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Experimental investigation and finite element analysis on P-M interaction diagram of RC square columns made of steel fiber reinforced concrete (SFRC)

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ABSTRACT: Reinforced concrete (RC) columns are often designed and assessed under the assumption that axial loads and bending moments are applied simultaneously. In this case, the actual loading history varies from the assumed design loading history. While this deviation from the design loading history may be inconsequential, cases may exist in which this new loading history results in a significant reduction of the reliability of the column. The reason for this is easily explained by studying the column's P-M Interaction Diagram. A typical P-M Interaction Diagram depicts all combinations of axial loads and bending moments which correspond to a prescribed limit state. These limit states may indicate column failure, or they may simply identify critical material or geometric states. To this end, this study attempts to construct the P-M Interaction Diagram for short square column made of steel fiber reinforced concrete (SFRC) experimentally and via finite element (FE) approach. The columns are modelled and analyzed in the FE platform of ANSYS 11. The use of SFRC in the construction industry of Bangladesh is not yet started for reliable experimental results and FE modelling. This study will provide real experimental data as well as FE analysis on P-M Interaction Diagram of square RC columns for predicting the axial load as well as bending capacity.

1 INTRODUCTION

Steel fiber-reinforced concrete (SFRC) is a composite material whose components include the traditional constituents of Portland cement concrete (hydraulic cement, fine and coarse aggregates, and admixtures) and a dispersion of randomly oriented short discrete steel fibers (Islam et al. 2012, Islam et al. 2014a, b, c, d, e, f, g, h, i, j, k). The development of SFRC began in the early 1960s when researchers first studied the concept of using steel fibers to improve the mechanical properties of concrete (ACI 544.1R-96). Since then, the use of SFRC has gathered great interest, with research demonstrating the potential benefits that may lie in the use of the material in both structural and nonstructural applications. Over the past years, the results of several research projects demonstrated that adding discrete, randomly distributed steel fibers can improve mechanical properties of concrete, such as tensile strength, toughness, durability, fatigue life and impact resistance (ACI 544.4R-88). The resulting composite material, typically referred to as steel fiber-reinforced concrete (SFRC), has several applications in the fields of shotcrete, rock slope stabilization, tunneling, pavement construction etc. Because of its enhanced tensile strength and toughness in compression, SFRC has great potential to be used in structural members to carry axial load and bending moments. Steel fibers are used to increase the compressive toughness of the concrete to allow controlled crushing and thus prevent catastrophic failures (ACI 544.1R-96). Reinforced concrete (RC) columns made of SFRC with axial and eccentric loading has a contribution in the P-M Interaction Diagram. SFRC is being used in the construction industry of different countries for its well known engineering properties like superior crack control, ductility, energy absorption capacity and improving the internal tensile strength of the concrete due to the bonding force between the fibers and the matrix.

P-M Interaction Diagram of building columns, bridge piers, towers of cable stayed and suspension bridges is a graphical representation of the combined effect of axial load and bending moment due to eccentricity (Islam 2011, Das et al. 2015, Patowary et al. 2015). It is a curve plot of points, where each point has two ordinates. The first ordinate represents the bending moment and the second ordinate represents the axial load. Both ordinates are linked with eccentricity. P-M Interaction Diagram of RC column is divided into two major zones (Fig. 1a) by a balanced failure conditional line. In compression controlled zone (small eccentricities), failure of column occurs by crushing of concrete before yielding of steel. In case of the tension controlled zone (large eccentricities), failure of column occurs by yielding of steel before crushing of concrete. The type of failure for a column depends on the magnitude of eccentricity. It is observed that in the region of compression failure, the larger the axial load P_n, the smaller the bending moment M_n that the section is able to sustain before failing. However, in the region of tension failure the reverse is true. Failure envelope of the P-M Interaction Diagram changes for a column of fixed size for various percentages of steel used in the column. Percentage of steel required for a column for any safe combination of axial load and bending moment can be determined with the help of P-M Interaction Diagrams. Any combination of axial load and bending moment outside the envelope is unsafe and will cause failure of the column. P-M Interaction Diagram is a much faster way of analyzing a concrete column for large eccentricities.

Finite Element (FE) Analysis software ANSYS 11 has been used to model and analyze the RC column specimens made of plain concrete (PC) and SFRC and also P-M Interaction Diagram is construction via FE outcomes. This paper introduces a numerical model for SFRC as well as PC specimens with varying eccentricities and a good correlation has been obtained between FE model and experimental results. Thus the FE models of SFRC and plain RC columns are validated experimental results.

2 EXPERIMENTAL PROGRAM

2.1 *Strategy for Specimen Design*

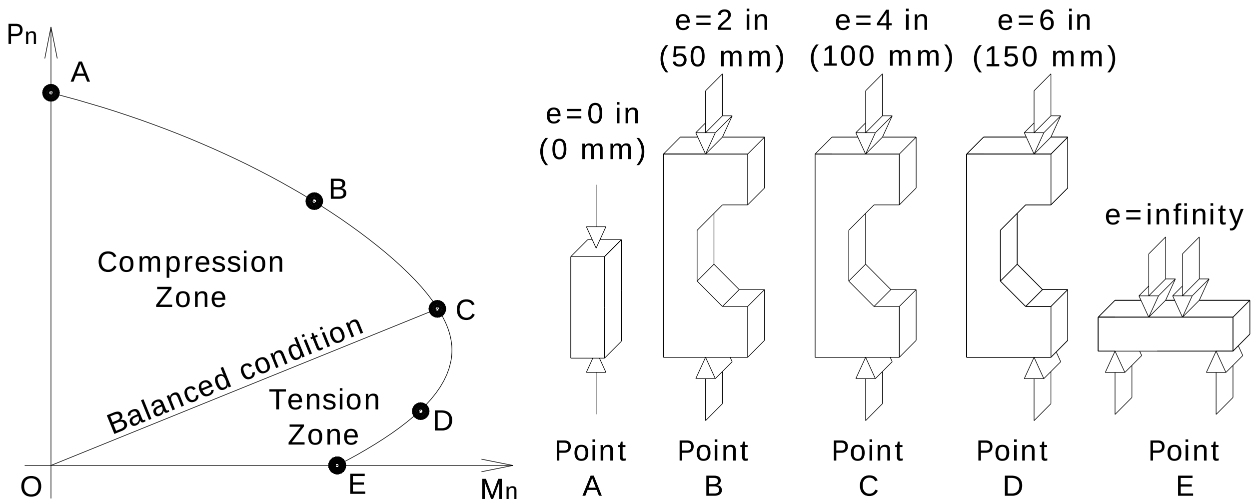
To get the actual axial and bending behaviour of square RC columns due to eccentric loading, it was intended to construct P-M Interaction Diagram experimentally. To this end, special types of specimens (Fig. 1a) are casted to apply eccentric loading and tested in a 1000 kN digital universal testing machine (UTM). Figure 1 shows details of strategy for specimens to get different points in a P-M Interaction Diagram (Points A, B, C, D and E with varying eccentricities), images of specimen dimensions and reinforcement detail, images of steel fibers, casted specimens and testing in UTM. A total of 2 pure compression specimens (for point A), 6 eccentric loading specimens (for point B, C and D) and 2 pure bending specimens (for point E) are made using PC and SFRC. The eccentric loading specimens (Point B, C, D) are made with larger cross section with over reinforcement at top and bottom to prevent any failure at loading points and haunch are made to provide stiffness against local stress concentration. Also PC and SFRC cylinders of 4 in diameter and 8 in height are made to determine compressive and splitting tensile strengths.

2.2 *Material Properties*

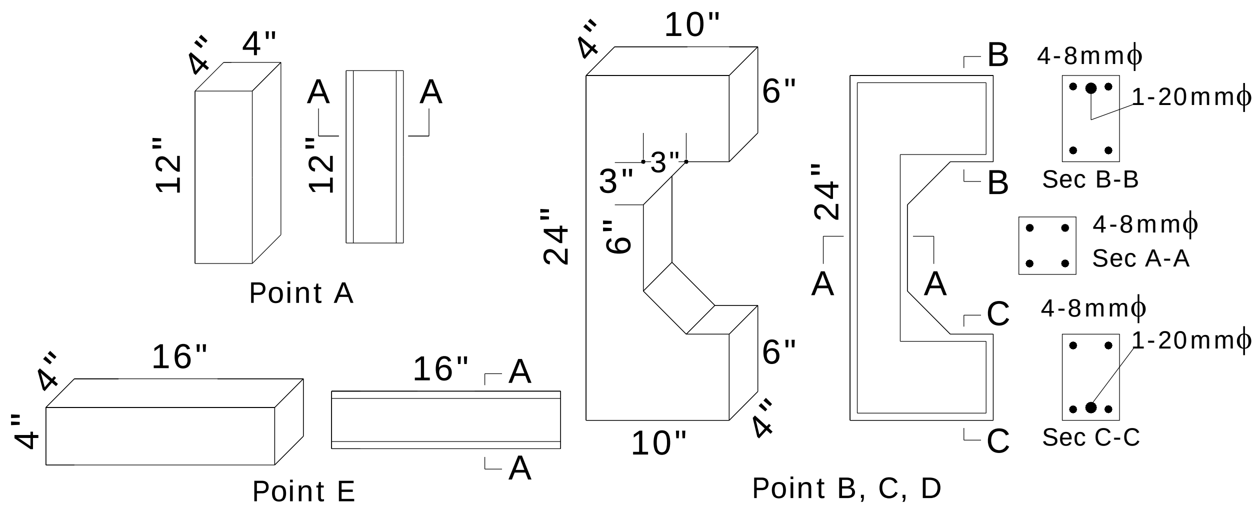
Stone aggregate is used to make the PC and SFRC specimens. The size of the aggregate is maintained 25 mm passing & 19 mm retained and 19 mm passing & 12 mm retained with a ratio of 1:1. The average compressive strength (Fig. 2a) of plain concretes is 18 MPa (2600 psi) and splitting tensile strength (Fig. 2b) is 3.5 MPa (500 psi) and in case of SFRC the compressive strength (Fig. 2a) is 30 MPa (4300 psi) and tensile strength (Fig. 2b) is 8 MPa (1143 psi). The water-cement ratio was kept 0.5 to maintain the workability of the mixture. The mix ratio C:FA:CA was maintained 1:2:4 with 1.5% steel fiber volume ratio. In this research customized laboratory prepared end-enlarged steel fiber is used for SFRC casting. The aspect ratio (length/dia of fiber=*l/d*) of fibers was 40. According to ASTM A 820/ A 820M-06 the average tensile strength of each fiber shall not be less than 345 MPa (50 ksi). The average tensile strength of steel fibers were 1100 MPa (160 ksi) which satisfies the minimum requirement. Ordinary Portland Cement was used in this research. The yield strength of steel rebar used in this work was 500 MPa (72.5 ksi).

2.3 *Testing and Data Acquisition*

Digital universal testing machine (UTM) of capacity 1000 kN is used to perform compressive, eccentric and bending test, of this experiment. This is a displacement controlled machine. Load and displacement values are measured from load cell of UTM. The splitting tensile strain was measured employing digital image correlation technique (DICT) using HD video footage of testing as also followed in Islam 2011, Islam et al. 2011 and Islam et al. 2015. In this experiment the displacement rate of 1 mm per minute was applied.



(a)



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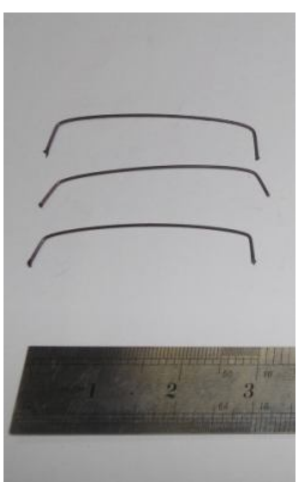


(c)

(d)

(e)

Figure 1. (a) Illustration of PC and SFRC specimens with varying eccentricities for different points on a P-M Interaction Diagram, (b) dimension and reinforcement detail of specimens, (c) steel fibers used in this study, (d) casted specimens ready for testing, (e) testing of specimen with eccentric loading in UTM.

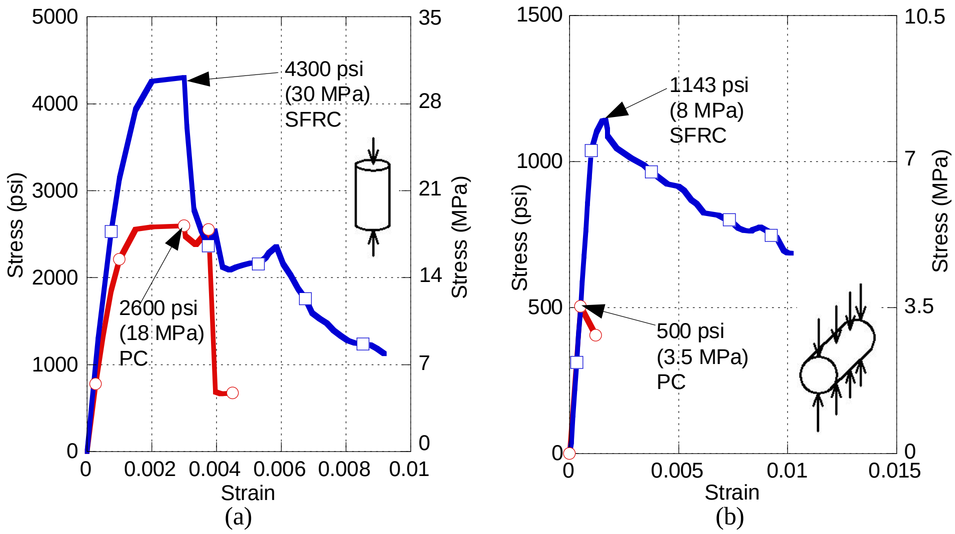


Figure 2. (a) Compressive stress-strain behaviour of PC and SFRC, (b) Tensile stress-strain behaviour of PC and SFRC.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 *Effects of SFRC on Compressive Strength*

The compressive strength of plain concrete and SFRC has been evaluated according to ASTM: C 39/C 39M – 05. Though steel fiber has a significant effect on the enhancement of tensile strength but in case of compressive strength the effects has been found variable. As a result of Poison’s effect the concrete member under compression begins to crack and hence dilate laterally and it fails due to spalling of concrete (Islam 2011, Islam et al. 2011, Islam et al. 2015). Steel fibers arrest the micro-cracks in concrete and thus delays spalling of concrete and enhance axial capacity. ACI 544.4R-88 does not consider axial capacity enhancement due to SFRC. On the other hand, compared to the plain concrete, the compressive strength capacity of SFRC with steel fiber of aspect ratio 40 has increased 66.67% (Fig. 2a). Besides this, the ductility has also enhanced 1.41 times for steel fiber aspect ratio of 40 considering the post peak behaviour.

3.2 *Effects of SFRC on Tensile Strength*

The splitting tensile strength of the SFRC has been evaluated according to ASTM C 496/C 496M-04. Plain concrete is a brittle material which splits under load whereas steel fibers in SFRC arrests the initial cracks and prevent the concrete from spalling and the concrete continue to carry load without failure. Compared to the plain concrete, the tensile capacity of SFRC with steel fiber of aspect ratio 40 is increased 128.57% (Fig. 2b). Beside this, the ductility has also enhanced 9 times. So it can be easily said that steel fiber is more effective to increase the tensile strength compared to compressive strength.

3.3 *Effect of SFRC on P-M Interaction Diagram*

Figure 3(a) to (e) shows the load displacement behavior of RC columns made of plain concrete and SFRC respectively for point A to E on P-M Interaction Diagram with an eccentricity of zero to infinity. It has been observed that axial capacity of SFRC specimen (Point A) is found to be increased by 58.9% compared to the control specimen and the ductility for SFRC specimen has increased by 1.92 times compared to control specimen. Axial load and bending moment (Point B) are found to be increased by 15.4% and 15.38% respectively compared to the control specimen and the ductility for SFRC specimen has increased by 3.5 times compared to control specimen. The axial load and bending moment (Point C) found to be enhanced by 11.5% and 11.8% respectively compared to the control specimen. It is observed that both the axial and bending moment capacity (Point D) of SFRC specimen is found to be increased by 14.2% and 17.6% respectively compared to the control specimen. Besides this, the ductility of SFRC specimen is also increased by 1.57 times compared to control specimen. The pure bending moment capacity (Point E) of SFRC specimen is found to be increased by 52.5% compared to the control specimen. Beside this the ductility of SFRC specimen is also increased by 2.5 times compared to control specimen.

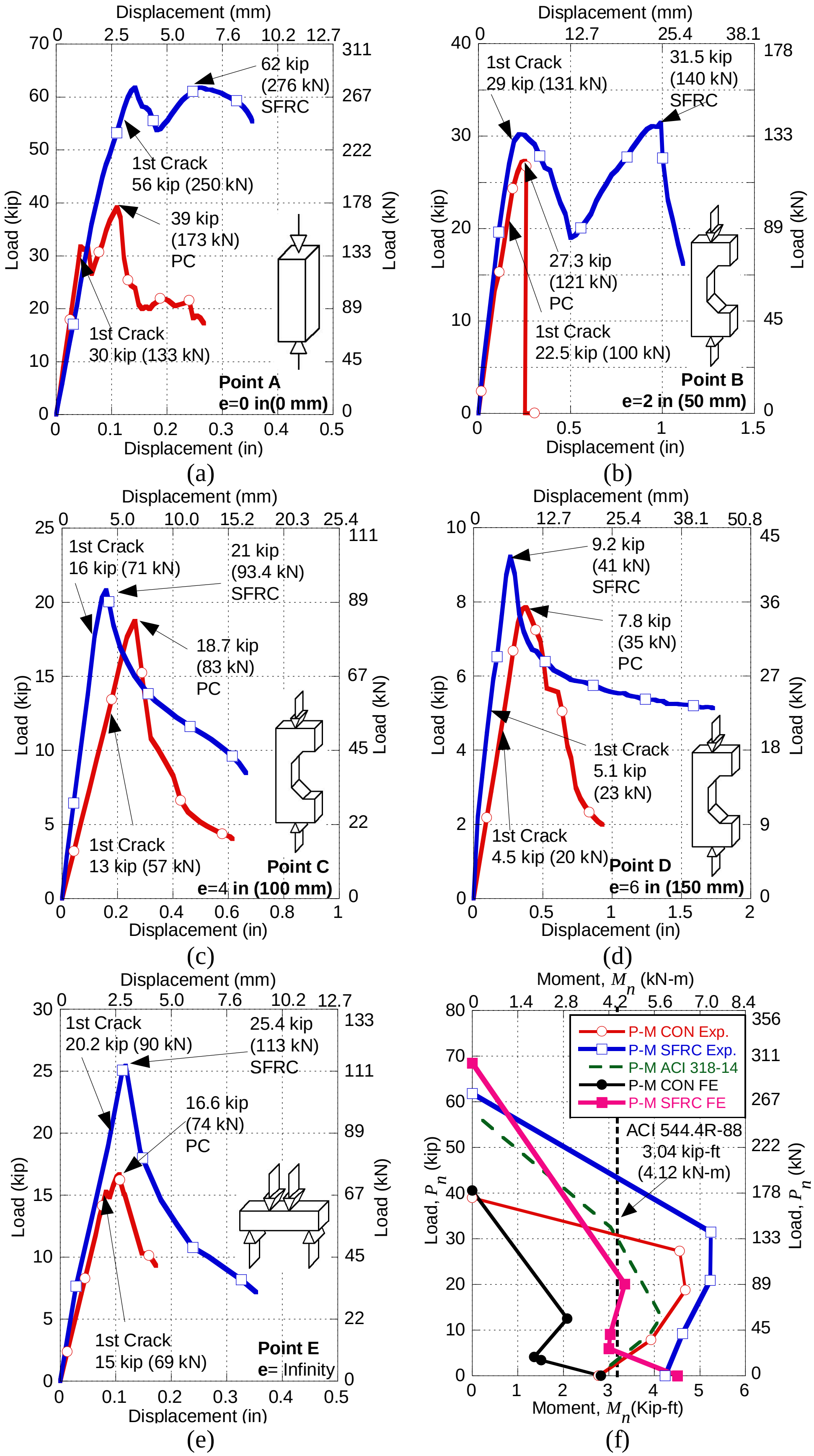


Figure 3. (a), (b), (c), (d), (e) Load-displacement behaviour of Point A, B, C, D and E respectively of P-M Interaction Diagram, (f) P-M Interaction Diagram of PC, SFRC, ACI 318-14 and FE models.

Figure 3(f) shows the comparison between P-M Interaction Diagram of control, SFRC specimen and analytical values as per ACI 318-14 including both the compression and tension zone. But compared to ACI 318-14, the control specimen showed lower axial strength at the point of pure compression (Point A). In fact, ACI 318-14 considers tie reinforcement for square columns whereas there were no tie reinforcement provided in the the experimental columns to get the actual contribution of steel fiber in concrete matrix against dilation, hence slightly reduced strength was found. But in case of pure bending capacity, the control specimen showed same result as ACI 318-14. Again, ACI 544.4R-88 does not consider any axial capacity enhancement due to steel fibers, but the experimental testing shows almost 58.9%, 15.4%, 11.5% and 17.6 % axial capacity enhancements for points A, B, C and D respectively. The P-M Interaction Diagram for SFRC specimen has exhibited greater load and moment capacity compared to control specimen. Moreover, ACI 544.4R-88 formulae exhibits conservative fashion in predicting pure bending capacity whereas experimental results showed 16%, 11% and 18% bending capacity enhancement for Points B, C & D and 52.5% enhancement for pure bending compared to control specimens.

4 FINITE ELEMENT MODELING AND ANALYSIS

To study the behavior of concrete, Finite Element Modeling and Analysis is a widely accepted method. The objective of the FE Modeling and Analysis is to verify the results with the experimental findings of the present research and to propose an acceptable SFRC model to be applied in further analysis. All the PC and SFRC RC specimens of the current investigation are modeled in ANSYS 11 framework. A reasonable modeling of concrete on a FE platform using suitable element type, adequate mesh size, appropriate boundary conditions, realistic loading environment and proper time stepping can represent the actual situation of test condition and thus can help to estimate the capacity from FE models.

An eight node solid element, SOLID65 is used to model the concrete and also SFRC. The solid has eight node with three degrees of freedom at each node-translational in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The element is also applicable for reinforced composites such as fiberglass as well as SFRC (ANSYS 11). The 3-D spar element, LINK8 is used to model the steel reinforcement which is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions and material properties like Plasticity, creep, swelling, stress stiffening, and large deflection capabilities are included.

Material properties for PC and SFRC such as (i) elastic modulus, (ii) density, (iii) Poisson's ratio, (iv) multilinear elastic stress-strain behavior, (v) ultimate uniaxial tensile strength, (vi) shear transfer co-efficient for closed and open crack, (vii) Willam and Warnke (1975) failure criterion were applied together with Newton-Raphson approach to obtain the simplest nonlinear solution. Figure 3(f) shows the P-M Interaction Diagram of PC and SFRC specimens from the experimental results and FE outcomes. The FE analyses showed similar results for pure compression and pure bending (Point A and E respectively) for both PC and SFRC specimens but conservative results for specimens with eccentric loading (Points B, C and D). The conservative results of FE models ensures higher factor of safety for axial and bending capacity prediction of PC and SFRC square RC columns.

5 FAILURE PATTERN

Reinforced concrete fails in two different modes i.e. brittle failure and ductile failure. Failure pattern of concrete specimens has been observed during experimental testing. Another important objective of this study was to prevent the brittle failure of concretes by increasing ductility using steel fibers without compromising the strength. Brittle failure has been successfully resisted by using SFRC and post peak ductility is increased in a significant amount. The plain concrete RC specimens showed spalling of unconfined clear cover under loading on the other hand SFRC specimens showed effective crack arresting and crack control behaviour. FE analyses showed similar failure pattern compared to experimental specimens which also validate the FE analysis done in this current work (Fig. 4). Figure 5 represents the principal stress distribution in the PC and SFRC test specimens. Principal compressive stress distribution clearly depicts the compressive stress vector in eccentrically loaded column. The principal compressive stress is uniform in pure compression and in pure bending specimen it forms a compression arch. In all cases SFRC specimens shows larger compressive stresses.

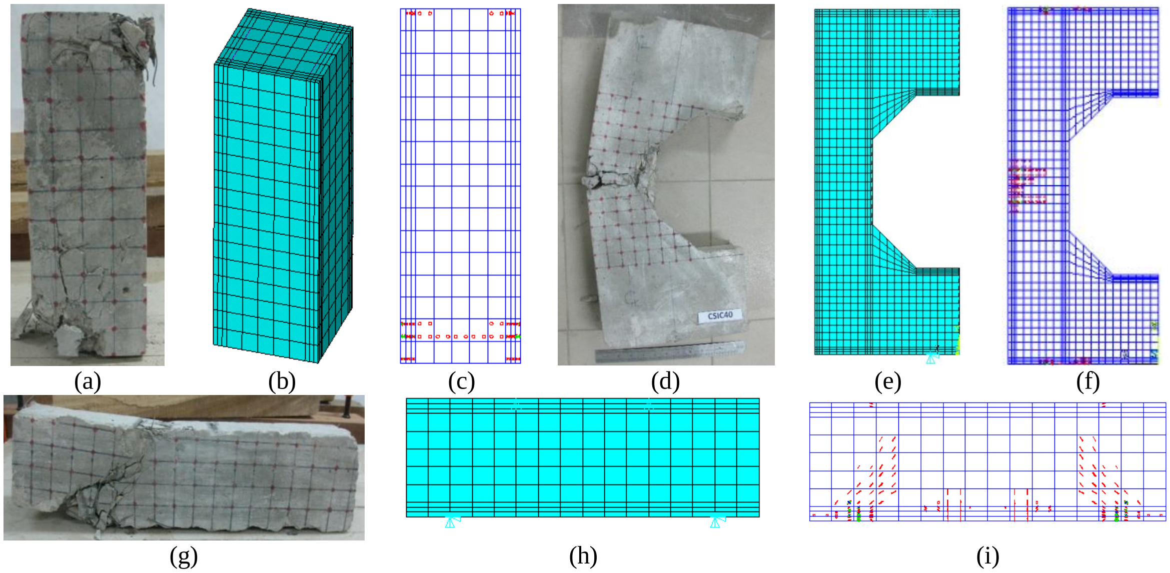
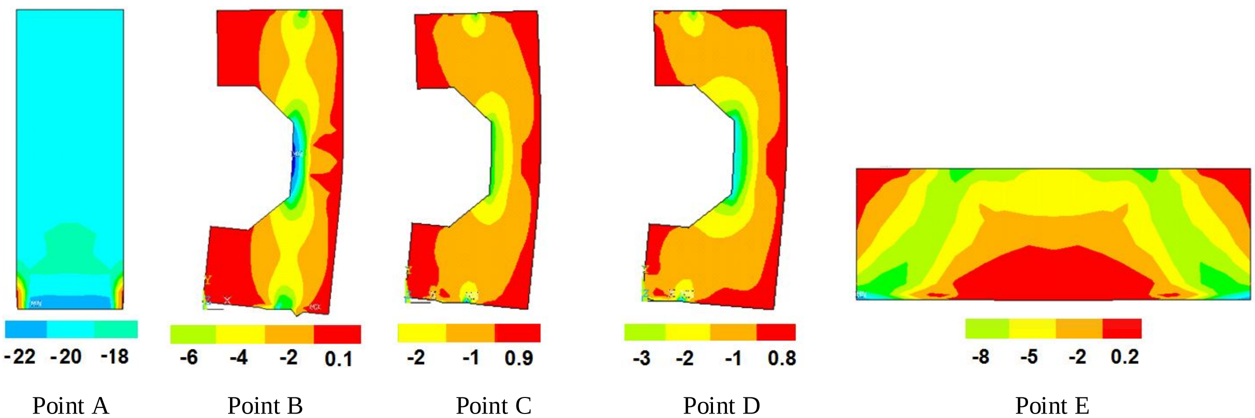
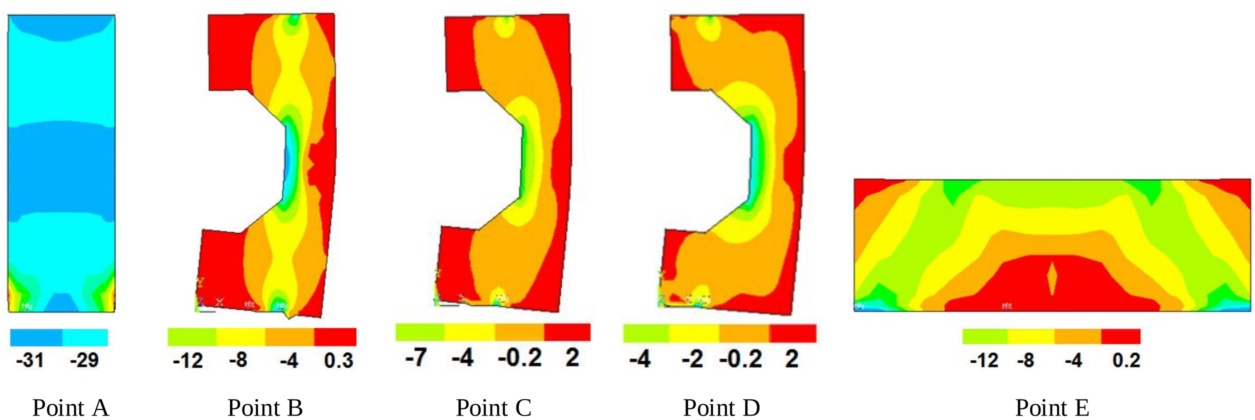


Figure 4. Typical experimental failure pattern, FE model and failure of FE model of SFRC specimens for (a), (b), (c) specimen with pure compression (Point A), (d), (e), (f) Specimen with eccentric loading (Point D), (g), (h), (i) specimen with pure bending (Point E).



(a)



(b)

Figure 5. Principal compressive stress distribution of specimens made of (a) PC and (b) SFRC. The numbers are the values of stresses in MPa and the minus sign represents compressive stress.

6 CONCLUSIONS

The following conclusions may be drawn from this work:

i. According to the experimental program, P-M Interaction Diagram was successfully developed for PC and SFRC square columns and combined effect of axial load and bending moment capacity due to eccentricity is effectively investigated.
ii. The SFRC specimens showed compressive strength enhancement of 66.67%, splitting tensile strength enhancement of 128.57%, pure axial capacity enhancement of 58.9%, pure bending capacity of 52.5%, and axial and bending capacity enhancement of 11-15% and 11-17% respectively under eccentric loading.
iii. Plain concrete RC square column specimen under pure axial loading showed lower capacity compared to ACI 318-14 which is due to absence of tie reinforcements. On the other hand, SFRC square RC column without tie reinforcement showed close capacity compared to ACI 318-14. The randomly distributed steel fibers in concrete matrix should provide resistance to dilation and thus capacity enhanced.
iv. ACI 544.4R-88 does not consider any axial capacity enhancement due to steel fibers, but the experimental testing shows almost 58.9%, 15.4%, 11.5% and 17.6 % axial capacity enhancement for points A, B, C and D respectively and 66.67% compressive strength enhancement for cylinder test. Again in case of bending moment capacity of SFRC, the enhancement is very small with a provision of conservative design as per ACI 544.4R-88, but experimental results showed 16%, 11% and 18% bending capacity enhancement for Points B, C & D and 52.5% enhancement for pure bending compared to control specimens.
v. The FE analyses showed similar results for pure compression and pure bending (Point A and E respectively in P-M Interaction Diagram) for both PC and SFRC specimens but conservative results for specimens with eccentric loading (Points B, C and D). The conservative results of FE models ensures higher factor of safety for axial and bending capacity prediction of PC and SFRC square RC columns. FE analyses showed similar failure pattern compared to experimental specimens which also validate the FE analysis done in this current work.
vi. This research work puts light on the axial and bending capacity of square RC columns made of PC and SFRC and construction of P-M Interaction Diagram experimentally. SFRC specimens showed enhanced capacity as well as ductility compared to plain concrete specimens. The SFRC construction has not yet been started in Bangladesh due to lack of reliable experimental results and FE analyses. The observations and data of this work may help the building and bridge construction industry of Bangladesh to start the journey of SFRC construction.

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