Mühendislik Bilimleri ve Tasarım Dergisi
11(4), 1496 – 1507, 2023
e-ISSN: 1308-6693

Journal of Engineering Sciences and Design
DOI: 10.21923/jesd.1215389

Araştırma Makalesi | Research Article

MODELING THE BENDING BEHAVIOR OF STEEL FIBER-REINFORCED CONCRETE BEAMS

Mehmet Alper ÇANKAYA [1] *

[1] İzmir Kâtip Çelebi University, Faculty of Engineering and Architecture, Civil Engineering Department, İzmir, Türkiye

Keywords

Steel Fiber-Reinforced Concrete (SFRC), Analytical Modeling of Steel Fiber Contribution, Finite Element Analysis, Bending Behavior of SFRC Beams.

Abstract

In this study, modeling of the bending behavior of large-scale steel fiber-reinforced concrete beams (SFRC) was investigated using the Modified Compression Field Theory (MCFT) based non-linear finite element (NLFE) method and an analytical method. The two analysis methods included different modeling approaches for the contribution of steel fibers to the tensile strength of reinforced concrete. In the first approach, the residual tensile strength of fibrous concrete was related to the crack width and adopted into the MCTF-based NLFE method. However, the residual tensile strength was free from the crack width in the second approach, which was employed in the analytical method. The capabilities of the mentioned analysis methods were investigated on an experimental study selected from the literature. The experimental study included the four-point bending tests of five four-meter-long simply supported SFRC beams having various ratios of longitudinal reinforcement and fiber content. Results revealed that the MCTF-based NLFE method performed superior in representing the large-scale member responses (such as load-carrying capacity, crack profiles, and flexural stiffness) for the selected loading and boundary conditions while the simplified analytical tool was found to be always conservative in the determination of strength regardless of conventional reinforcement and fiber ratio. However, the rate of error was apparently proven to be highly dependent on the tensile reinforcement ratio.

ÇELİK LİFLİ BETONARME KİRİŞLERİN EĞİLME DAVRANIŞININ MODELLENMESİ

Anahtar Kelimeler

Çelik Lifli Betonarme, Çelik Lif Katkısının Analitik Modellenmesi, Sonlu Elemanlar Analizi, Çelik Lifli Betonarme Kiriş Eğilme Davranışı.

Öz

Bu çalışmada, büyük ölçekli ve çelik lif takviyeli betonarme kirişlerin eğilme davranışının modellenmesi incelenmiştir. Araştırmada, Değiştirilmiş Basınç Alanları Teorisi' ne (DBAT) dayanan doğrusal olmayan bir sonlu elemanlar yöntemi (DOSE) ile analitik bir yöntem kullanılmıştır. Analiz yöntemlerinde çelik liflerin betonarme çekme dayanımına katkısı farklı yaklaşımlarla modellemiştir. İlk yaklaşımda lifli betonun artık çekme dayanımı çatlak genişliği ile ilişkilendirilmiş ve DBAT tabanlı DOSE yöntemine uyarlanmıştır. Analitik yöntemde ise artık çekme dayanımı çatlak genişliğinden bağımsız olarak kabul edilmiştir. Söz konusu analiz yöntemlerinin performansları literatürden seçilen deneysel bir çalışma üzerinde incelenmiştir. Deneysel çalışmada, değişken oranlarda boyuna donatı ve lif içeriğine sahip dört metre uzunluğundaki beş adet betonarme kirişin dört nokta eğilme testleri gerçekleştirilmiştir. Sonuçlar, DBAT tabanlı DOSE yönteminin, seçilen yükleme ve sınır koşullarında büyük ölçekli betonarme eleman davranışını (yük taşıma kapasitesi, çatlak profilleri ve eğilme rijitliği gibi) başarıyla temsil ettiğini göstermiştir. Diğer yandan, analitik metodun, yük taşıma kapasitesini donatı ve lif oranından bağımsız olarak her zaman daha düşük tespit ettiğini ortaya koymuştur. Bu yöntemdeki hata oranının büyük ölçüde çekme donatısı oranına bağlı olduğu açıkça ortaya konmuştur.

Alıntı / Cite

Çankaya, MA., (2023). Modeling the Bending Behavior of Steel Fiber Reinforced Concrete Beams, Journal of Engineering Sciences and Design, 11(4), 1496-1507

Yazar Kimliği / Author ID (ORCID Number)	Makale Süreci / Article Process	
M. A. Çankaya, 0000-0002-5491-3425	**Başvuru Tarihi / Submission Date**	06.12.2022
	Revizyon Tarihi / Revision Date	21.06.2023
	Kabul Tarihi / Accepted Date	19.10.2023
	Yayım Tarihi / Published Date	30.12.2023

* Corresponding author: mehmetalper.cankaya@ikcu.edu.tr, +90 232 3293535 (Ext: 3730)

MODELING THE BENDING BEHAVIOR OF STEEL FIBER-REINFORCED CONCRETE BEAMS

Mehmet Alper Çankaya[1†]
[1]İzmir Kâtip Çelebi University, Faculty of Engineering and Architecture, Civil Engineering Department, İzmir, Türkiye

Highlights

- A detailed review of modeling methodologies of fiber-reinforced concrete.
- Analyzing the four-point bending behavior of large-scale steel fiber-reinforced concrete beams through two different modeling approaches.
- The investigation of sensitivity and accuracy of the selected modeling methods in estimating the structural characteristics.

Purpose and Scope

This study aims to investigate the capabilities of different approaches in modeling the bending behavior of large-scale SFRC beams. Within this scope, the MCFT-based NLFE analysis method and a simplified analytical method were used for modeling the bending behavior of fibrous beams selected from the literature.

Design/methodology/approach

In the selected analysis methods, different approaches were adopted for the contribution of steel fibers to the tensile strength of reinforced concrete. The variable engagement model (VEM) was used in the MCTF-based NLFE method as a constitutive model for FRC in tension. This model established a link between the crack width and the residual tensile strength. However, in the analytical method, the residual strength was free from the crack width.

Findings

- Introducing the fiber contribution to the tensile strength through VEM in the MCTF-based NLFE is successful in estimating the load-bearing capacity, crack pattern, and the overall trend of the load-deflection curve until a defined failure point for the fibrous beam members subjected to four-point bending.
- The simplified analytical method always underestimated the load-bearing capacity and the error tended to increase in lightly reinforced beams having relatively high fractions of fibers. Finally, it should also be noted that this method will not yield a reliable estimation of flexural stiffness since the crack profile of the members is not taken into consideration.

Originality

The main novelty of this study is investigating the sensitivity and accuracy of a relatively recent modeling methodology, VEM, for the fiber contribution to concrete tensile strength in the MCFT-based NLFE method.

1. Introduction

The usage of steel fibers is still limited to non-critical members of civil engineering structures such as precast tunnel lining segments (Plizzari and Tiberti, 2006), concrete pavements (Elsaigh et al., 2011; Meda and Plizzari, 2004), and industrial building floors generally for crack control and durability (Saatci and Batarlar, 2017). However, there is an increasing trend in understanding the effect of steel fibers on the behavior of load-carrying reinforced concrete (RC) members (Saatci and Batarlar, 2017; Xu et al., 2019) in recent studies.

In the literature, analytical methods are available to model and analyze the structural behavior of steel fiber-reinforced concrete (SFRC) members through cross-sectional analysis (Campione, 2008), (Hameed et al., 2018). Two basic approaches are followed in the flexural analysis of fiber-reinforced concrete beams. In the first and simple approach, in addition to some basic assumptions such as the perfect bond between steel bars and concrete

† Corresponding author: mehmetalper.cankaya@ikcu.edu.tr, +90 232 3293535 (Ext: 3730)

and plane section remaining plane after bending, uniformly distributed strength contribution of residual tensile strength of fiber reinforced concrete (FRC) free from the crack width is being utilized (Campione, 2008). However, the second approach is more complicated since the residual tensile strength in the cracked region is related to the width of the crack (Lee et al., 2013). From the mechanical point of view existence of steel fibers in concrete material results in a ductile post-cracking behavior since it provides a bridging effect in the cracks (ACI, 2018). This also prevents the state of brittle failure due to a large collection of mechanical stress around the cracked region as reported by (Yaylacı, 2016, and 2022), and many studies (Marti et. al, 1999; Leutbecher and Fehling, 2008) have been undertaken regarding the residual tensile stress after cracking as a function of crack width in the literature. Apart from the analytical methods, more sophisticated non-linear finite element (NLFE) implementations were also developed and using such a complex method generally requires experience and extreme caution since they are backed by various theoretical approaches and behavior models (second-order effects, constitutive relations) (Vecchio and Palermo, 2000). Among these theoretical approaches, the Modified Compression Field Theory (MCFT) was proven to be one of the most powerful tools in representing the member behavior by considering the cracked concrete as an orthotropic material using a smeared, rotating crack model (Vecchio and Collins, 1986; Vecchio, 2000).

Adoption of modeling the fiber contribution to the tensile strength of concrete as in (Marti et. al, 1999; Leutbecher and Fehling, 2008) into the MCTF-based NLFE method is a relatively new topic and thus, the research on the accuracy of this method is very limited in the literature (Susetyo et al., 2013). The current study is original in this context since it aims to investigate the applicability of the MCFT-based NLFE approach with one of the recently introduced constitutive models for FRC in tension, the variable engagement model (VEM), on the bending behavior of large-scale and doubly reinforced concrete beams having steel fibers. Furthermore, an attempt is also made to analyze the performance of the simplified analytical method in describing the bending behavior of such SFRC members. For this purpose, an experimental study involving four-point bending tests of five SFRC beams was selected from the literature (Meda and Plizzari, 2012). All the beam specimens were four meters long and consisted of two groups. Each group had either light or dense tensile reinforcement ratio. Besides, three of them included various volume fractions of fibers while the remaining two were the control samples w/o fibers. Once the analytical analysis was completed, the numerical study was followed using MCFT-based NLFE code VecTor2 (Vecchio and Wong, 2002). Finally, analytical, and numerical results were compared with those of the experimental.

2. Selected Experimental Study

The current study aimed to analyze the pure flexural behavior of large-scale SFRC beams identical to those used in practical applications. Therefore, an experimental work involving four-point bending tests of four-meter-long simply supported and doubly reinforced beam specimens was selected from the literature (Meda and Plizzari, 2012). The geometry of beams and reinforcement details are presented in Figure 1.

As can be seen from the figure, the clear span between the supports was 3600 mm leaving 200 mm overhangs at each end. Additionally, the shear span to effective depth (a/d) ratio was 4.6. All the beams were full-scale and doubly reinforced. Moreover, they were designed to have two different tensile reinforcement ratios (0.75% and 1.5%) and volumetric steel fiber fractions (0.38% and 0.76%).

Ribbed and S500 type of steel was used as longitudinal reinforcements. The experimental mean yield and ultimate strengths were reported to be 534 and 630 MPa, respectively. On the other hand, the shear reinforcements with 8 mm diameter were located at each 100 mm spacing in the regions where shear forces are developing. During the testing stage, which is 147 days after concrete pouring, the cylinder compressive strength of plain concrete was reported to be 49.7 MPa while the remaining two concrete batches with 0.38 and 0.76% steel fibers were 45 and 43.2 MPa. The hooked-end steel fibers used in the study had a tensile strength of 1100 MPa with a geometry of 50 mm length and 1 mm diameter. Fracture properties of FRC were detected by four-point bending tests using 150x150x600 mm notched beams. In the experimental program, specimens were named with respect to their tensile reinforcement and fiber reinforcement content. For example, beam 2ϕ16-30 has two tensile reinforcements with 16 mm diameter and 30 kg/m^3 steel fiber reinforcement content corresponding to 0.38% volume fraction. More details can be found in Meda and Plizzari (2012).

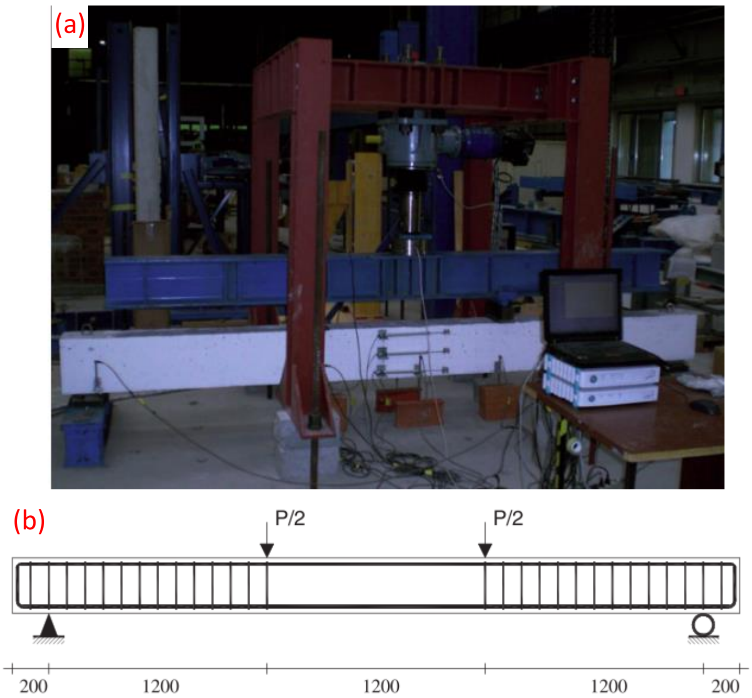

Figure 1. Overview of test setup (a), beam specimen, and reinforcement details with specimen geometry (b) (Meda and Plizzari, 2012)

3. Analytical Method

To investigate the flexural response of steel fiber-reinforced concrete beams, a relatively simple analytical method proposed by Campione (2008) was implemented in the current study. The method assumes average tension stress over the cracked region, independent of crack width and instantaneous curvature of the section. A typical strain and stress distribution on the uncracked and cracked beam sections is presented in Figure 2.

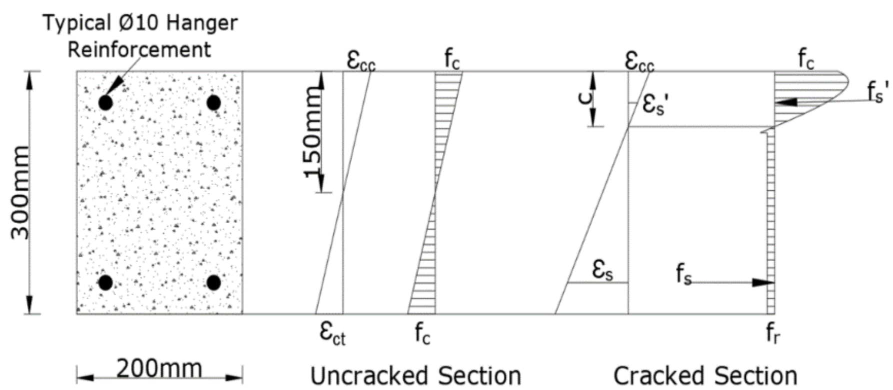

Figure 2. Strain and stress distribution over the beam cross-section

In the calculations, the stress-strain relation of concrete material prior to cracking was assumed to be linear, and the flexural cracking strength of fiber-reinforced concrete (f_{cr}) was taken from the experimental study as the results of four-point bending tests. These are reported to be 3.08 and 4.75MPa respectively for 0.38 and 0.76% or in other words for 30 and 60 kg/m^3 fiber content. The compressive stress-strain behavior of fiber-reinforced concrete was represented using a model proposed by Lee et al. (2015). This constitutive model accounts for the effects of fibers and separates the behavior pre- and post-peak since no significant lateral crack opening will be observed in the pre-peak compression behavior while the confinement effect due to the steel fibers will restrain the lateral crack opening. The modulus of elasticity (E_c) was calculated using the expression proposed by Lee et al. (2015). On the other hand, the compressive behavior of the beam specimens having plain concrete was modeled by Hognestad parabola (Hognestad, 1951) and E_c calculated from the expression given in TS500 (2000). Here it should be noted that the steel fiber additives will enhance the deformation capacity in concrete and therefore, strain beyond the peak point was evaluated to be triple the crushing strain of concrete (0.01) suggested in ACI 544. Based on Campione (2008), tension stress (f_r) was assumed to be constant in the cracked region, and the magnitude was detected according to ACI (1988) as given in Equation 1, in which λ_1, λ_2 and λ_3 are expected pullout length ratio, efficiency factor of orientation in the cracked condition and group reduction factor related with the number of fibers pulling out per unit area, respectively. In addition, τ is the average bond stress of a single fiber embedded in the concrete and calculated using Equation 2 offered by Valle and Büyüköztürk (1993), and $L/_d$ is the ratio of fiber length to diameter.

Sectional analyses of beams were performed by utilizing a layer-by-layer analysis approach (Collins and Mitchell, 1997). Using the force equilibrium over the cross-section, moment and corresponding curvature values were detected in a stepwise procedure for a wide range of assumed compressive strains of concrete. Thus, moment-curvature curves could be obtained and were used in the computation of load-deflection curves. Analytically obtained moment-curvatures were detected to be in good agreement with that of experimentally available, Figure 3. Here, it should be stated that strain in the outermost concrete layer was detected up to 0.0066 and 0.003 in the experimental study since potentiometric devices that measures the curvature were removed before the end of the tests due to safety concerns.

$$f_r = \lambda_1 \lambda_2 \lambda_3 \tau V_f (L/_d) \quad (1)$$

$$\tau = 0.66\sqrt{f_c{'}} \quad (2)$$

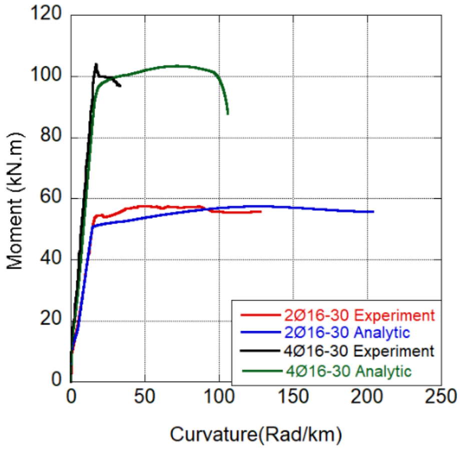

Figure 3. Analytical and experimental moment-curvature relations of beams 2ϕ16 and 4ϕ16 with 30 kg/m³ steel fiber additive

To determine the mid-span deflection, the full length of the beam was evaluated and divided into three pieces considering the existence of three different moment zones in the moment diagram. The moment value at the tip and end of each piece under a specific load and the corresponding curvature for the moment value were detected from the moment-curvature relation. Afterward, the mid-span deflection was calculated using the moment-area theorem. For this purpose, a MATLAB code was developed. In the analysis, the computation of mid-span deflection was done based on load increments.

4. Numerical Method

4.1 The Modified Compression Field Theory and Variable Engagement Model (VEM)

MCFT (Vecchio and Collins, 1986) is an analytical tool for predicting the load-deformation response of RC membrane elements subjected to shear and normal stresses. The model assumes that the cracks forming in the concrete are distributed over the entire volume (smeared crack) and it consists of three sets of relationships. These are (1) compatibility conditions of concrete and reinforcement average strains, (2) equilibrium conditions relating the external loads and internal resisting forces in concrete and reinforcement, and (3) constitutive relationships which are required to provide a connection between average stresses in the equilibrium relations and average strains in the compatibility relationships for both the reinforcement and the concrete. More details about the theory and finite element implementation can be found in Vecchio and Collins (1986) and Vecchio and Wong (2002).

Because average stresses and strains were used in the compatibility and equilibrium conditions, the average tensile stress in the cracked concrete is also taken into account. Therefore, a tension stiffening model is recommended for reinforced concrete. Furthermore, if fibers exist in RC, the tensile behavior should be assessed using one of the methods described in the literature. In the current study, the Variable Engagement Model (VEM) (Voo and Foster, 2003) which is one of the outstanding constitutive models for FRC in tension, was selected. This model expresses the peak and post-peak characteristics of FRC under uniaxial tension and relates the tensile stress to the width of the crack. The main assumptions of the model are that the behavior of fiber-reinforced composites might be stated as the summation of concrete and fiber contributions, and constant bond stress between the fibers and concrete matrix identical to Marti et al. (1999). Each of the individual and randomly oriented, discontinuous fiber effect may then be summed in 3D space to represent the overall behavior of the composite.

4.2 Non-Linear Finite Element Modeling of Reinforced Concrete

The numerical simulations of four-point bending tests were conducted by a two-dimensional non-linear finite element code VecTor2 (VT2) (Vecchio and Wong, 2002). This software was developed for the analysis of RC members in plane stress conditions. It is using a rotating crack approach and is based on MCFT formulations (Vecchio and Collins, 1986).

Taking advantage of the symmetric load and support conditions, one-half of the beams were modeled instead of expensive full-scale modeling, Figure 4. Preprocessor FormWorks (Vecchio and Wong, 2002) was used for this purpose. All nodes located at the centerline of the beam were restrained against translation in the x-direction. The support plate was explicitly modeled and restrained against translation in the y-direction.

Four-point plane stress rectangular elements and two-point truss bar elements were used for modeling the concrete and rebars. A total of 1046 rectangular and 303 truss elements were created, and a perfect bond assumption was made between the concrete and rebar elements. The accuracy of each element size was determined by a mesh sensitivity analysis using 20-, 25- and 30-mm mesh size configurations. Considering a balance between the computational time and accuracy of obtained results such as the load-deflection curve, an optimum mesh size of 25 mm was selected for each element having an aspect ratio of a maximum 1.5. The beam specimens were subjected to 0.1 mm incremental displacement load in the negative y-direction from the loading plate. Selected constitutive models for concrete and steel are given in Table 1, and analysis models were taken to be default except for the crack allocation. In the preprocessor, the existing crack spacing/allocation formulations such as CEB-FIB 1978 or Eurocode 2 were derived for the plain reinforced concrete members without fibers, and hence average crack spacing was detected by visual inspection of the tested SFRC beams and found to be 120 mm. The compressive strength of fibrous and plain concrete, aggregate diameter, yield, and ultimate strength of steel rebars, in addition to the length, diameter, and tensile strength of fibers were taken from the experimental study. Rest of the necessary parameters were evaluated to be the software default which can be found in Vecchio and Wong (2002). Finally, it is worth mentioning that geometric non-linearity was incorporated in the numerical analysis regarding the secondary displacements, P-Delta effects, and other large displacements.

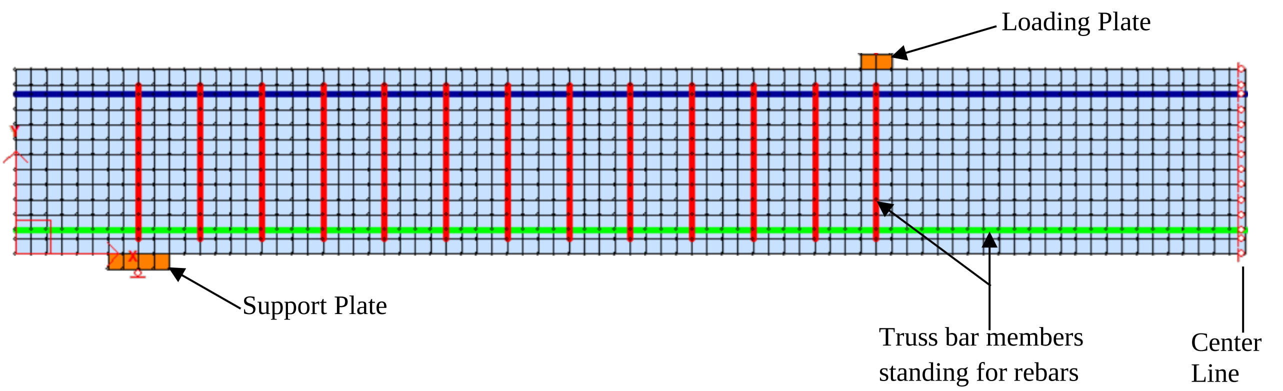

Figure 4. Numerical model of RC beams

Table 1. Constitutive models for the materials used

Material and Property	Model
• Concrete - Compression Pre-Peak	Beams w/o fibers: Popovics (HSC) Beams w/fiber: Lee et al 2011 (FRC)
• Concrete - Compression Post-Peak	Beams w/o fiber: Popovics/Mander Beams w/fiber: Lee et al 2011 (FRC)
• Concrete – Compression Softening	Vecchio 1992-A (e1/e2 form)
• Concrete – Tension Stiffening	Beams w/fibers: Lee 2010 (w/Post Yield) Beams w/o fibers: Modified Bentz 2003
• Concrete – Tension Softening	Beams w/o fiber: Exponential Beams w/steel fibers: Exponential
• FRC Tension	Variable engagement model (VEM)
• Steel Reinforcement - Dowel Action	Tassios (Crack Slip)
• Steel Reinforcement -Buckling	Akkaya 2012 (Modified Dhakal - Maekawa)

5. Comparative Results and Discussion

5.1 Behavior Under Load

Analytically and numerically calculated load-midspan deflection curves are compared with that of the experimental and presented in Figure 5 and 6. As can be seen from the figures below, analytically computed maximum external loads were detected to be 2.70 to 6.20% lower than those of the experiment. In fact, the underestimation tends to increase in beams having fibers due to the error introduced to the calculation by the constant stress model used in the tension region instead of relating the tensile stress with crack width. Moreover, it was noted that as the tensile reinforcement ratio increases, the introduced error tended to decrease since the contribution of steel fibers becomes less effective. This observation is consistent with the findings of Saatci and Batarlar (2017). Large-scale, doubly reinforced SFRC beams having an a/d ratio of 4.6 was experimentally investigated by Saatci and Batarlar (2017). Two different tensile reinforcement ratios leading to either flexural or shear critical behaviors were selected and, in each case, the simplified method remained on the safe side by underestimating the actual ultimate load. On the other hand, the load-carrying capacities could be captured almost precisely from the numerical analysis. The results showed a maximum overestimation of 3% and an underestimation of 2.5% for beams 2ϕ16 with 0.76% SF and 4ϕ16 w/o fibers, respectively.

Next, the flexural stiffness before yielding of beams was conventionally computed as the slope of the load-deflection curve (P/Δ) and the results are tabularized in Table 2. It can be deduced from the table that the analytical analysis always exhibited the highest post-crack flexural stiffness. The reason for high flexural stiffness can be attributed to observed crack distribution over the specimen surfaces. In the experimental study widely distributed cracks, which are resulting in a softening in the flexural stiffness, were reported. However, the current analytical model does not consider crack width and distribution. Additionally, assumes the maximum curvature always occurring in the maximum moment region located at the mid-span. On the other hand, numerical analysis performed better in representing the post-crack flexural stiffness. Moreover, either increasing the tensile reinforcement ratio or inclusion of fiber additive increased the accuracy. An identical outcome was reported by Zhang (2020) and thus further optimization was recommended for stiffness formulation of VT2 specifically for high strength fiber reinforced concrete members having low conventional reinforcement ratio.

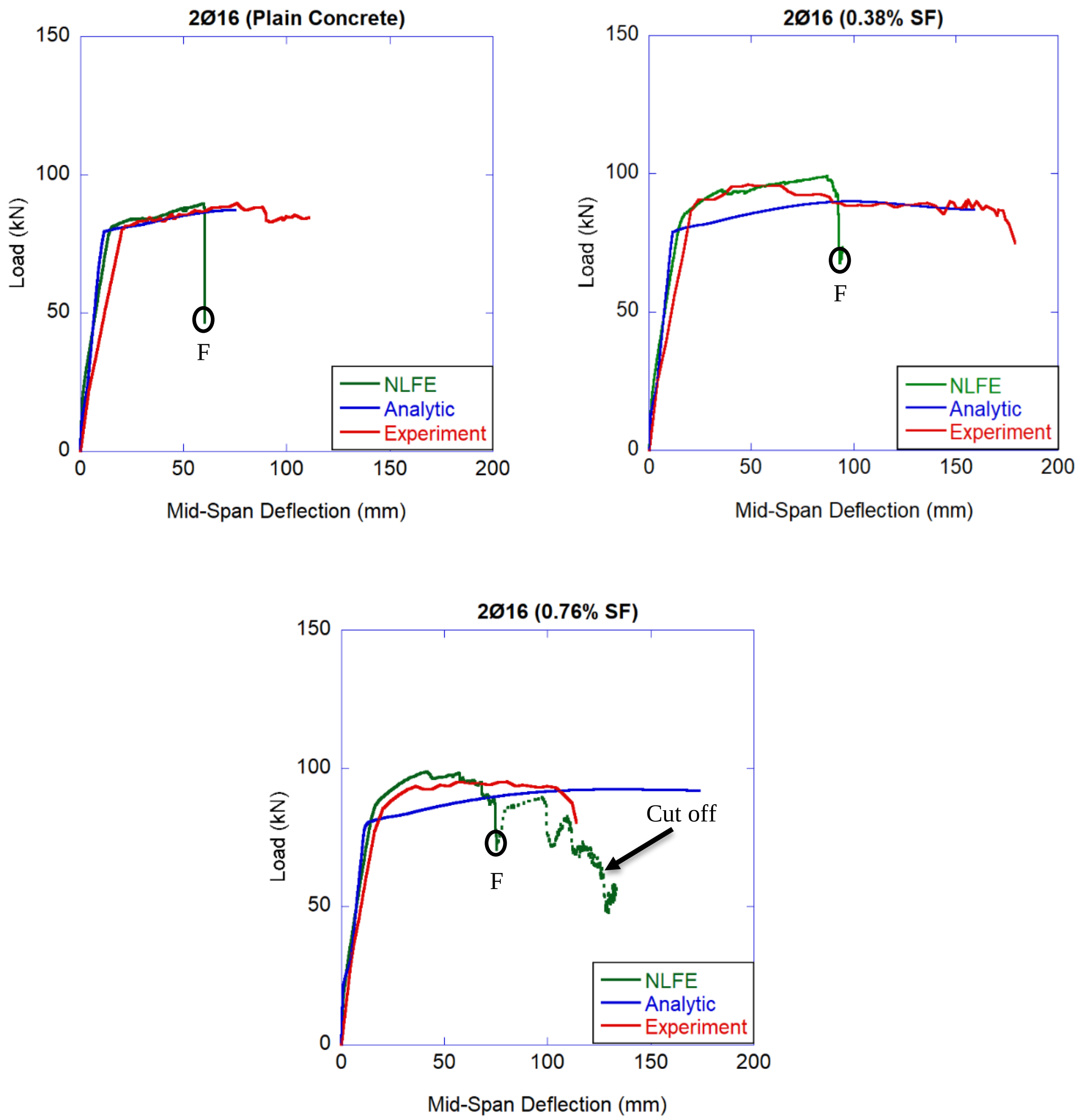

Figure 5. Load-mid span deflection curves of 2ϕ16 beam series

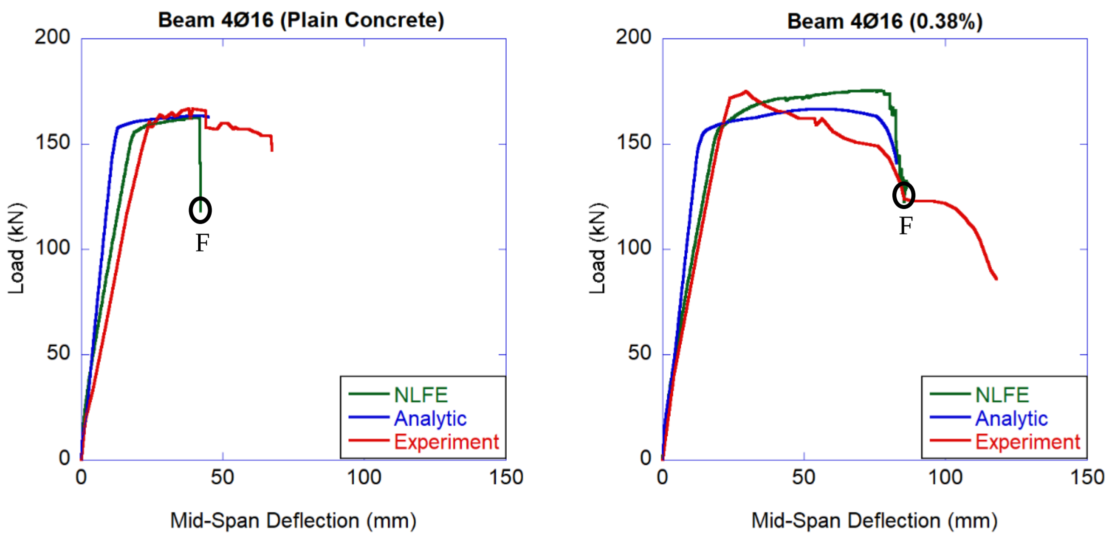

Figure 6. Load-mid span deflection curves of 4ϕ16 beam series

Table 2. The Flexural stiffness of beam specimens

Specimen	Flexural Stiffness - k (kN/mm)			Ratio (Analytic/Experiment)	Ratio (Numeric/Experiment)
	Experimental	Analytical	Numerical		
2ϕ16 –PC	3.70	7.80	4.60	2.10	1.24
2ϕ16 –30	3.80	7.42	4.55	1.95	1.20
2ϕ16 –60	4.05	7.35	4.65	1.80	1.15
4ϕ16 –PC	7.25	13.40	7.70	1.85	1.06
4ϕ16 –30	7.25	12.15	7.42	1.67	1.02

5.2 Cracking Pattern and Failure Mode

Clarification of ultimate (failure) deflection is important in determining appropriate crack patterns in numerical analysis. According to Shin et. al. (1989) and Hadi and Elbasha (2007), the ultimate deflection is defined as the displacement corresponding to 80% of the peak load in the descending portion of the load-deflection curve. In addition, Yoo and Yoon (2015) described the failure displacement by an abrupt decrease in load-carrying capacity due to either rebar rupture or crushing of the outermost concrete layer.

When the predicted load-displacement curves were investigated, at least 30% strength loss was detected for all beams depending on the concrete crush and was represented by point "F". This point was regarded as the failure deflection since it fits well with the three definitions proposed in the literature. Here it should be noted that the numerical analyses were terminated beyond the failure point "F", which subsequently resulted in an underestimation of total deflection capacity compared to that of the experiment. An example of this cut-off is illustrated by the 2ϕ16 beam having 0.76% SF. After clarification of failure displacements, the crack patterns could be captured and shown by red color in Figure 7. According to most of the design codes, such as TS500 (2000) and ACI 224R-01 (2001), the cracks should not exceed 0.3 mm in width. Therefore, the bold lines indicated the severe cracks which have a thickness greater than 0.3 mm in the estimated patterns. As can be seen from Figure 7, major flexural cracks and severe concrete crushing were observed at the constant moment regions of all beams. Additionally, hairline thick (<0.3 mm) flexural-shear cracks distributed along the length of the beams. Despite a general agreement in the detected crack profiles of the experiment and numerical analysis, in the two beams of 2ϕ16 with SF, mode of the failure could not be captured by numerical analysis as rebar rupture. Instead of this, all the beams were estimated to fail from concrete crushing at the outermost layer.

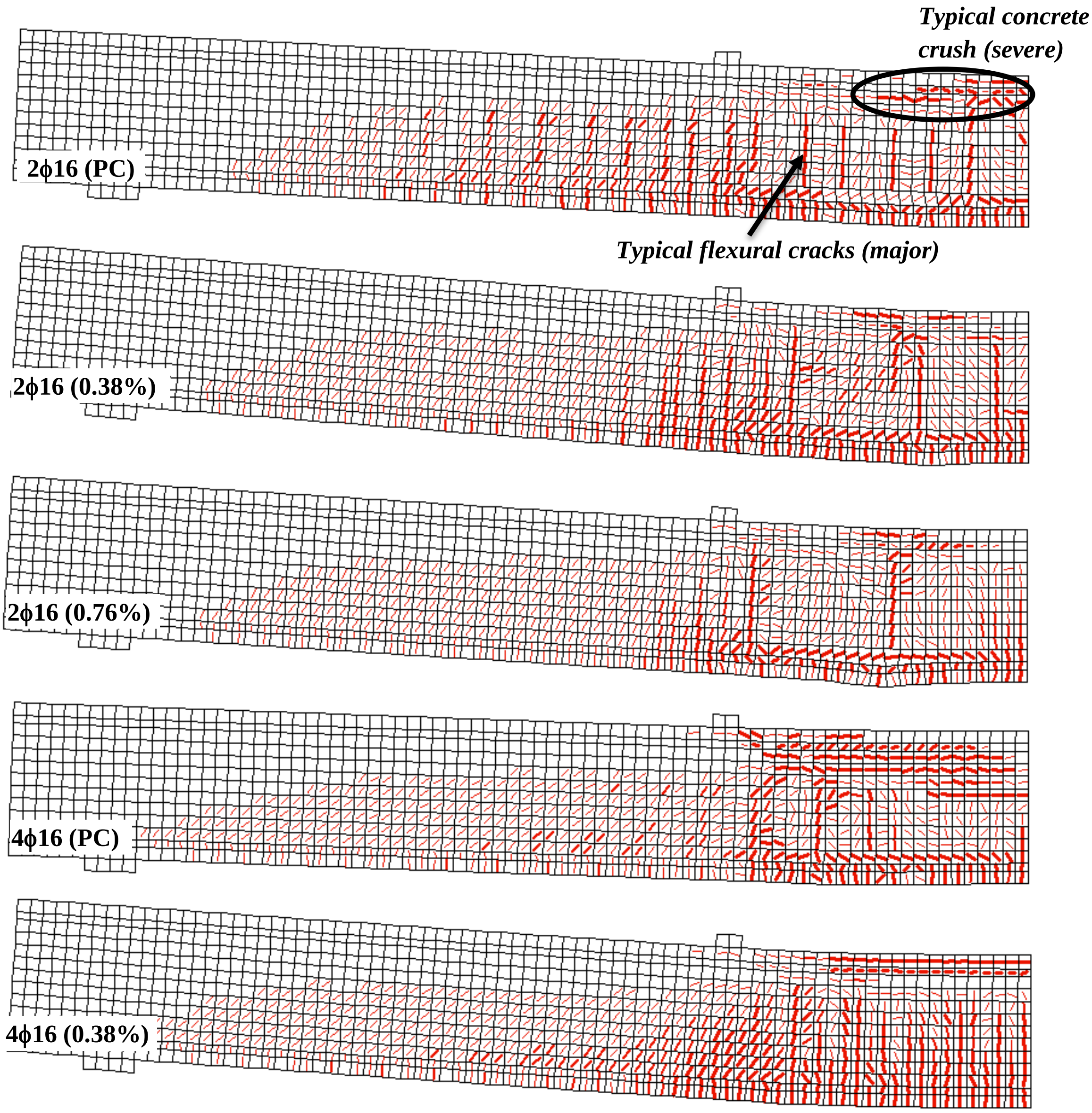

Figure 7. The estimated crack patterns by FEM corresponding to failure deflection

6. Conclusion

The performance of numeric and analytic techniques on the pure bending behavior of large-scale and doubly reinforced RC beams with the tensile reinforcement and fiber ratios as variable parameters was investigated by introducing two different methods of residual strength of the fibrous concrete.

The following conclusions can be inferred from the above discussions.

- The MCTF-based NLFE method was previously found to be successful in representing the response of various types of non-fibrous reinforced concrete test specimens as well as real-life structures (Palermo and Vecchio, 2004; Vecchio, 2002). The current study revealed that introducing the fiber contribution to the tensile strength through VEM in the MCTF-based NLFE is also superior in estimating the fibrous member response (as the load-bearing capacity, crack pattern, and the overall trend of the load-deflection curve until a defined failure point) under static loading. In addition, the flexural stiffness could be captured satisfactorily in densely reinforced beams while a slight overestimation reaching up to 25% was estimated for lightly reinforced beams.

- Simplified analytical method always stayed on the safe side by slightly underestimating (a maximum of 6.20%) the load-bearing capacity in flexure critical SFRC beams. Here it is worthwhile to mention that the error tended to increase in lightly reinforced beams having relatively high fractions of fibers. These observations coincide well with Saatci and Batarlar (2017). As a result, analyzing the flexure critical SFRC beams was found to be efficient in capturing the load-carrying capacity. However, further extension of the study to the SFRC beams subjected to various types of loading and boundary conditions might be beneficial to understand the functionality of the method. Finally, it should be noted that this method will not yield to reliable estimation of flexural stiffness since the crack profile of the members is not taken into consideration.

Conflict of Interest

No conflict of interest was declared by the author.

References

American Concrete Institute (ACI) 224R-01, 2001. Control of Cracking in Concrete Structures.
Amin A, Foster SJ., 2016. Shear strength of steel fibre reinforced concrete beams with stirrups. Engineering Structures, 111, 323-332.
American Concrete Institute (ACI) 544.4R-18, 2018. Guide to Design with Fiber-Reinforced Concrete. Michigan, USA.
Arslan G, Keskin RSO, Ulusoy S., 2017. An experimental study on the shear strength of SFRC beams without stirrups". Journal of Theoretical and Applied Mechanics, 55(4), 1205-1217
American Concrete Institute (ACI 544.4R-88), 1988. Design considerations for steel fiber reinforced concrete. Michigan, USA.
Campione G., 2008. Simplified flexural response of steel fiber-reinforced concrete beams. Journal of Materials in Civil Engineering, 20(4), 283-293.
Collins MP., Mitchell D., 1997. Prestressed concrete structures. Toronto, Canada, Response Publications,
Comité Euro International du Béton (CEB/FIP), 1987. Model Code for Concrete Structures, CEB-FIP International Recommendations, Third Edition, Paris, France, 348 pp.
Elsaigh WA, Kearsley EP, Robberts JM., 2011. Modeling the behavior of steel-fiber reinforced concrete ground slabs II: Development of slab model. Journal of Transportation Engineering, 137(12), 889-896.
EN 1992-1-1:2004, 2004. Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings, 226 pp.
Hameed R, Sellier A, Turatsinze A, Duprat F., 2013. Flexural behavior of reinforced fibrous concrete beams: experiments and analytical modelling. Pakistan Journal of Engineering and Applied Sciences, 13, 19-28.
Hadi MN., Elbasha N., 2007. Effects of tensile reinforcement ratio and compressive strength on the behavior of over-reinforced helically confined HSC beams. Construction and Building Materials, 21(2):269–76.
Hognested E., 1951. Study of combined bending and axial load in reinforced concrete members. Urbana: University of Illinois Engineering Experiment Station, Bulletin series no. 399.
Lantsoght EOL., 2018. How do steel fibers improve the shear capacity of reinforced concrete beams without stirrups?. Composites Part B: Engineering, 175.
Leutbecher T, Fehling E., 2008. Crack width control for combined reinforcement of rebars and fibers exemplified by ultra-high-performance concrete. Fib Task Group 8.6 Ultra High-Performance Fibre Reinforced Concrete (UHPFRC), 1-28.
Lee SC, Cho JY, Vecchio J., 2013. Simplified diverse embedment model for steel fiber-reinforced concrete elements in tension. ACI Materials Journal, 110(4), 403-412.
Lee SC, Cho JY, Vecchio FJ., 2016. Analysis of steel fiber-reinforced concrete elements subjected to shear. ACI Structural Journal, 113(2), 275-285.
Lee SC, Oh JH, Cho JY., 2015. Compressive Behavior of Fiber-Reinforced Concrete with End-Hooked Steel Fibers. Materials, 8, 1442-1458.
Mahmood SMF, Agarwal A, Foster SJ, Valipour H., 2018. Flexural performance of steel fibre reinforced concrete beams designed for moment redistribution. Engineering Structures, 177, 695-706.
MATLAB. Programming Software. The MathWorks Inc.
Marti P, Pfyl T, Sigrist V, Ulaga T., 1999. Harmonized test procedures for steel fiber reinforced concrete. Materials Journal, 96(6), 676-685.
Meda A., Plizzari G, 2004. New design approach for steel fiber-reinforced concrete slabs-on-ground based on fracture mechanics. ACI Structural Journal, 101(3), 298-303..
Meda A, Minelli F, Plizzari GA., 2012. Flexural behavior of RC beams in fibre reinforced concrete. Composites Part B: Engineering, 43, 2930-2937.
Naaman AE., 2003. Strain hardening and deflection hardening fiber reinforced cement composites. Fourth International Workshop on High Performance Fiber Reinforced Cement Composites, Ann Arbor-USA, 95-113.
Palermo, D., Vecchio, F. J., 2004. Compression Field Modeling of Reinforced Concrete Subjected to Reversed Loading: Verification. ACI Structural Journal, 101(2).
Plizzari GA, Tiberti G., 2006. Steel fibers as reinforcement for precast tunnel segments. Tunnelling and Underground Space Technology, 21(3-4), 438-439.
Saatci S, Batarlar B., 2017. Çelik fiber katkılı etriyesiz betonarme kirişlerin davranışı. Journal of the Faculty of Engineering and Architecture of Gazi University, 32(4), 1143-1154.
Shin SW, Ghosh SK, Moreno J., 1989. Flexural ductility of ultra-high-strength concrete members. ACI Structural Journal, 86(4):394–400.
Susetyo J, Gauvreau P, Vecchio FJ., 2013. Steel fiber-reinforced concrete panels in shear: analysis and modeling. ACI Structural Journal, 110(2), 285-295.
Turkish Standard (TS 500), 2000. Requirements for design and construction of reinforced concrete structures. Ankara, Türkiye.
Valle M, Buyukozturk O., 1993. Behaviour of fiber reinforced high-strength concrete under direct shear. Materials Journal, 90(2), 122-133.

Vecchio FJ., Palermo D., 2000. NLFEARC: look Both Ways Before Crossing. ACI Fall 2000 Convention.

Vecchio FJ., Collins MP., 1986. The Modified Compression Field Theory for reinforced concrete elements subjected to shear. ACI Journal, 83(2), 219-231.

Vecchio FJ., 2000. Analysis of shear-critical reinforced concrete beams. ACI Structural Journal, 97(1), 102-110.

Vecchio, F. J., Wong, P., S., 2002. VecTor2 & FormWorks User's Manual

Vecchio, F. J., 2002. Contribution of Nonlinear Finite-Element Analysis to Evaluation of Two Structural Concrete Failures, Journal of Performance of Constructed Facilities,16,110-115.

Voo JYL, Foster SJ., 2003. Variable engagement model for fibre reinforced concrete in tension. School of civil and environmental Engineering, The University of New South Wales, Sydney, Australia, UNICIV Report, NO. R-420.

Xu C, Cao PZ, Wu K, Lin SQ, Yang DG., 2019. Experimental investigation of the behavior composite steel-concrete composite beams containing different amounts of steel fibres and conventional reinforcement. Construction and Building Materials, 202, 23-36.

Yaylaci, M., 2016. The investigation crack problem through numerical analysis. Structural Engineering and Mechanics, 57(6), 1143-1156.

Yaylaci, M., 2022. Simulate of edge and an internal crack problem and estimation of stress intensity factor through finite element method. Advances in Nano Research , 12(4), 405-414.

Yoo DY., Yoon YS., 2015. Structural performance of ultra-high-performance concrete beams with different steel fibers. Engineering Structures, 102:409–23.

Zhang, Z., 2020. Finite Element Modelling of Ultra-High Performance Fibre Reinforced Concrete. MSc. Thesis, Graduate Department of Civil Engineering, University of Toronto.