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Finite Element modelling of Synthetic Fibre reinforced concrete members under bending

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Abstract— *The inclusion of randomly oriented fibres in concrete has been studied experimentally by various researchers. The influence of various types of fibres on the mechanical behavior of concrete is characterized by the residual flexural strength obtained from three-point bending tests on notched beams. However, the numerical behaviour of fibre reinforced concrete members has not been investigated to a great extent despite the significance of precise modelling of post-cracking behaviour of Fibre reinforced concrete and its relevance to the stress-distribution in concrete and reinforcing bars.*

This paper presents the results from the finite element analysis performed to study the behaviour of synthetic FRC prisms and compares them with the experimentally obtained results. Concrete prisms reinforced with synthetic fibres were subjected to three-point bending to evaluate the influence of using different dosages of synthetic fibres on the mechanical behaviour of concrete. Modelling the notched beams with different fibre contents emphasizes the importance of using the stress-crack opening response as a tensile property of synthetic FRC in finite element analysis.

Keywords— *Synthetic fibre, residual flexural strength, finite element, constitutive model.*

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I. Introduction

Fibres have significantly improved the post-cracking performance of structural members upon formation of the first crack, particularly in the steel fibre reinforced concrete, which can be used for the partial or full replacement of conventional reinforcement [1, 2]. However, fibres other than steel have been limited to restrain and control plastic cracks. Non-metallic fibres have lower strength and modulus of elasticity but lower carbon footprint. Synthetic fibres (a type of non-metallic fibres) have attracted researchers' attention as a promising material due to their reduced environmental impact [3]. Moreover, several studies reported that non-metallic fibres increased the ductility and contributed to the delay of cracks coalescence [4-6].

Cracking in concrete structure is modelled by using either the smeared or the discrete crack approaches. In the smeared crack approach, Rashid and design (1968) proposed that cracking is represented by standard continuum elements, whereas cracks are modelled as displacement discontinuities in the discrete crack approach. Various guidelines and design methods available in the CEB-FIP Code [7] and RILEM TC162-TDF [8] provide rational principles for designing SFRC structural members and are compatible with their unreinforced counterparts. Guidelines utilize the direct post-cracking tensile behaviour as a stress-crack opening response. Despite the theoretical models provided by guidelines, the adequate finite-element computations model of FRC structural application is required to overcome the shortfalls in existing techniques and methods for modelling and analyzing the flexural and cracking performance of FRC reinforced elements.

In this work, the approach adopted for the finite element modelling of synthetic FRC is presented and discussed. The flexural response obtained from notched FRC beams with different volume fractions was used to characterize the material mechanical properties in the FEA.

II. Ease of Use

2.1 Background experimental program

The experimental campaign investigated 42 notched prismatic concrete specimens prepared and tested to EN 14651 at 28 days under a three-point bending test. A test was carried out to characterize and modify the contribution of fibres to the residual flexural strength. Inclusion of different dosages of fibres up to 15 kg/m^3 were considered in concrete mixes with two different water/cement ratios of 0.26 and 0.39. The part related to different contents of synthetic fibres is considered in this study, and their corresponding residual flexural parameters obtained from the 3PBT is used to model FRC prisms by using finite-element analysis.

2.1.1 Materials

Synthetic fibres with polymeric fibres of 54-mm long and 600 MPa tensile strength were used to produce the FRC concrete. Materials proportions of all mixes were designed to the reference mix design having a w/c ratio of 0.26 (See Table 1). Concrete mixes were produced with 0, 5, 7.5, and 10 kg/m^3 synthetic fibre contents (corresponding to fibre's volume fraction of 0, 0.55%, 0.83 and 1.1%, respectively).

Table 1. Reference mix designs

Constituents	Quantity (kg/m^3)			
	Mix 1	Mix 2	Mix 3	Mix 4
Water	130	130	130	130
Cement	510	510	510	510
Fine aggregate	950	950	950	950
Coarse aggregate (20 mm)	300	300	300	300
Coarse aggregate (10 mm)	580	580	580	580
Synthetic fibres	0	5	7.5	10
Superplasticizer	9.4	12	13	14

2.1.2 Specimens

Prismatic specimens complying to the standard EN 14651 [9] were produced and tested under flexure. All mixes were produced following the same mixing sequence, and further details of the process are available in Al Marahla and Garcia-Taengua [10]. Parameters obtained from the 3PBT test were the limit of proportionality (f_L) and the parameters of residual strength of f_{R1}, f_{R2}, $f_{R3,}$ and f_{R4} associated to crack opening displacement values of 0.5, 1.5, 2.5, and 3.5 mm, respectively. The postcracking load–displacement response is used as material properties (stress-CMOD) in the modelling to define the constitutive curve in the modelling.

2.2 Finite-element modelling

A two-dimensional plane stress finite element method (2D quadratic quadrilateral finite elements) is applied to model the notched prisms under bending. Prisms modelled in DIANA have the same dimensions as those of the experimentally tested specimens. Smeared crack approach is considered to model the behaviour in this study, where the softening function and the material fracture energy govern the simulation. The rotating crack model is selected to evaluate the behaviour of the prisms, in which the primary crack forms perpendicular to the direction of principal strain.

In this study, concrete mechanical properties were assigned according to standard FIB Model Code 2010. The Theornfeldt model presented by Thorenfeldt [11] to identify the concrete compressive behaviour for plain and fibre reinforced concrete. However, the tensile behaviour of experimentally tested prisms with plain concrete and the FRC showed a significant difference. For plain concrete, various models are available to describe and identify the pre- and post-cracking tensile behaviour, i.e., the model proposed by Hordijk (1991) is extensively used in different software (DIANA and Midas FEA). In this model, the non-linear softening behaviour is considered to predict the concrete post-cracking tensile behaviour. Concrete in this model exhibits a linear elastic relationship up to the cracking stress and thereafter exhibits a gradual decay up to zero at the ultimate strain. Identifying this behaviour is done through the concrete tensile strength, the element size, and the mode 1 fracture energy G_{fi} according to the Model code 2010. For incorporating the concrete tension stiffening in FEA, the constitutive relationships obtained from members under tension are used for modelling the flexural members [12]. And for the fixed crack model, shear behaviour of cracked concrete is defined by the shear retention factor with a value of 0.01 to 1.0.

For FRC members, the residual flexural strength and members toughness are improved due to the inclusion of fibres. Therefore, curves for residual flexural strength versus the CMOD are used to define tensile behaviour in the FE model, as shown in Fig. 1.

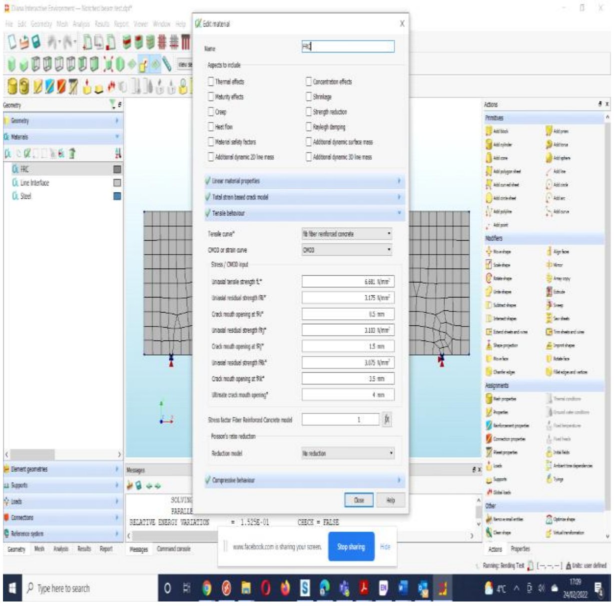

Fig. 1: Tensile function of concrete using DIANA

Mesh adopted for this model has a finer mesh size of 5 mm for the central parts (notch and the region above) and a relatively coarser mesh size of 15 mm for the other parts.

Simply supported boundary conditions were assigned for the notched prisms in DIANA, which allows modelling the support as individual elements interfaced to the concrete specimen. Steel blocks are used and modelled with linear elastic material properties. The selected nodes of the prisms represent the location of supports. The vertical translation was restrained only at one support and restrained the translation along with vertical and horizontal directions in the other support. Modelling the FRC notched prisms with different loading approaches has shown that using the displacement control approach here yielded a better post-cracking pattern when compared to the load control method using the Quasi-Newton iteration scheme in conjunction with the Arc-length method. A prescribed deformation of 3 mm acting downwards was applied for a convergence tolerance of 0.001 for energy and displacement norms.

III. Results

3. 1 Characterization test

Prisms without fibres exhibited abrupt failure after the formation of the single crack at the tip of the notch, and accordingly, prisms split into two parts. Unsurprisingly, specimens with different volume fractions of synthetic fibres exhibited comparatively better ductile behaviour than specimens without fibres. Residual flexural parameters presented in Table 2 are the average of three different values obtained experimentally.

Table 2. Residual flexural parameters

Fibre content (kg/m^3)	Residual flexural strength (MPa)				
	LOP	fR1	fR2	fR3	fR4
5	7.283	2.662	2.563	2.531	2.531
7.5	7.480	3.095	2.842	2.785	2.748
10	6.681	3.173	3.103	3.093	3.075

Load-crack displacement pertaining to each volume fraction is shown in Fig. 2.

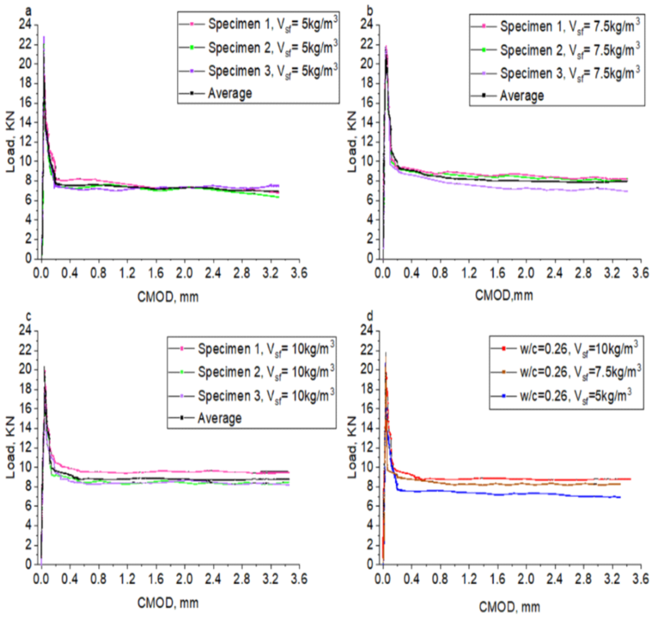

Fig. 2: Load-CMOD for concrete members with different dosages of synthetic fibres

Prisms vertical displacement (deflection) obtained from the flexural bending test can be converted into approximate CMOD using the general formula proposed in the standard EN 14651.

IV. FEA model

Results obtained from the finite-element model are discussed in terms of deflections, stresses, and crack width (CMOD) for each case. Fig. 3 illustrates the vertical displacement (deformed shape) obtained at the maximum fibre content (10 kg/m^3).

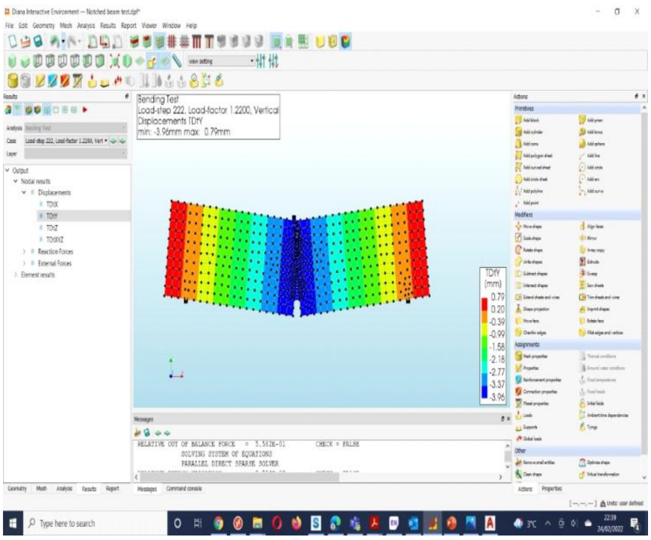

Fig. 3: Vertical displacement obtained from DIANA

Results obtained from the FE analysis of prisms with 5, 7.5, and 10 kg/m^3 are plotted in terms of stress S_{xx} and crack-width E_{cw1} and compared with the experimentally obtained data.

V. Discussion

The inclusion of synthetic fibres leads to improvements in the toughness of a member tested under flexure. Regarding the effect of increasing the volume fraction of synthetic fibres, it has been found that increasing the content of synthetic fibre resulted in an increase in the level of the residual flexural strength. Consequently, increasing the synthetic fibre content led to an increase in toughness. Incorporating synthetic fibres in the volume fractions considered in the experimental program led to an increase of 0.61 in the ratio of the residual flexural strength to the limit of proportionality (fR1/fL). The residual strength-CMOD curves presented in Fig. 3 showed that the difference observed in residual strength values between specimens with dosage of 5 kg/m^3 and those with 7.5 kg/m^3 were more pronounced than the differences observed when the fibre dosage was increased from 7.5 kg/m^3 to 10 kg/m^3.

A comparison between results obtained from DIANA FEA and those obtained experimentally was carried out considering different fibre contents (V_f: 5, 7.5, and 10 kg/m^3). Fig. 4 presents the residual tensile strength-CMOD for prisms with different synthetic fibre contents. It can be noticed that curves obtained from DIANA were in well agreement with those obtained experimentally

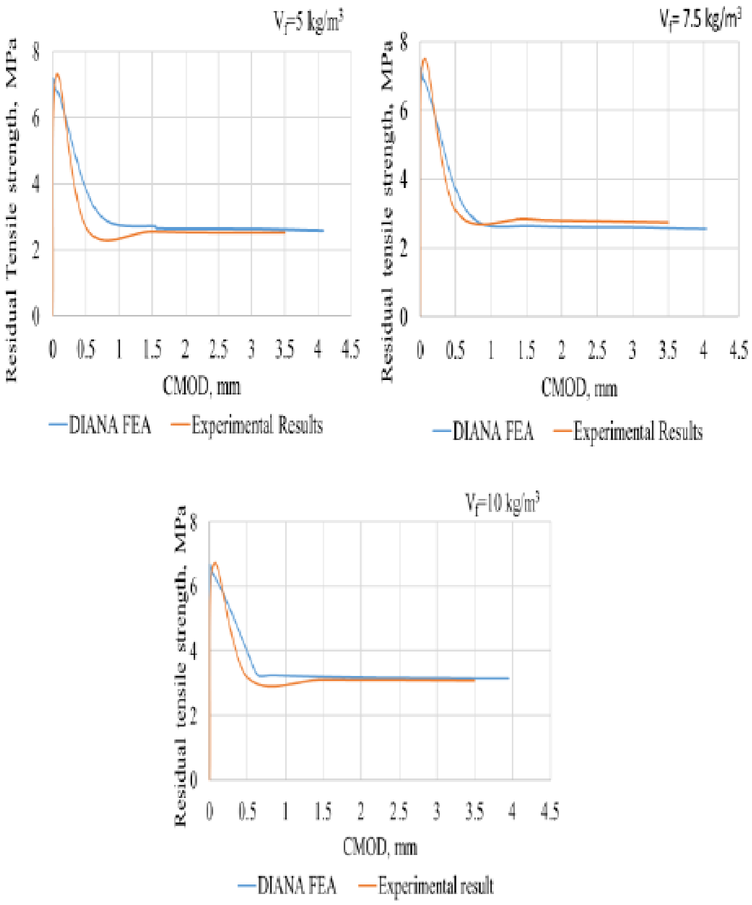

Fig. 4: Comparison between residual tensile strength-CMOD curves obtained experimentally and in DIANA FEA

Comparison between curves from DIANA FEA and those obtained experimentally show a good correlation. However, a slight disparity was observed between the experimental and models results. This may be attributed to the test conditions.

VI. Conclusions

This study presents a numerical model using DIANA FEA to analyze the reinforced concrete prisms under three-point bending. The fracture mechanism of synthetic FRC with different fibre contents is considered in terms of crack widening in the crack tip of notched beams. The non-linear analysis based on the smeared crack model of DIANA proved to be very efficient in analyzing the post-cracking performance of FRC beams tested under bending, and the 2D model presented a ductile behaviour close to that one obtained experimentally. It can be pointed out that the contribution of synthetic fibres across the crack can be presented through the residual tensile strength, and the behaviour is identified as a function of concrete tensile strength.

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