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NONLINEAR FINITE ELEMENT ANALYSIS OF STEEL FIBRE-REINFORCED CONCRETE BEAM UNDER STATIC LOADING

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Abstract

A nonlinear finite element analysis of steel fibre-reinforced concrete beams subjected to static loading was explored using ADINA software. A predefined 3D model of concrete beam of dimension 100 mm×100 mm×500 mm was prepared using the smeared crack approach to fracture of concrete in the mode I; this model simulates a nonlinear response in tension. Stress redistribution was performed by the equilibrium iterations process. Both stresses and displacements occurring at different node locations of the element were carefully examined. In addition, the results of laboratory experiments conducted on concrete beams with a fibre content of 60 kg/m^3 based on volume (that is: 0.75% and 1% by volume of concrete) were compared to the analytical results in order to ascertain the consistency of the results. It was realized that the interfacial bond between the concrete and the fibres has a significant effect on the overall performance of the strengthened members.

Keywords: Steel fibre, Finite element, Concrete, ADINA, Crack.

1. Introduction

In recent years, different approaches have been employed in the construction environments on the use of concrete and its constituent materials. As a result, distinct problems constituting great concern emanates in structural elements which include but not limited to: response to loading, fire resistance, water absorption and displacements [1-3]. Lately, experimental researches have been conducted on the static behaviour of concrete elements [4], and most analytical experiments show that concrete behaves in a highly nonlinear manner in uniaxial compression [5], also with poor resistance to tensile loading [6]. However, there is a persistent need for concrete elements made for particular purposes to be investigated, among others, for effect of response to any form of loading.

Abbreviations

ADINA	Automatic Dynamic Incremental Nonlinear Analysis
FEM	Finite Element Method

Shende et al. [7] studied the mechanical properties of steel fibre reinforced concrete, it was revealed that compressive strength, split tensile strength and flexural strength increases with increasing fibre contents for the percentages of fibre considered. Steel fibres are used in concrete production in order to enhance its ductility; thereby improving the brittle plain-concrete material [8, 9]. More so, steel fibres prevent brittle modes of collapse such as shear failure in plain concrete.

Over the years, complex problems encountered in the field of engineering are treated with the aid of FEM, most often, adopted via the use of sophisticated software. A very important aspect in the development of a finite element program is the use of appropriate numerical techniques [10]. Past few decades have witnessed various advancement in computing techniques and the computational capabilities which in turn led to a better understanding of the behaviour of construction materials. However, Nazem et al. [11] revealed there is complexity in FEM applied to concrete due to non-linear stress-strain relation of the concrete under multi-axial stress conditions, strain softening and anisotropic stiffness reduction, progressive cracking caused by tensile stresses and strains, bond between concrete and reinforcement, aggregate interlocks and dowel action of reinforcement, time dependent behaviour such as creep and shrinkage. More so, It was indicated by Chaudhari et al. [12] that increasing use of computer based methods for designing and simulation in a way has increased the urge for the exact solution of the problems, and this influenced difficulties in simulation and modeling of concrete structures.

In spite of all shortcomings, researchers have developed several FEM based software for solving simple to complex problems in engineering. Currently, several commercial software are available for nonlinear analysis of materials and elements, they include: ABAQUS, ANSYS, NASTARAN, and ADINA. Taking cognizance of financial and time constraint [13], results from experiments may not be forthcoming. FEM provides a unique approach to investigating concrete members using computer software. Accordingly, this study is focused on the nonlinear finite element analysis of fibre-reinforced concrete beam under static loading, using ADINA finite element software, and it also compared both the experimental and analytical test results.

2. Materials and Methods

This section describes the laboratory experimental analysis conducted on fibre-reinforced concrete. Three different tests namely: compressive test, flexural test and split tensile test were performed. These tests were carried out in accordance with the provisions of British standard codes [14-16].

Among the materials that were utilized for the laboratory experiments are the following: Ordinary Portland cement, Fine aggregate, Coarse aggregate, Potable water, Steel fibre, and CONPLAST SP 430 super-plasticizer

River sand was used as fine aggregate and granite crushed stone of maximum size 20mm was used as coarse aggregate. Figure 1 shows the steel fibres used which is the hooked-end type, it is 25 mm long and 0.38mm wide in diameter (aspect ratio 65.79) with a density of 7947 kg/m^3. A fibre content of 60 kg/m^3 based on volume (that is: 0.75% and 1% by volume of concrete) was adopted and maintained throughout the investigations. A predesigned mix proportion of 1: 1.21: 2.0 of cement, sand and granite, with water/cement ratio of 0.4 was adopted. Samples cast for the experiments include: concrete cubes of dimension 150 mm x 150 mm x 150 mm, cylinders of dimension 150 mm x 300 mm, and beams of dimensions 100 x 100 x 500 mm. The concrete samples were cured in a water tank at 32$\pm$2^{0}C. All samples were tested accordingly after 28 days curing. Beams were subjected to centre point loading flexural testing using the ELE flexural testing machine (Fig. 2). Figure 3 presents a sample of cylinder under loading.

Deformation was measured at the centre point of the beams. The flexural strength (or Modulus of Rupture) known as the maximum tensile stress in the beam at peak load was obtained using

$$\sigma = \frac{PL}{BH^2} \tag{1}$$

where P is the peak load [N], L is the beam span length [mm], B is the beam width [mm], and H is the beam height [mm].

Fig. 1. Hooked-end type steel fibre used.

Fig. 2. Concrete beam under flexural strength test.

Fig. 3. Cylinder specimen under splitting tensile strength test.

3. Finite Element modelling

The concrete beam considered for the analysis was modelled with an eight-node 3-D solid element, having three degrees of freedom at each node; with translations in the nodal x, y, and z directions. Also, the modelled element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The geometrical dimension of the concrete beams for both the analytical and laboratory experiment was 100 mm x 100 mm x 500 mm.

The analytical investigation that was performed entails the use of the following concrete properties: Young's modulus = 2.1E+10, Poisson ratio was assumed to be 0.2 [17], Material density = 2400 kg/m^3, and Coefficient of thermal expansion = 5E-5.

The steel fiber reinforcement was integrated into the concrete in ADINA system by adopting the physical properties of concrete represented in cube compressive strength and split tensile strength. Thus, the cube compressive strength and split tensile strength utilized were obtained for concrete mix with 0.75% and 1% steel fibre from experimental analysis.

The results obtained for compressive strength and split tensile strength are respectively 53.83 MPa and 6.4 MPa for 0.75% steel fibre-reinforced concrete, 53.83 MPa and 7.29 MPa for 1% steel fibre-reinforced concrete. Hence, after the concrete beam was modelled, it was subjected to a single point loading of 2000 kN until failure. Figure 4 presents the beam and the loading arrangement for the flexural strength test.

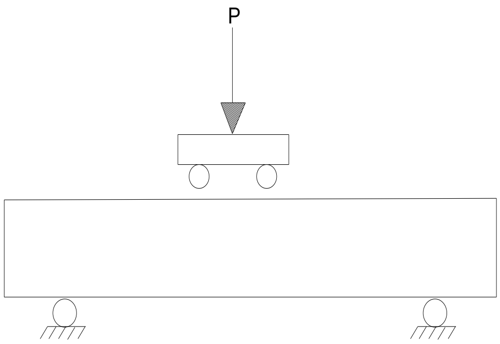

Fig. 4. Beam and loading arrangement for flexural testing.

However, analytical investigations of reinforced concrete elements are not performed without the consideration for the bond stress – slip condition at the contact between reinforcements and the concrete. Usually bond-slip between reinforcement and concrete are modeled using interface elements [18]. More so, Interface elements often use empirical, nonlinear bond stress-slip relationships. Figure 5 shows a nonlinear experimentally-based stress-strain law for the behaviour in compression and tension.

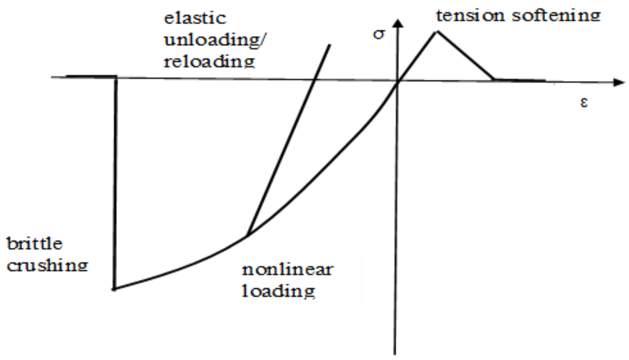

Fig. 5. Stress-strain behaviour of the data fitted concrete material model [5].

In order to obtain local bond stress-slip relationships for finite element modeling, the force to pull short lengths of embedded reinforcement out of concrete are measured [19]. In ADINA system, the solution process was performed using nonlinear iteration, comprising iteration scheme of BFGS matrix update method and fifteen maximum number of iteration. Under the control, time steps were maintained constant; both the number of steps and constant magnitude is 100. Apart from modelling the concrete such that it represents the material behaviour adequately, the solution response is highly nonlinear; also the iterative schemes was used in static solutions in order to make it converge when cracking and crushing of the finite element model occurs.

According to Shivaji and Partha [19], tensile stress transfer performed across a crack using a smeared crack approach and tension softening behaviour results in a negative stiffness for the cracked element. Therefore, the smeared crack approach was implemented using a residual load vector to redistribute the stresses during equilibrium iterations.

Different research findings have revealed that the parameters influencing bond-slip behavior include load history, confinement; clear bar spacing, bar size and configuration, concrete strength, transverse pressure and loading rate [20]. The finite element meshed model of the beam is shown in Fig. 7. A total of 254 nodes and 2244 elements were generated in the model.

4. Results and Discussion

The results of the experimental and analytical tests performed on the fibre-reinforced concrete are presented in this section. Experimental test depict that the addition of 0.75% steel fibre to plain concrete produced a 20% increment in compressive strength more than the control samples (i.e. plain concrete). Likewise, an appreciable increase in strength was also recorded for beams reinforced with 0.75% fiber than the control samples, both in the flexural and split tensile tests after 28th day curing; 26% increment in flexural test and 58.83% in split tensile strength. More so, addition of 1.0% steel fibre increases the flexural strength of the concrete by 42.3% than the control samples. The increase in strength of steel fibre-reinforced concrete was attributed to the fact that micro level fibres arrest the development of micro-cracks propagation in plain concrete, thereby resulting in higher compressive strengths.

Generally, strength of the concrete increased with increasing steel fibre contents. The greater the volume of fibres in the matrix, the higher the probability of a micro-crack being intercepted by the fibre. The load-deflection results for both experimental and the analytical tests is presented in table1. Figure 6 shows the load – deflection curve for experimental and analytical concrete. The values of deflection plot for the beam from the finite element analyses agrees quite well with the experimental data. From the start of the loading process, a unanimous behaviour was seen in the 0.75% fiber beams and the analyrical beam. However, in the 1% fiber reinforced beam, there was a bulging that occurred between 4 kN and 10 kN load, which could be attributed to the effects of creep and shrinkages in concrete; thus in alignment with the report by Hall and Ghali [21]. At ultimate load, there was a variation of deflection by 18% approximately between the 1% fiber reinforced beams and the analytical plot. Consequently, it was deduced that the addition of steel fibres to concrete influences its durability and reduces the propagation of cracks. The presence of steel fibre prevents total failure of the beam, in that, the fibre tends to hold the concrete together at failure. The failure of the beam occurred within the middle third of the span which was the point where bending moment is maximum; a fact that corroborates the findings of Kamal et al. [22]. However, this behaviour could be attributed to the fact that there was no horizontal shear failure at the level of loading. More so, crack propagation at failure point was gradual and it widens according to the intensity of the loading.

Table 1. Load – deflection Results for Experimental and Analytical Tests

Load (kN)	Deflection			
	Experimental			Analytical
	0% fiber	0.75% fiber	1% fiber	
0	0	0	0	0
2	0.1	0.1	0.18	0.07
4	0.16	0.16	0.20	0.16
6	0.19	0.18	0.29	0.18
8	0.20	0.26	0.38	0.23
10	0.24	0.28	0.46	0.19
12	0.29	0.38	0.52	0.44
14	0.41	0.42	0.56	0.39
16	0.45	0.46	0.59	0.38
18	0.50	0.55	1.24	0.51

20	0.51	1.23	1.29	1.41

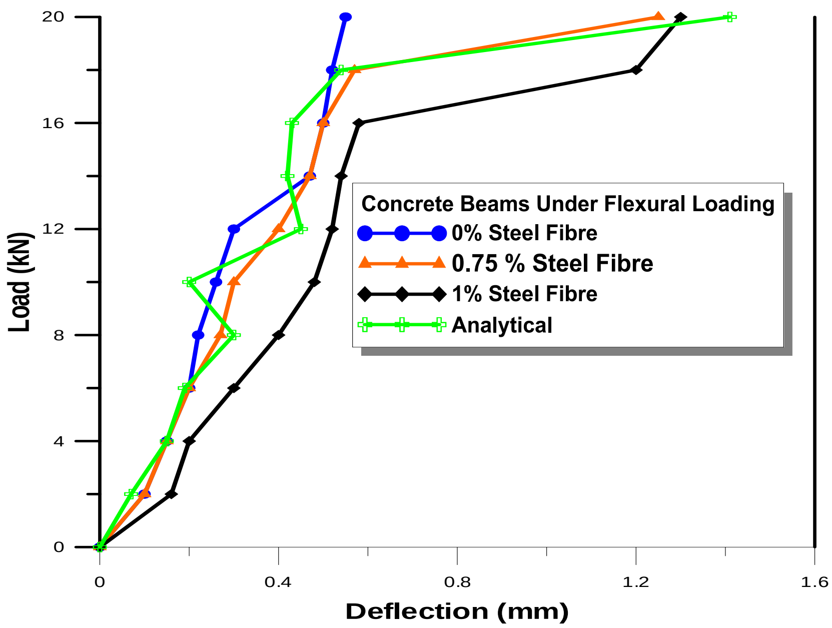

Fig. 6. Load – Deflection curve for experimental and analytical concrete.

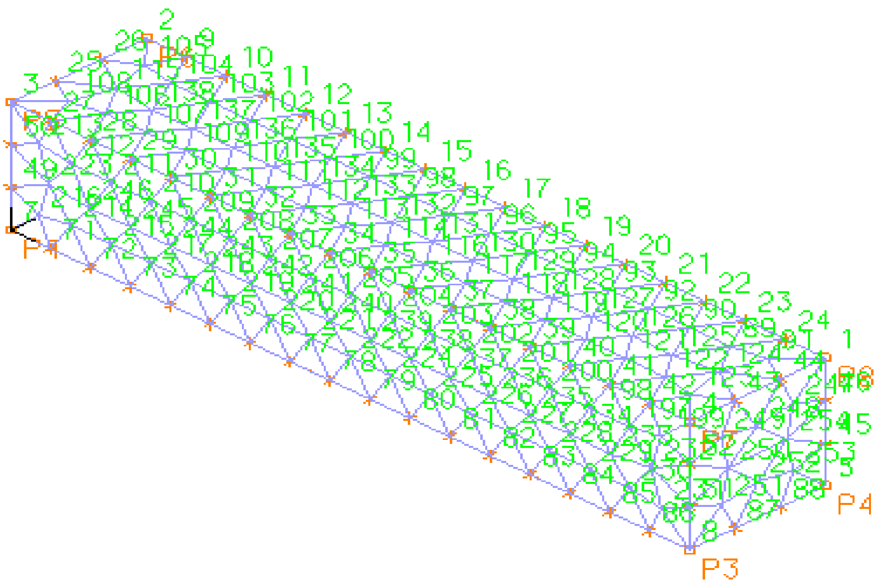

Fig. 7. Meshed concrete beam model in ADINA.

5. Conclusions

From the study conducted on nonlinear finite element analysis of fibre-reinforced concrete beam under static loading, following conclusions were drawn:

- Increasing steel fibre volume in plain concrete facilitates appreciable strength development in steel fibre-reinforced concretes. At 28 days testing, compressive strength, split tensile strength and flexural strength for plain concrete measured: 42.06 MPa, 4.0 MPa and 7.87 MPa respectively, while for concrete with 0.75% fiber, the values are: 53.37 MPa, 6.4 MPa and 9.95 MPa respectively. The presence of steel fibres curbs the propagation of micro-cracks in plain concrete.
- The occurrence of beam failure within the middle third span in flexural testing which was the point where bending moment is maximum; could be attributed to the fact that there was no horizontal shear failure at the level of loading.
- In static analysis, failure of beams occur as result of steel fibre pull-out, most significantly when the micro-crack coalescence is negligible, the beams fail mainly due to breaking of the fibres.
- Generally, it has been affirmed that the use of advanced analysis tools with strong capacity in finite elements and matrix structural analysis concepts enables the solutions of complex problems.

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