn in a textile fabric, three dimensional modelling could be implemented. Meso-scale models could be used to get more accurate results as it does not ignore the inhomogeneity inside the yarn. Finally, it would be beneficial to carry out pull-out test for E-glass textile fiber to get the bond-slip data more accurately.

## 6 ACKNOWLEDGEMENT

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