ASPS Conference Proceedings 1: 245-250 (2022)

Proceedings of

12th Structural Engineering Convention - An International Event (SEC 2022)

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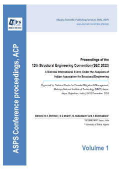

Geometric Nonlinear Analysis of RC Frame structure using Applied Element Method (AEM)

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Paper ID -030159

Abstract

Reinforced Concrete (RC) structural elements having vast varieties of applications. Understanding the failure mechanism, deflection capacity beyond elastic limit is very important from the structural engineering point of view. Various RC structures are slender in nature which produces large deformations due to geometric nonlinearity. Nonlinear analysis of RC structures is very complex in nature and hence there is need of highly efficient numerical method. Applied Element Method (AEM) is a displacement-based method which can track highly nonlinear behavior of the structure i.e. crack initiation and propagation, element separation, rigid body motion of structural elements and total collapse process with the high accuracy. In this study, the aim of the geometrical nonlinear analysis is to predict the deflection of the RC structure at various loading interval. In this paper the results obtained using AEM are compared with the Finite Element Method (FEM) based results obtained using the ABAQUS software. It is observed that there is a close agreement between the results obtained using AEM and FEM which shows that, AEM can be used for the geometric nonlinear analysis of the structures effectively.

Keywords: Geometric Nonlinearity, Applied Element Method, Finite Element Method, RC structures, large deformations.

1. Introductio

Earthquakes in the past history have caused tremendous damages to the structures [1]. The damage from these disasters can be controlled by calculating the deflection capacity of the members of the structure. As the commonly used software are mostly applicable up to elastic limit. For obtaining structural capacity afar its elastic limit, the analysis such as pushover process is need to be done. Hence to predict the outcome of such effects like earthquake, blast, progressive collapse highly efficient software tools need to be used. For reinforced concrete structures which are more brittle as compare to steel structure the failure mechanism of structure should be studied correctly for safety and serviceability conditions. To perform this nonlinear analysis highly efficient mathematical modelling & numerical techniques are required. RC structures are slender in nature which produces large deformations causing geometric nonlinearity [2]. Applied Element Method (AEM) is a displacement-based method which can track nonlinear behaviour of the structure i.e. crack initiation and propagation, element separation, rigid body motion of structural elements and total collapse process with the high accuracy [3]. In AEM structure or structural members are discretized with rigid elements connected by springs. Computer based mathematical modelling and programs can be efficiently used for simulation in the nonlinear state of structure. The finite element method-based programs need to be modified to simulate the state of structure for the reduced resistance after yielding. There are several limitations in adopting the currently available methods because in FEM analysis, element separation in non-linear state cannot be performed because it is the main assumption that the elements are connected at the nodes only and it can't be separated. The main problem of modelling using the FEM is the modelling of large cracks and element separation. In FEM the crack location can be either pre-defined or automated (both of these are not practical). To overcome the above difficulties newly developed numerical method for analysis which is Applied Element Method (AEM) can be used. This method is based on the discrete element approaches like Rigid Body and Spring Model (RBSM).AEM was established by Hatem Tagel-Din at the University of Tokyo during his doctoral studies during the late 1990's [3]. AEM has a capacity to follow the structural behavior from zero loading condition to total collapse of the structure such as Reliable amount of accuracy, appreciable CPU time, relatively simple material modelling [3]

The present study consists of the geometric nonlinear analysis of RC beam and five different RC frame structures using AEM.The objective of the geometrical nonlinear analysis is to predict the deflection magnitude of the RC structure at various loading interval. Parametric study is carried out considering different number of elements, different number of springs and various load increments.

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Proceedings of the 12th Structural Engineering Convention (SEC 2022), NCDMM, MNIT Jaipur, India | 19-22 December, 2022

doi:10.38208/acp.v1.504

2. Applied Element Method

The AEM was established by Hatem Tagel-Din at the University of Tokyo during his doctoral studies during late 1990's [4]. AEM had been established based on continuum mechanics to do complete collapse analysis for overcoming the limitations of present methods.Modelling of the structure is similar to FEM where the structural members are divided into small elements but only the difference is in the connection process where the elements are connected along the surface of an elements. In AEM, distributed number of springs i.e. normal & shear springs are connected at the edges of rigid elements at a particular interval.Modeling of the structure to be analyzed can be converted to number of elements and springs at the edges as shown in the Fig 1. The Figure 1(a) explains the modeling of concrete and Figure 1(b) describes the modeling of reinforcement in concrete with the help of example using springs in AEM.
Spring stiffness can be determined as given below:

$$K_n = \frac{E \times d \times t}{a} \qquad (1)$$

$$K_s = \frac{G \times d \times t}{a} \qquad (2)$$

Where,
d: distance between springs
t: Thickness of the element
a: Length of the representative area
E: Young's Modulus
G: Shear Modulus
K_n: Normal spring stiffness
K_s: Shear spring stiffness

From the equation (1) and (2) each spring represent the stiffness of volume having area of (d x T) with the length of 'a'. In two-dimensional element problem each element possesses the three degrees of freedom. All the springs are geometrically related to the centroid of the element because each spring has particular distance from centroid of the element [4]. Spring forces are found out for each set of spring under the unit displacement at centroid of an element to find the stiffness matrix. Then these stiffnesses are added together to form the Global stiffness matrix. Hence the stiffness matrix between two elements shows the stiffness at centroid of an element.

The size of stiffness matrix is 6 x 6 for the 2D element. The analysis can be done using the equation,

$$\{F\} = [KG]\ \{\Delta\} \qquad (3)$$

Where,
{F} - Applied load vector
{Δ} - Displacement vector

[KG] - Global stiffness matrix

Displacement at centre of an element is transferred to the ends of each spring for evaluation of forces in them. In case of element separation and crack generation, based on the material properties springs are cut when the ultimate stress level is reached in particular spring. It can be possible for any spring at any location. Hence pre-definition of the Crack Propagation is not required and hence Crack Propagation can follow up to complete failure of the structure [2].

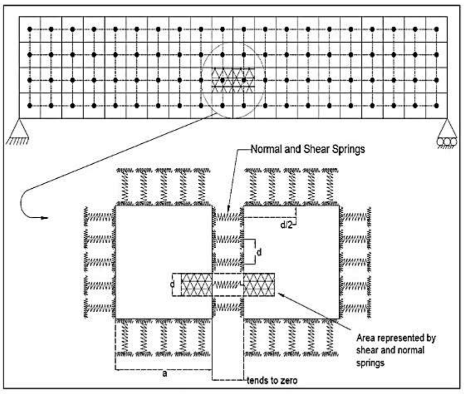

Figure 1(a). Modelling of concrete to AEM

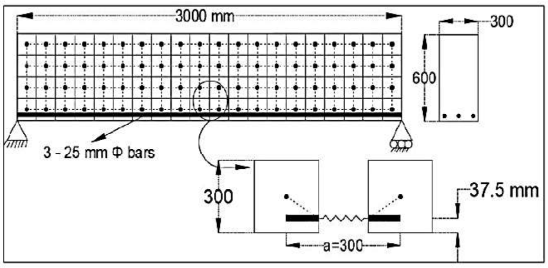

Figure 1(b). Modelling of reinforcement in AEM

$$K_n = \frac{Es \times d \times t}{a} = \frac{200000 \times 3 \times \frac{3.142}{4} \times 25^2}{300} \qquad K_s = \frac{Gs \times d \times t}{a} = \frac{76923.1 \times 3 \times \frac{3.142}{4} \times 25^2}{300}$$

Fig. 1. Modelling of structure to AEM

2.1. Stiffness matrix formulation for 2D element

In two-dimensional element there are 2 numbers of springs includes one normal spring and one shear spring. Each element has 3 degree of freedom. The spring connectivity for 2-D element is shown in the Fig. 2.
Internal deformations of an element are represented by springs connected around element because it is assumed to be rigid body motion. Unit displacement is applied in each degree of freedom one by one by keeping other restrained to derive 6 × 6 stiffness matrix. At the C.G of element force represents the stiffness in that particular direction of force.
Let,
$A = \sin(\alpha+\theta)$, $A_1 = \sin(\alpha_1+\theta_1)$
$B = \cos(\alpha+\theta)$, $B_1 = \cos(\alpha_1+\theta_1)$
$C = L \sin(\alpha)$, $C_1 = L_1 \sin(\alpha_1)$
$D = L \cos(\alpha)$, $D_1 = L_1 \cos(\alpha_1)$
Where,
α & θ be the inclination of the spring at first node.
α_1& θ_1 be the inclination of the spring at second node.

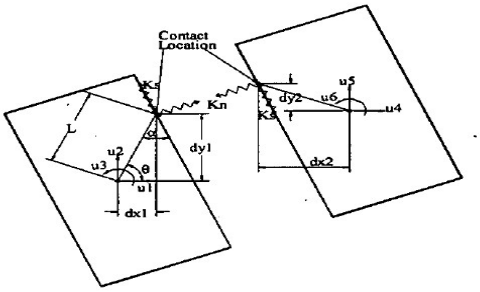

Fig. 2. General position of deformed element and Spring Connectivity [4]

Stiffness matrix of 6 x 6 can be derived for each element by summing up the stiffness matrix of all springs around the surface of an element which is also a 6 x 6 matrix. Then the global stiffness matrix can be assembled and derived to find the unknown displacement at each node. Theupper left quarter elements of stiffness matrix [K] for individual spring is as given below,

$K_{11} = K_n A^2 + K_s B^2$, $K_{12} = K_{21} = - K_n AB + K_s AB$,
$K_{13} = K_{31} = - K_n AD + K_s BC$, $K_{22} = K_n B^2 + K_s A^2$
$K_{23} = K_{32} = K_n BD + K_s AC$, $K_{33} = K_n D^2 + K_s B^2$

2.2. Development of computer program for geometric nonlinear analysis using AEM

The computer program is developed using C Language.The program has three stages are (1) Preprocessing (2) Processing (3) Post processing. Applied Element Method is nothing but the logical and speedy iteration of these three stages continuously. The Preprocessing and Postprocessing stages require huge efforts if the data is to be handled manually.Detailed procedure of geometric nonlinear analysis to develop computer program is as follows [4]:

(a) For geometric nonlinear analysis of RC structure following inputs are required given below:
  - Number of elements(ne), Number of Springs(ns), Number of Nodes(nn)
  - Nodal Joint connectivity for each element(i.e. je and ke)
  - Material properties of each element(E, G, E_s, G_s etc.)
  - Reinforcement details like diameter of bar and cover to reinforcement.
  - Coordinates of an each joint i.e. node which is at the centroid of a square element.
  - Number of retrained joints

(b) Start the first load increment in which first of all the stiffness matrix to be developed which is discussed in the section 2.1. To develop the 6 × 6 matrix for each spring the stiffness $K_n$and $K_s$for normal and shear spring respectively should be determined. Then add matrices of individual spring to get the final stiffness matrix[sm] for each element.

(c) The stiffness matrix for all elements and find the global stiffness matrix [SJ_1] which will be of size (3nn) × (3nn).

(d) Consider the load increment [ax] obtained by dividing total applied load into number of intervals, residual force vector as null for only first load increment and find the combined load vector [ac1].Using the equation (3) to find the global displacement vector [$disp_1$]. Using the displacement vector update the geometry and add the rotation from the nodal displacement to Gama(which is the rotation of the element with respect to considered axis).Find the updated joint stiffness matrix [SJ_2].

(e) Find the internal force vector [F_{Int}] using the equation, [F_{Int1}] = [SJ_2] × [$disp_1$].

(f) Find residual force vector [RG_2] using difference between the applied load vector[ac_1] and internal force vector [F_{Int1}].

(g) Update the load vector for next increment [ac_2]=[ac_1]+[ax]+[RG_2].

(h) Print the Applied Load and displacement at desired location and go to step (b) and follow all next steps upto the total applied load.

3. Numerical Study

3.1. Deflection analysis of RC beam considering geometric nonlinearity

To understand the effect of element size and number of springs, the problem of cantilever RC beam is taken into consideration. For the analysis, the size of the elements are taken as 75 mm, 50 mm, 37.5 mm of square shape for all as shown in the Fig. 3. For the analysis 1, 3, 5, 7 number of springs are considered. Assuming the concentrated loading at the end of the beam.Increments of 0.1 kN, 0.5 kN, 1 kN and 5 kN are taken into consideration for the analysis and the results are compared for different increments.For the analysis following geometrical data, restraint conditions, type of loading, material properties are considered given below:

Length of cantilever beam: 1350 mm
Cross section of beam: 150 mm × 150 mm
Ec: 25000 N/mm^2&Gc: 10417 N/mm^2 for concrete
Es: 200000 N/mm^2&Gs: 77000 N/mm^2 for steel

The deformed shape of a cantilever RC beam is shown in the Fig.4 at various load interval considering geometrical non-linearity. The more realistic results can be obtained by performing large displacement analysis.

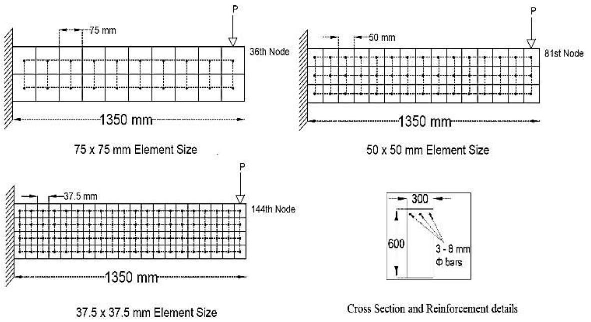

Fig. 3. Discretization of RC beam, Cross section & Reinforcement details

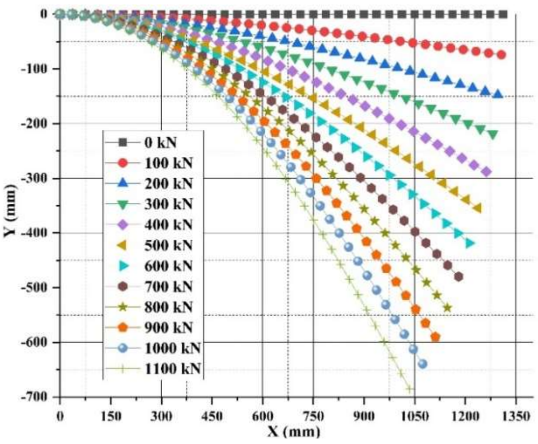

Fig. 4. Deformed Shape of Cantilever Beam (Large displacement analysis)

The results obtained using analytical method are compared with the FEM and AEM based results as shown in the Table-1 and Fig. 5.

From Fig. 5 and Table-1, it is observed that AEM performs better even using 2D analysis as compared with FEM which is carried out using 3D analysis. This shows that even in large deformation cases AEM can be used. From the results it is observed that, the results converges to the analytical solution with the reduction in the size of an element.
In Fig. 6 Load-displacement curve for 0.5kN load increment using 3 springs is described below.

Table-1. Comparison of results for maximum Vertical displacement of AEM and FEM with analytical solution

Maximum Vertical Displacement in mm at 1000 kN (Considering 7 numbers of springs)				
Size of Element	AEM	% Error	FEM	% Error
75 mm	732.76	12.11	870.98	33.26
50 mm	714.76	9.36	775.28	18.62
37.5 mm	699.27	6.99	773.38	18.33
Analytical Solution	653.59			

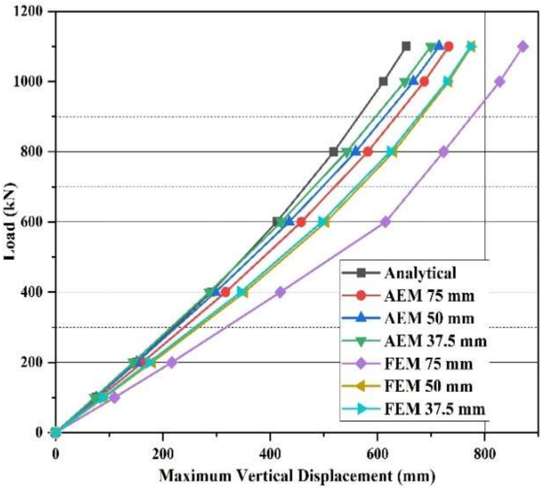

Fig. 5. Comparison of results of AEM and FEM with analytical solution obtained using strain energy method

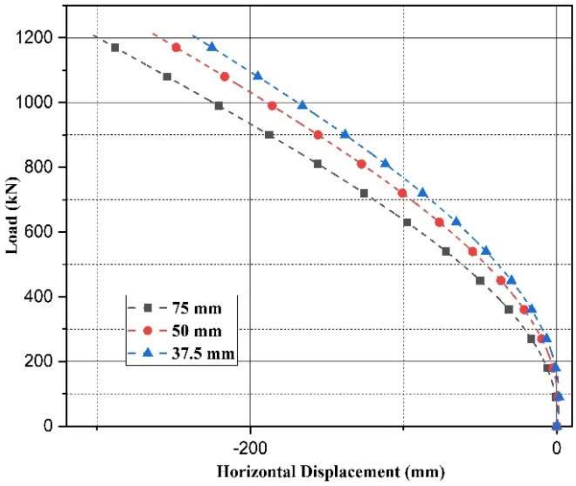

Fig. 6. Load-displacement curve for 3 springs for 0.5kN load increment

From Fig. 6 it is also observed that, the load-displacement curve negative at the beginning for horizontal displacement, this is due to the rotation of the beam's cross section about the neutral axis.

3.2. Geometric Nonlinear analysis of RC frames

To understand the effect of geometric nonlinearity 5 types of RCC frames are taken into consideration having different number of bays and storeys. To understand easily, the nomenclature for frames is given as shown below:

- 1B1S - 1 bay and 1 storey
- 1B2S - 1 bay and 2 storeys
- 2B1S - 2 bay and 1 storey
- 2B2S - 2 bay and 2 storeys
- IBS - 2 bay at bottom and only 1 bay at above storey as shown in the Fig. 8.

For the analysis 300 mm size of square element and following geometrical data, restraint conditions, loading condition, material properties are considered given below. The cross section and reinforcement details of RC column and beam are shown in the Fig. 7 in the form of line sketch.
Material Properties:

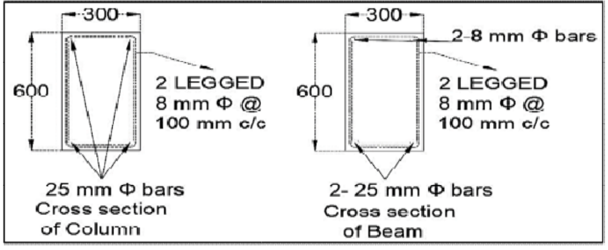

Fig. 7. Cross Section & Reinforcement details of RC element of frame

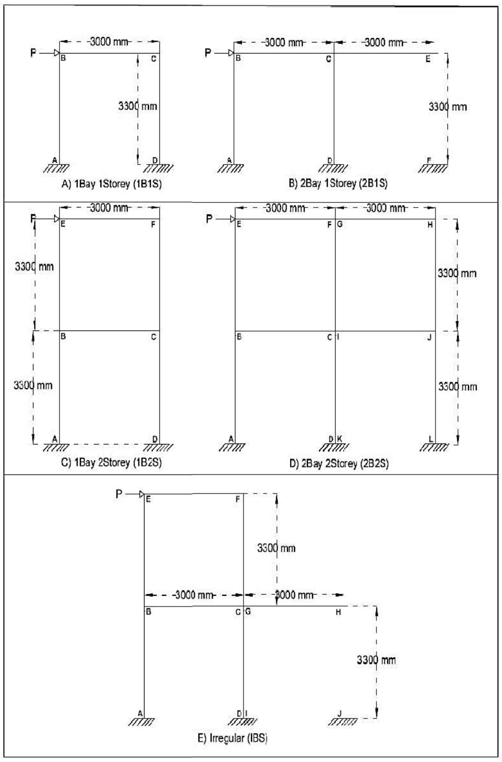

Fig. 8. Problem statement in terms of lines diagram

- Modulus of Elasticity Ec of Concrete : 25000 N/mm^2
- Modulus of Rigidity of concrete Gc: 10417 N/mm^2
- Grade of concrete : M25 ; Poisson's ratio : 0.20

Geometrical Properties and reinforcement details:

1) Column
   - ➢ Length of column: 3300 mm
   - ➢ Section of column: 300 mm × 600 mm
   - ➢ 4-25 mm Φ bars and 8 mm Φ stirrups at 100 mm c/c
2) Beam
   - ➢ Length of beam: 3000 mm
   - ➢ Cross section of column: 300 mm × 600 mm
   - ➢ 2-25 mm Φ bars at bottom
   - ➢ 2-8 mm Φ bars at top and 8 mm Φ stirrups at 100 mm c/c

For 2B1S type of frame,load v/s Displacement curve is plotted by considering and not considering the effect of reinforcement i.e. PCC and RCC as shown in the Fig. 9.

It is observed that, by neglecting the effect of reinforcement the magnitude of lateral displacement increases as shown in the Fig. 9.The load increments are varied by keeping number of springs constant and the graphs are plotted as shown in the Fig. 10.

From Fig. 10 it is observed that, Smaller the load increment, more is the lateral displacement.By keeping load increment constant the number of springs are varied to compare the results shown in the Fig. 11.

From Fig.11 it is observed that, with the increase in the number of springs, there is less variation in the value of lateral displacement.The results of Load v/s Displacement for all five types of portal frame is evaluated using computer program considering 10 kN load increment with 10 number of springs as shown in the Fig. 12.

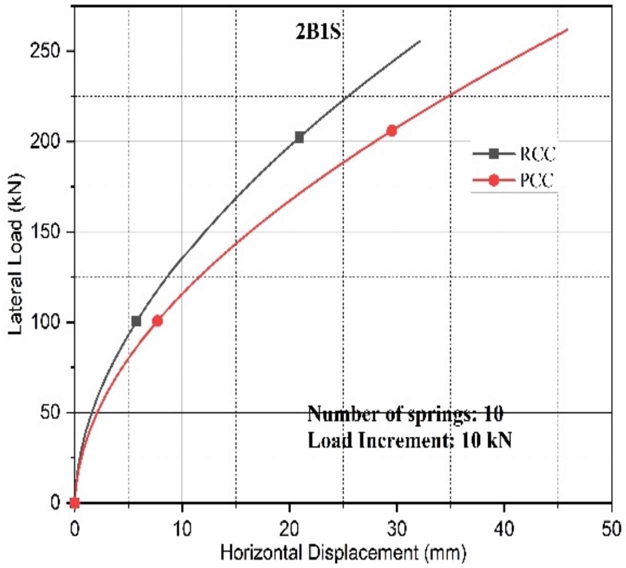

Fig. 9. Load v/s Displacement for 2B1S frame with and without considering the effect of reinforcement

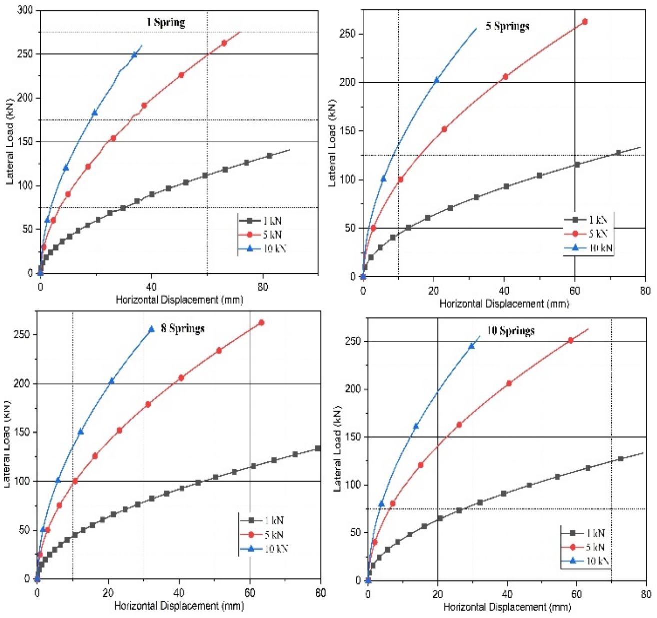

Fig. 10. Load v/s Displacement for 2B1S frame using 1, 5, 8 and 10 springs

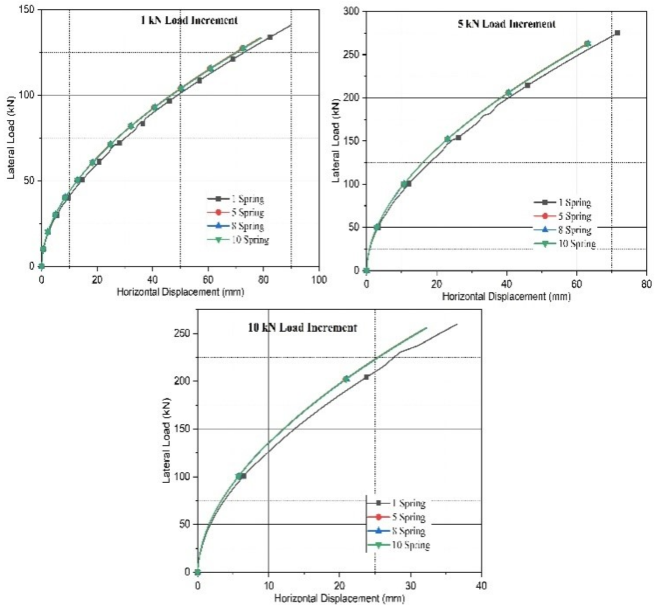

Fig. 11. Load v/s Displacement curve for 2B1S frame using 1 kN, 5kN and 10 kN Load Increment

As per structural point of view, from above 5 types of RC frames, the 1B2S type of frame is most slender in nature and 2B1S is the least slender in nature with respect to lateral load. So that, for a particular lateral load the displacement of 1B2S should be the maximum and of 2B1S should be minimum. From Fig. 12 it is observed that, similar results are obtained using AEM, indicating applicability of AEM for geometrical nonlinear analysis.

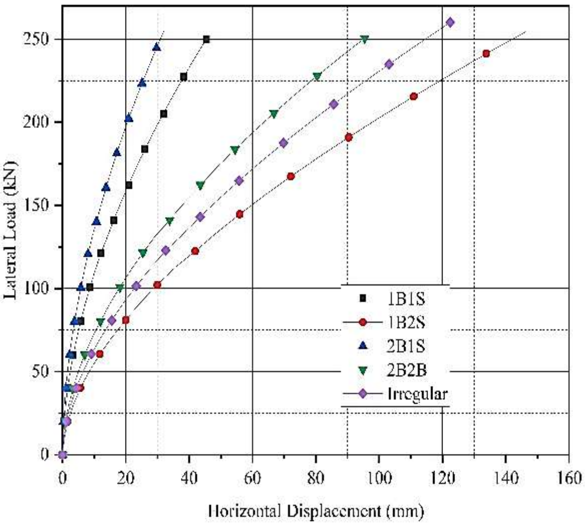

Fig. 12. Load v/s Displacement curve for 1B1S, 1B2S, 2B1S, 2B2S and IBS types of RC **frames**

4. Concluding Remarks

Based on parametric study on geometric nonlinear analysis of RC portal frame using Applied Element method (AEM) with varying size of rigid element, varying numbers of connecting spring between elements and varying load increments following concluding remarks are made:

- The study shows that, the results do not converge with more than 5 numbers of springs. Hence 3 to 5 numbers of connecting springs between rigid elements are sufficient for the analysis.
- For constant load increment and number of spring the displacement magnitude is more for large size element. The load-displacement curve is negative at the beginning for horizontal displacement, this is due to the rotation of the beam's cross section about the neutral axis.
- The results show that, the smaller element size and less number of springs gives accurate results for geometric nonlinear analysis.
- For the smaller load increment, Load-displacement curve obtained is smoother.
- When AEM is used the error with reference to analytical results in maximum transversedisplacement of RC cantilever beam reduces from 12.11% to 6.99% with the change of element size from 75 mm to 37.5 mm. Similarly the error reduces from 33.16 % to 18.33 % for FEM. This shows that, even though AEM results are obtained using 2D analysis performs better than analysis using 3D element in FEM.
- It is also concluded that, AEM can be used to predict the large displacement behavior of RC frame structures.

Disclosures

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