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Finite element analysis of steel fiber reinforced concrete (SFRC): validation of experimental shear capacities of beams

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Abstract

Finite element models are analyzed and validated with the experimental shear capacities of steel fiber reinforced concrete (SFRC) as well as plain concretes. In this work, steel fibers with low aspect ratio which are commonly available in Bangladesh are used and sufficient capacity enhancements are attained. Two different aggregate types are used to make the SFRC and plain concrete beam specimens, i.e. stone and brick, and also modelled in the finite element (FE) platform of ANSYS 10.0 with SOLID65 element. The experimental plan intended to investigate the shear capacity enhancement of three different types of beam specimens, i.e. single shear, double shear and flexural shear. All the specimens are tested in the 1000kN capacity digital universal testing machine (UTM) and the strain data are obtained from digital image correlation technique (DICT) using high definition (HD) images and high speed video clips. Test results showed the increase in shear capacity of about 30% to 170% of beams made of SFRC with an indication of increase in ductility. FE models are analyzed extensively and validated with the experimental stress-strain behaviours by optimizing the Poisson's ratio, modulus of elasticity, tensile capacity and stress-strain behaviours. FE models showed the same structural response and failure modes as found in experimental investigation. This paper can contribute to the construction industry of Bangladesh about SFRC with reliable experimental data and FE analyses.

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Keywords: Finite element analysis (FEA); steel fiber reinforced concrete (SFRC); shear capacity; ANSYS.

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1. Introduction

Steel fiber reinforced concrete (SFRC) is being increasingly used in shotcrete as tunnel linings, pre-cast structures, off-shore platforms, water-retaining structures, structures in high seismic risk areas, bridges, industrial or factory pavements, highways, roads, parking areas, bridge decks, airport runways and also in versatile engineering structures. In concrete pavements, steel fibers are particularly suitable both for limiting shrinkage effects and for increasing fatigue resistance. Steel fibers can be substituted totally or partially for conventional reinforcement, thus reducing the working time for placing conventional reinforcement (reinforcing bars or welded mesh) and cutting construction costs.

Steel fiber reinforced concrete (SFRC) is a composite material whose components include the traditional constituents of port-land cement concrete (hydraulic cement, fine and coarse aggregates, and admixtures) and a dispersion of randomly oriented short discrete steel fibers [1]. The use of steel fiber-reinforced concrete (SFRC) is increasing due to its improved material and structural behavior relative to plain concrete and even to conventionally reinforced concrete with the same steel volume fraction. One of the most beneficial aspects of the use of fibers in concrete structures is that non-brittle behavior after concrete cracking can be achieved with fibers. Adding steel fibers increases ultimate shear strength, reduces deflections, increases stiffness and transforms failure modes from brittle and dangerous shear failures into more ductile flexural failures [2]. Steel fiber reinforcement is also effective in increasing punching shear resistance and deformation capacity of slab-column connections under combined gravity load and lateral displacement reversals [3].

A Finite Element Analysis (FEA) software package ANSYS 10.0 is used to analyze the shear capacities and introduce a good concrete model for steel fiber reinforced concrete (SFRC) as well as plain concrete made of brick and stone aggregate. Results gathered from finite element analyses are validated with the experimental test results by evaluating the controlling parameter. Poisson’s ratio, modulus of elasticity, stress-strain behaviour and tensile strength of concrete is found to be the main governing parameters for successfully model SFRC in a finite element platform. After the evaluation of these parameters by extensive analysis, finite element (FE) models showed a good correlation with the experimental results. This investigation is intended to analyze and validate the shear behaviour of ANSYS models with the experimental results by estimating the pertinent parameters as well as to provide a successful FE SFRC model for analyzing future problems on SFRC.

2. Experimental program

Enlarged end fibers with 1.5% volume fractions are used to cast the shear specimens. The steel fibers used in this research are easily available in the markets of Bangladesh. The fibers are slightly customized to make enlarged ends for better anchorage. Two different kinds of aggregates are used to make the SFRC shear specimens and also plain concrete specimens, i.e. stone (CS is used in the specimen designation) and brick (CB) aggregate and the effects of SFRC on these two types of concretes are investigated. Significant increase of the shear capacity is achieved using this kind of steel fibers. Three kinds of shear capacity are tested, i.e. single shear (SS), double shear (DS) and flexural shear (FS). Concretes are made of OPC i.e. Ordinary Portland cement (O). All the shear specimens are tested in a 1000kN capacity digital universal testing machine (UTM). The strain data are measured by applying digital image correlation technique (DICT) using high definition (HD) images and high speed video clips and these data are synthesized with the load data from the load cell of UTM which is also applied in the work of Islam, 2011[4] and Islam et al., 2011[5]. Experimental tests show the increase in shear capacity of about 30% to 170% of shear specimens due to SFRC which also showed an indication of increase in ductility of these members. All the specimens are then modeled in the FE platform of ANSYS 10.0 and also validated with the experimental results and failure patterns. These validated models provide more interesting behaviour of SFRC from further analyses of FE outcomes which also discussed in this paper.

3. FE modeling, analyses and validation

3.1. FE modeling and analyses

The shear specimens are modeled on the FE platform of ANSYS 10.0. SOLID65 is used to model the concrete and also SFRC. The element is defined by eight nodes having three degrees of freedom at each node; translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions and crushing. In concrete applications, for example, the solid capability of the element is used to model the concrete while the rebar capability is available for modeling reinforcement behavior. Other cases for which the element is also applicable would be reinforced composites [6], such as, fiberglass and in this case fiber reinforced concrete (FRC). The geometry and node locations for this type of element are shown in Fig. 1(a).

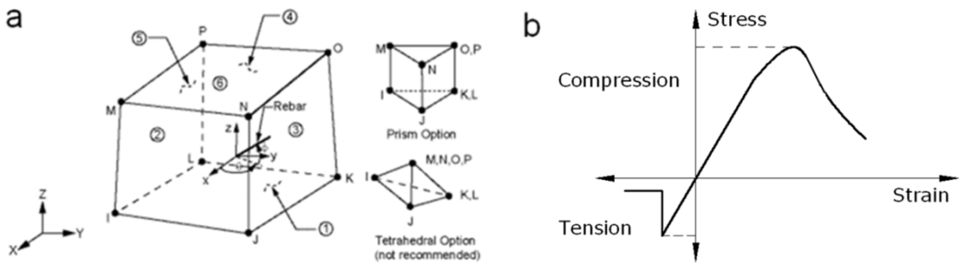


Fig. 1. (a) Geometry of SOLID65 in ANSYS 10.0 platform (b) typical uniaxial compressive and tensile stress-strain curve for concrete.

Concrete is a quasi-brittle material and has different behavior in tension and compression. In compression, the stress-strain curve for concrete is linearly elastic up to 30 percent of the maximum compressive strength. Above this point, the stress increases gradually up to the maximum compressive strength (Fig. 1b). After it reaches the maximum compressive strength, the curve descends into a softening region, and eventually crushing failure occurs at an ultimate stain. In tension, the stress-strain curve (Fig. 1b) for concrete is approximately linearly elastic up to the maximum tensile strength. After this point, the concrete cracks and strength decreases gradually to zero [7].

For perfect modeling, ANSYS requires to provide data for material properties, such as (i) elastic modulus, (ii) ultimate uniaxial compressive strength, (iii) ultimate uniaxial tensile strength and (iv) Poisson's ratio. All the values are provided from experimental outputs. Poisson's ratio for concrete and SFRC is estimated to be 0.25 and 0.35 for stone and brick concretes. William and Warnke, 1975[8] failure criterion is applied to model the concrete as well as SFRC. Four important parameters, i.e. i) shear transfer coefficients for an open crack, ii) shear transfer coefficients for a closed crack, iii) uniaxial tensile cracking stress and iv) uniaxial crushing stress are also considered to model the concretes perfectly. Typical shear transfer coefficients range from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). The shear transfer coefficients for open and closed cracks are determined from the work of Kachlakev, et al., 2001[9] as a basis. Convergence problems occurred when the shear transfer coefficient for the open crack dropped below 0.2. No deviation of the response occurs with the change of the coefficient. Therefore, the coefficient for the open and close crack is set to 0.3 and 1.0 for SFRC.

The dimension of the flexural shear specimen is 6x6x24 in (153x153x610 mm) and is analyzed with two point loading and each load is placed at a distance of 6in (153 mm) from the end supports. Loading is applied as displacement boundary condition. Supports are placed 3 in (76 mm) from the edge of the beam. The span between the two supports is 18 in (458mm). These beams are restrained only vertically as it is tested experimentally. The dimension of S-shaped single shear specimen is 4x4x16in (100x100x400mm) for the main beam part and is connected monolithically with a relatively higher stiffened part, which is used apply the single shear. The dimension of double shear specimen is also 4x4x16in (100x100x400mm) and again monolithically stiffened parts are attached to apply double shear. The single shear and double shear specimens are notched (Fig. 2d & e) at the critical locations for the concentration of shear stress and to control the failure location. Fig 2 shows typical diagram of FE models with boundary conditions.

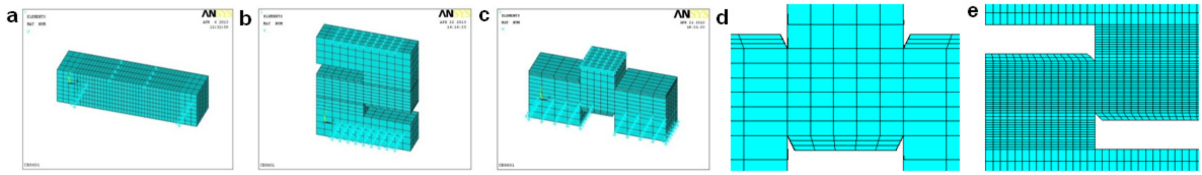


Fig 2: Boundary condition of (a) flexural shear, (b) single shear (c) double shear specimens (d) notch of double shear specimen and (e) notch of single shear specimen.

The loading is applied as displacement at a rate of 0.05 in. (1.27mm) per min in the experiments by the UTM. In the FE modeling displacement boundary condition is applied to provide the actual loading environment. The displacement boundary condition is applied in 500 steps followed by 2 sub-steps for each step.

Finite Element modeling requires optimum mesh size for better analysis. A suitable mesh size helps to achieve sufficient accuracy and also saves time. Mesh size may vary in the analysis of a single structure. Different mesh alignments generally give slightly varying solutions. In fact in real life problems mesh size is constantly refined to get a representative solution. To get the accurate results, stress vs. number of element curve is plotted and found interesting relationship between them (Fig. 3). The stress changes with the increase of number of elements of a specimen, but at a certain point the curve becomes horizontal. It means after a certain number of elements, the stress does not vary significantly. The amount of elements at the horizontal location of stress vs. number of elements curves are considered during FE meshing of a particular specimen. Fig. 3 (a to c) shows that at a low number of elements, stress is changing abruptly whereas at a higher number of elements the reaction became stable, but so much higher number of elements will increase the complexicity and also the analysis time. A resonable number of elements are selected with maximum accuracy and minimum analysis time. The number of elements taken are 3000, 3000 and 2000 for the flexural shear, single shear and double shear specimens in FE analyses.

3.2. Validation of shear capacity and failure patterns

The validations of FE analysis by ANSYS 10.0 of shear specimens with the results gathered from the experimental measurements are shown in Fig. 4 (a to l) which satisfactorily demonstrates the accuracy of the FE model of plain concrete as well as SFRC made of brick and stone concrete specimens. The shear stresses of flexural shear specimens are taken near support, at the notch locations for the single shear and double shear specimens. The FE results in most of the cases found to be more or less conservative with respect to the experimental outcomes which also ensure higher factor of safety as well as reliability of the models. In all the cases the increase of shear capacity is found in SFRC which is also seen in the experimental results. In most of the cases the ANSYS curve is following the experimental path but in a conservative fashion which indicate the higher factor of safety of these FE models. After the FE analysis, similar results and failure patterns are found which enhanced the confidence of the validity of the modeling and analyses. Typical failure patterns and stress contours of SFRC brick concrete specimens from experimental and FE analyses are provided in Table 1. It shows the similarities of failure pattern between the experimental specimens and the FE models using ANSYS. This indicates that the FE modeling of SFRC specimens using the pertinent parameters gathered from experimental testing are validated and there remains a good agreement as well as it can be used in future SFRC models to predict the shear capacity enhancements.

3.3. Critical investigation via FE analyses

The FE models discussed in this paper are further analyzed to evaluate the shear stress distribution at different locations which is not so easy task to find experimentally. Fig. 5 (a to l) shows the shear stress distribution due to flexure, double shear and single shear. The shear stresses are plotted against load steps and gradual increment of shear stress is clearly found. The shear stress is found maximum (Fig. 5a and b) near neutral axis which satisfies the shear behaviour due the flexure and at support it is higher near support. Fig. 5(c to f) represents the shear stress distribution of double and single shear specimens where the stresses are found higher at the notch locations.

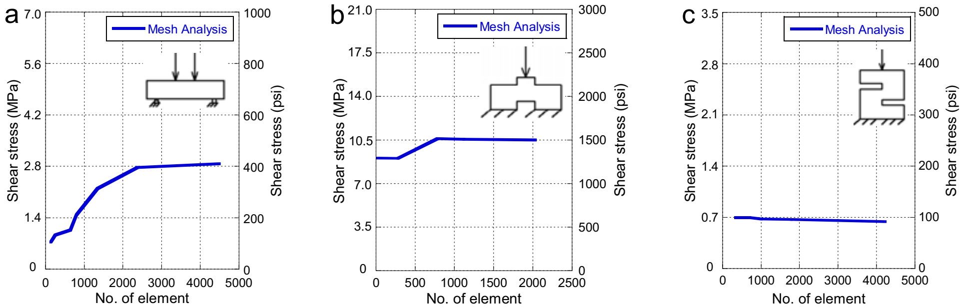


Fig. 3. Stress vs. number of elements curve for (a) flexural shear, (b) double shear and (c) single shear specimen.

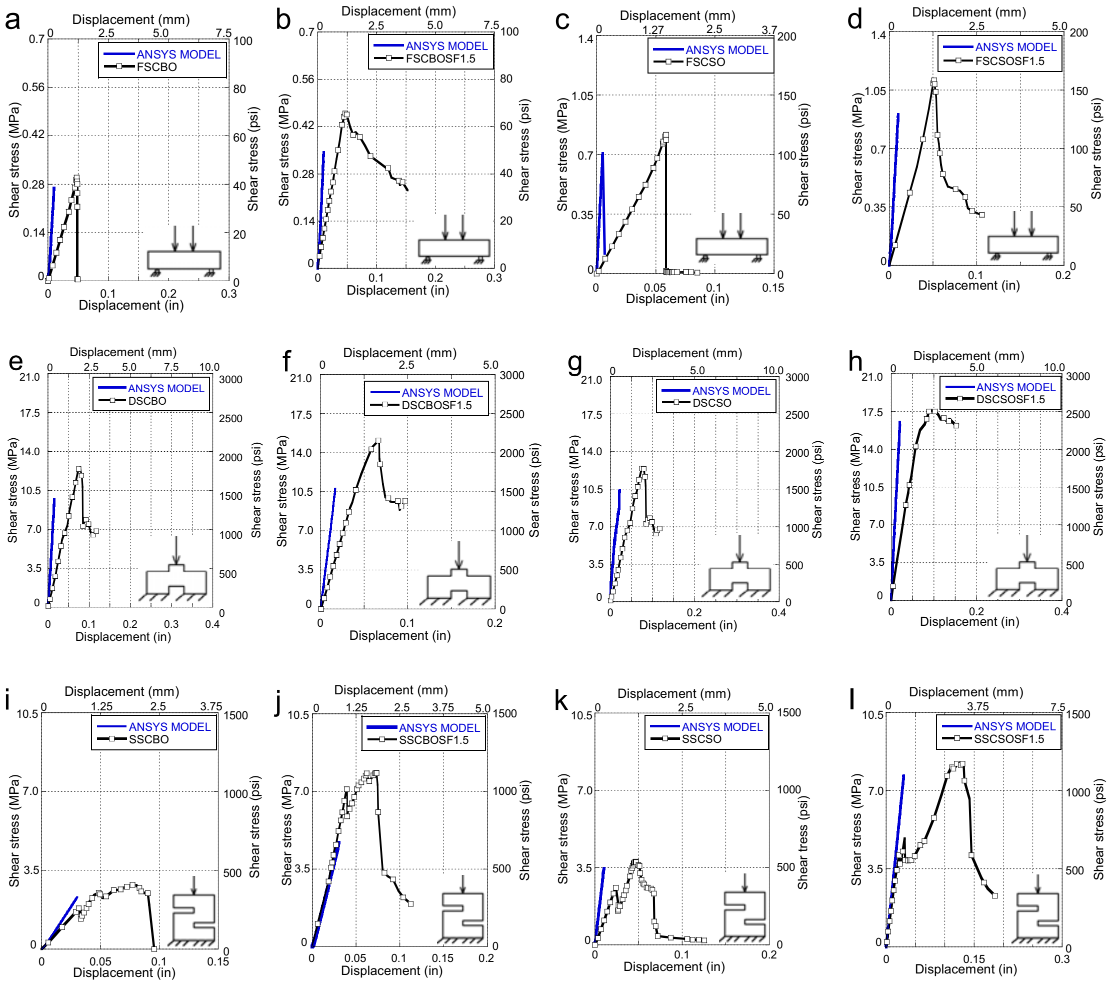
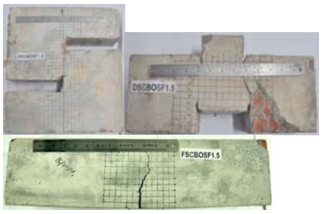
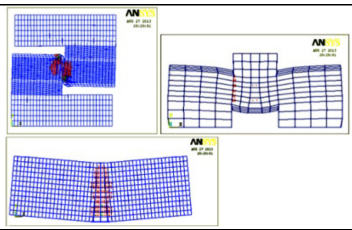
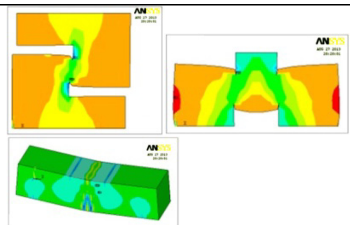


Fig. 4. (a) to (l) Validation of FE models of plain concrete and SFRC specimens made of brick and stone concrete.

Table 1: Evaluation of failure pattern

Failed experimental specimen	Failed FE model in ANSYS	Shear stress contour
		

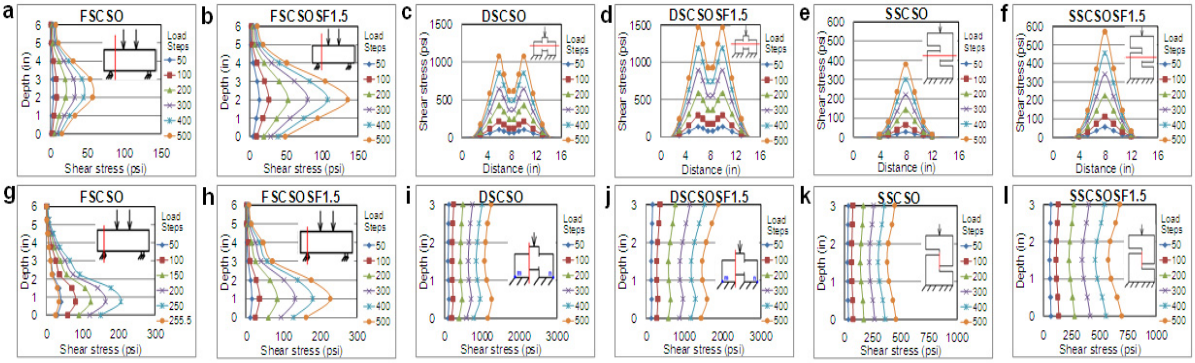


Fig. 5: Shear force distribution of plain and SFRC stone concrete at different locations (a), (b), (g), (h) flexural shear specimen; (c), (d), (i), (j) double shear specimen and (e), (f), (k), (l) single shear specimen.

4. Conclusion

The following conclusions can be drawn from this investigation:

- Shear capacity is found enhanced 30% to 170% by using steel fibers of 1.5% volume ratio which prevented brittle failure. The FE models showed similar analyses result compared to experimental outcomes which ensures good agreements. The failure patterns are also similar which also validated the FE models.
- Further investigation shows the capability of the models to predict shear distribution due to SFRC which ensures reliability of FE models. This FE analyses will definitely help to predict shear behaviour of SFRC structures which will be useful for the construction industry of Bangladesh.

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