CUSTOM MATERIAL MODEL FOR SIMULATION OF FRP STRENGHTENED REINFORCED CONCRETE

Vladimir Vitanov [1]

Summary: The conventional earthquake resistant design of reinforced concrete structures advises use of shear walls as effective way to add earthquake resistance to the reinforced concrete frames. A problem arises with structures erected decades ago following design rules which are by today's standards obsolete, inadequate and inefficient. Major earthquake events from around the world have shown the design deficiencies of these structures by inducing extensive damages in the structural members. One of the newest and most promising strengthening techniques is the use of externally bonded FRP strips and sheets. Different modeling approaches have been employed in these designs. This paper presents a new material model that could be used to model FRP strengthened RC member. The formulated model is implemented into ANSYS. The model results are compared to the available experimental data for verification.

Keywords: FRP strengthening, ANSYS, reinforced concrete, numerical model

1. INTRODUCTION

The use of shear walls as a primary earthquake resistant mechanism is traditionally accepted and used in the aseismic design of RC structures. However, major earthquake events from around the world have shown the design deficiencies the older structures which do not meet the requirements of modern building codes and standards by inducing extensive damages in the structural members. Many of the old shear wall buildings are at risk of suffering damages from a major earthquake mostly due to their insufficient in-plane stiffness, flexural and shear strengths and ductility.

Various methods and techniques of seismic strengthening and repair of shear wall structures have been developed and tested in the last decades. Recently, state-of-the-art strengthening and retrofit techniques utilize externally bonded fiber reinforced polymer (FRP) composites, taking advantage of their unique properties such as high strength-to-weight ratio, chemical resistance, and ease of application, fast execution and low labor and overall costs.

The increased experimental research in this field initiated the first attempts to simulate the behavior of reinforced concrete strengthened with FRP composites using the finite element method. The majority of the numerical models of FRP strengthened RC

[1] Vladimir Vitanov, Phd, Ass.Prof., Ss.Ciryl and Methodius University – Skopje, Civil Engineering Faculty - Skopje, R.Macedonia, tel: ++389 2 3116066, e – mail: v.vitanov@gf.ukim.edu.mk

members with FEM use element overlaying, where one-, two- or even three dimensional elements (solid or layered) that represent the FRP material are placed over the concrete elements, either with (ex. Khomwan and Foster, [1]; Wong and Vecchio, [2]) or without (ex. Kheyroddin and Naderpour, [3]) interface elements used to model the adhesive material or the bond between the FRP and the concrete.

This paper presents an attempt to formulate a new material model which will simplify the modeling of FRP strengthened reinforced concrete members. The newly formulated material model is implemented into ANSYS [4] and tested using available experimental data.

2. MODEL FORMULATION

The material model presented here is based on the inelastic model for biaxial loading of reinforced concrete of Darwin and Pecknold [5] which was formulated to be used for structures that can be considered to be in the plane stress state(shear walls, beams, slabs, shear panels, shells, reactor containment vessels) in conjunction with the finite element method.

The concrete in this model is treated as incrementally linear, elastic material, which means that during each load increment the material is assumed to behave elastically. Furthermore, it is also considered to exhibit stress-induced orthotropic material behavior – the material is treated as isotropic before and orthotropic after a crack occurs. The constitutive relationship for incrementally linear orthotropic material in the principal axes of orthotropy directions can be written as:

$$d\boldsymbol{\sigma} = \mathbf{D}_C d\boldsymbol{\varepsilon} = \frac{1}{1-v^2}\begin{bmatrix} E_1 & v\sqrt{E_1E_2} & 0 \\ v\sqrt{E_1E_2} & E_2 & 0 \\ 0 & 0 & (1-v^2)G \end{bmatrix} \tag{1}$$

where $d\boldsymbol{\sigma}$ and $d\boldsymbol{\varepsilon}$ are stress and strain increment vectors, E_1 and E_2 are initial concrete stiffness modules in principal directions, $v = v_1v_2$ is the equivalent Poisson's ratio, $G = \frac{1}{4(1-v^2)}(E_1 + E_2 - 2v\sqrt{E_1E_2})$ is the shear modulus, and $\mathbf{D}_C$ is the concrete constitutive matrix in the principle directions. The concrete constitutive matrix can be transformed to global coordinates using:

$$\mathbf{D}'_C = \mathbf{T}^T \mathbf{D}_C \mathbf{T} \tag{2}$$

where $\mathbf{T}$ is the strain transformation matrix [6]. At the moment when the principle tensile stress exceeds the concrete tensile strength a "crack" forms perpendicular to the principle stress direction. The model adopts the fixed and "smeared crack" approach when modeling the cracking behavior of the concrete. This is modeled by reducing the values of E and v to zero. In order to keep track of the material degradation, the

concept of "equivalent uniaxial strain" is used. It allows derivation of the actual biaxial stress-strain curves from uniaxial curves. The monotonic loading uniaxial stress-strain curves of concrete in compression are modeled using [7]:

$$\sigma_i = \frac{\varepsilon_{ui} \cdot E_0}{1 + \left(\dfrac{E_0}{E_s} - 2\right)\dfrac{\varepsilon_{ui}}{\varepsilon_{ci}} + \left(\dfrac{\varepsilon_{ui}}{\varepsilon_{ci}}\right)^2} \tag{3}$$

where E_0 is the tangent modulus of elasticity at zero stress, E_s is the secant modulus at the point of maximum compressive stress σ_{ci}, and ε_{ci} is the equivalent uniaxial strain at the maximum compressive stress. The value for the maximum compressive stress σ_{ci}, is determined using the biaxial strength envelope suggested by Kupfer and Gerstle [8].

Two different approaches in modeling of the reinforcing steel are generally adopted - discrete or distributed. The model presented here considers the reinforcing steel to be distributed, or "smeared", throughout the concrete. A simple, bilinear model with strain hardening is adopted for the stress-strain behavior of the steel. The constitutive matrix of the steel defined in the direction of the reinforcing bars is

$$\mathbf{D}_S = p_S \begin{bmatrix} E_{Steel} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4}$$

with E_{Steel} the tangent stiffness of the steel and p_S the reinforcing ratio. Depending on the stress level in the steel, E_{Steel} can be either equal to the initial steel stiffness E_S or reduced by a strain hardening stiffness ratio δ. Before using it in the composite material matrix, $\mathbf{D}_S$ is transformed to the global coordinates using the strain transformation matrix $\mathbf{T}$ as in Eq.(2).

The influence of the FRP strengthening is accounted for in the same fashion as the reinforcing steel. The material is treated as distributed, or "smeared" throughout the concrete. Its material behavior is assumed to be elastic-brittle, having abrupt failure after reaching its maximal strength (Fig. 1). It is also capable of transmitting only tension stresses. The constitutive matrix of the FRP defined in the direction of the FRP fibers is therefore:

$$\mathbf{D}_F = p_F \begin{bmatrix} E_F & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5}$$

with E_F the tangent stiffness of the FRP and p_F the "strengthening" ratio. Again, before using it in the composite material matrix $\mathbf{D}_F$ must also transformed to the global coordinates using the strain transformation matrix $\mathbf{T}$ as in Eq.(2).
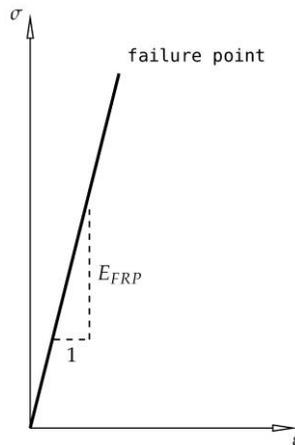

Figure 1. Stress-Strain Curve of FRP Adopted in the Model

After defining the constitutive matrices of the constituent materials, the constitutive matrix of the composite material in the global coordinates is obtained by their summation:

$$\mathbf{D}' = \mathbf{D}'_C + \sum_{i=1}^{n} \mathbf{D}'_{S,i} + \sum_{i=1}^{m} \mathbf{D}'_{F,i} \tag{6}$$

where $\mathbf{D}'$, $\mathbf{D}'_C$, $\mathbf{D}'_S$ and $\mathbf{D}'_F$ are the constitutive matrices if the composite material, concrete, steel and FRP in global coordinates, respectively, n is the number of different reinforcing steels and m is the number of different FRPs used for strengthening.

3. VERIFICATION

The proposed model was implemented into the general purpose finite element program ANSYS, using the supplied usermat.f Fortran subroutine. This program implementation was used to verify the previously described model by comparing its results to experimental data available in the literature. Here, the results of the numerical model and its ANSYS implementation are compared to the results of the experimental tests carried out by Garden and Hollaway [9].

Garden and Hollaway performed four-point bending test on a 1 m long RC beams strengthened with CFRP. The CFRP plates with a thickness of 0.82 mm were attached to the soffit of the beam. The beam with designation $3_{U,1.0m}$ was analyzed here (Fig.2). Three different section or parts of the beam (top, bottom and middle) were defined in

order to accommodate the steel reinforcement and FRP strengthening placement in the actual beam cross-section (Fig 3). Only half of the beam was modeled making use of the beam and load symmetry.
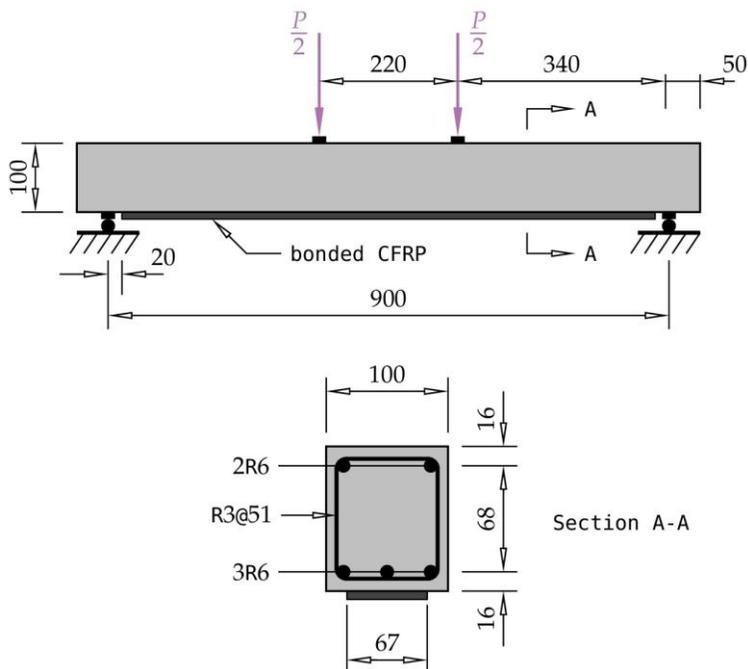

Figure 2. Test specimen $3_{U,1.0m}$

The concrete was modeled using: uniaxial compressive strength of 43 MPA, uniaxial tensile strength of 3 MPa, initial modulus of elasticity of 40 GPa, strain at the peak stress for the real uniaxial curve of -0.33% and Poisson ratio of 0.2. This concrete material properties were applied to all of the finite elements. The Steel was model using: yield strength of 350 MPa, modulus of elasticity of 215 GPA, and strain hardening stiffness ratio of 0. The reinforcement ration was 1.7% for the stirrups (applied to all of the finite elements) and 2.7% for the longitudinal reinforcement (applied only to finite elements of the top and bottom part of the beam – colored as green and orange in Fig.3).
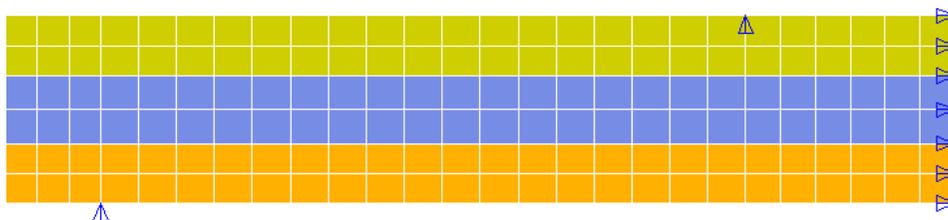

Figure 3. FEM model of the test specimen $3_{U,1.0m}$, utilizing the model and load symmetry
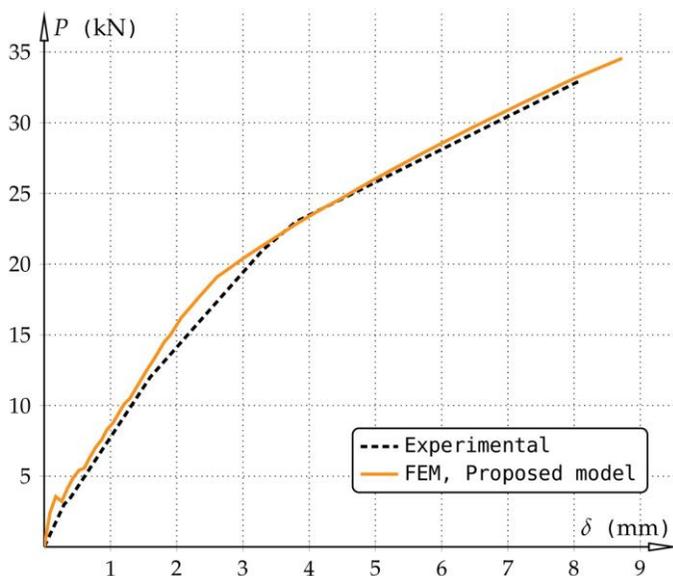
Figure 4. Load versus mid-span deflection of the test specimen 3$_{U,1.0m}$

The FRP strengthening was modeled using the values of 110 GPa for the modulus of elasticity, 1.2% for the ultimate strain and 1.7% strengthening ratio (applied to the finite elements of the bottom part of the beam – colored orange in Fig.3).

Displacement control analysis was performed by applying a series of vertical displacements at the point where the load was applied in the actual test.

The resulting load-deflection curve is shown in the Fig. 4. The figure shows that, while the beam stiffness in the initial load increments was apparently overestimated, the rest of the curve stays very close to the shape of the experimental curve.

4. SUMMARY AND CONCLUSION

An effort was made to formulate a simple and effective material model that could successfully simulate the behavior of RC members in plane stress, strengthened with externally bonded FRP. The model adopts the basic approaches and techniques of an earlier and widely adopted and used RC model and extends it to include the additional material component. The proposed model is subsequently implemented into the code of the general finite element method program ANSYS as a user material model in order to test its results against the available experimental data.

The result of the analysis of a RC beam strengthened by externally bonded FRP strips on the soffit using the newly formulated model was presented. It was compared with the experimentally obtained data. The presented result leads to a conclusion that the proposed model is able to correctly simulate the behavior of the RC beams strengthened with FRP, subjected to monotonic loading. Its ANSYS implementation facilitates its use in both research as well as in practical purposes.

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МАТЕРИЈАЛНИ МОДЕЛ ЗА СИМУЛАЦИЈУ АРМИРАНОГ БЕТОНА ОЈАЧАНОГ FRP-ОМ

Резиме: Рутинско димензионисање сеизмички отпорних армирано-бетонских конструкција тражи примену смичућих зидова као ефикасан начин додавања отпорности армирано-бетонским рамовским системима. Међутим, проблем настаје код конструкција које су изграђене пре више деценија и када се прате актуелни прорачунски захтеви, који их класификују као неодговарајуће. Јачи земљотреси широм света су показали недостатке димензионисања ових конструкција наношењем значајних оштећења носивим елементима. Једна од најновијих и обећавајућих техника ојачања је примена спољних спојених FRP трака и плахта. Различити приступи моделирања су примењени у овим истраживањима, а овај рад представља нови материјални модел који се може применити за моделирање армирано-бетонских елемената ојачаних FRP-ом и који је примењен у програму ANSYS. За потребе верификације, резултати из модела су упоређени са расположивим експерименталним подацима.

Кључне речи: FRP ојачање, ANSYS, армирани бетон, нумерички модел