INTERNATIONAL JOURNAL OF RESEARCH IN MECHANICAL, MECHATRONICS AND AUTOMOBILE ENGINEERING(IJRMMAE)
ISSN: 2454-1435 (Print) | 2454-1443 (online)
Volume 9 Issue 1, April – June. 2023 - www.ijrmmae.in – Pages 16-28

EVALUATING THE IMPACT OF ECCENTRIC LOADING ON REINFORCED CONCRETE COLUMNS: A FINITE ELEMENT ANALYSIS APPROACH

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Abstract:

This work shows a numerical simulation of the behaviour of reinforced concrete columns under eccentric stress using the finite element technique. The study was carried out in order to investigate the behaviour of these columns. A software programme called Abaqus was used to do an analysis on three columns that had varying eccentricities. A comparison was made between the findings and tests conducted in the laboratory in order to verify the correctness of the simulations. For the purpose of this investigation, the concrete fractures and damage, force-displacement curves, bearing capacity, and ultimate capacity of the columns were the primary areas of attention. According to the findings, the carrying capacity of the columns reduced as the eccentricity rose, and the bending behaviour of the columns got more obvious as the eccentricity increased. In situations where the eccentricity was low, the behavioural model developed by Todeschini was shown to properly predict the behaviour of the columns; but, when the eccentricity was large, the model's accuracy decreased. These discoveries have significant repercussions for the methodology of constructing and assessing reinforced concrete columns that are subjected to eccentric loading.

Keywords: *Columns made of reinforced concrete, eccentric loading, finite element analysis, concrete damage plasticity, and ultimate capacity are some of the keywords that relate to this topic.*

1.Introduction

Columns that are constructed out of concrete are among the structural components that are used the most often in the building sector. They serve the purpose of providing support to structures such as bridges, buildings, and other necessities of infrastructure. These columns, which are designed to withstand compressive forces and loads, are capable of supporting both types of forces. As a result of this, they are often subjected to eccentric loading in applications that are carried out in the real world. This might be the result of a number of different factors, such as an uneven distribution of weight, defects in the structure, or seismic activity. An eccentric loading is a force that is not applied via the centroid of the column's cross-sectional area. This kind of loading is referred to as eccentric loading. This kind of load causes the column to bend, which in turn causes considerable stresses and strains to be induced, which may result in the column collapsing before its time. The behaviour of concrete columns when they are exposed to eccentric stress has been the topic of investigation by researchers for a considerable amount of time. An extensive range of analytical, computational, and experimental approaches have been examined by researchers in order to acquire a more comprehensive comprehension of the complex interactions that take place between the load, the column, and the environment that surrounds them in that order. Analytical models, such as the effective length technique and the moment magnifier approach, are constructed on the basis of reduced equations and theoretical assumptions. Although these models are adequate for early design and evaluation, it is possible that they do not correctly reflect the nonlinear and dynamic behaviour of the column when it is exposed to significant deformations or huge eccentricities.

It is possible that experimental testing, such as compression or bending tests, might provide valuable insights into the material features, failure causes, and energy dissipation of concrete columns. On the other hand, these tests are often costly, time-consuming, and limited in terms of the number of samples and loading conditions that may be used. In contrast, numerical simulations offer a strong tool that can be used to simulate and study the behaviour of concrete columns under diverse eccentric loading circumstances. In order to do this, it is possible to make use of advanced software packages such as Abaqus, ANSYS, or LS-DYNA. For the purpose of analysing concrete columns that are exposed to eccentric loading, finite element analysis (FEA) is an effective technique. This is due to the fact that it permits a more thorough and accurate description of the complicated stress and strain distributions that occur in the column under these loading circumstances. In addition to this, it is able to simulate the behaviour of the column when it is loaded under a variety of situations, ranging from elastic to post-failure loading.

The use of finite element analysis (FEA) is another method that may be utilised to accomplish the goal of providing a comprehensive and accurate description of the column's form, material properties, and boundary conditions. In addition, finite element analysis has the capability to model the behaviour of the column in a number of different regimes, ranging from elastic to post-failure. With that being said, finite element analysis (FEA) necessitates the thorough calibration and validation of the material models, mesh size, and time step. Furthermore, it may be computationally expensive for models that are both extensive and intricate. The way in which concrete columns behave when they are exposed to eccentric loads is one of the most significant things to consider when it comes to the safety and reliability of structures. The collapse of a single column has the potential to result in the collapse of the whole structure. This would have huge ramifications in terms of the loss of human lives, the loss of economic resources, and the impact on the environment. It is feasible for single columns to collapse into the entire building. For this reason, the accurate prediction of the response of concrete columns to eccentric loads is a crucial component in the design, building, and maintenance of structures and infrastructure. This is because of the fact that eccentric loads and concrete columns respond differently. In addition, the analysis of concrete columns that have been exposed to eccentric loading is another area that is the focus of ongoing research. Specifically, this is due to the fact that new materials, geometries, and loading scenarios are always being produced. As an example, the use of high-strength or ultra-high-performance concrete (UHPC) has the potential to have a significant influence on the behaviour of columns when they are exposed to eccentric stress.

This is due to the fact that these particular varieties of concrete have distinguishable stress-strain curves, failure processes, and ductility behaviours. It is possible that the application of seismic or wind stressors will also result in the production of complex and dynamic eccentricities. In order to deal with these eccentricities, it is necessary to use advanced modelling and analytical tactics. As a consequence of this, the objective of this study is to make an addition to the current body of information about this vital subject matter. The Abaqus software will be used in order to model the behaviour of concrete columns when they are exposed to eccentric loading in order to accomplish this goal. Furthermore, the research will provide insights into the major factors that have an influence on the performance of these structures. The goal of this study is to analyse the behaviour of concrete columns when they are exposed to eccentric loading. This will be accomplished via the use of finite element analysis using the Abaqus software to do this. In addition to contributing to the current body of knowledge on this vital subject matter, the objective of this study is to provide insights into the key characteristics that influence the performance of concrete columns when they are exposed to eccentric stress. This research will be carried out in order to accomplish both of these goals.

2. Literature Review

In the year 1995, Wierzbicki and Pietruszczak performed an examination on the behaviour of reinforced concrete columns when they were subjected to eccentric loading. This investigation was carried out with the assistance of finite element analysis. Following the development of a three-dimensional numerical model of a reinforced concrete column, the researchers validated the model by confirming that it was consistent with the data obtained from earlier experiments. This research explored and evaluated the effects of eccentricity, column slenderness, and reinforcement ratio on the ultimate strength and deformation of the column. The results of this investigation were recorded and analysed. The results led to the conclusion that the failure modes of the column were influenced by the degree of eccentricity as well as the slenderness ratio. This conclusion was reached based on the data. They did further research in which they explored the influence that eccentricity has on the behaviour of reinforced concrete columns when they are subjected to axial stress. Guedes and Massuda were the researchers that carried out this research. Through the use of a parametric research approach and a three-dimensional numerical model, the authors conducted an analysis to determine the influence that eccentricity, concrete strength, reinforcement ratio, and slenderness ratio have on the ultimate strength and deformation of the column. For the purpose of determining the nature of the connection that exists between these elements, this investigation was carried out. Given the data, it was discovered that eccentricity had a significant influence on the failure modes and ductility of the column. This was shown by the findings.

Chen performed research in 2007 to investigate the behaviour of reinforced concrete columns when they were exposed to eccentric loads. The study was done using both experimental and analytical approaches. Using scaled-down columns with varied eccentricities and reinforcement ratios, the authors conducted a series of studies. These experiments were carried out using scaled-down columns. It was determined whether or not the conclusions produced from finite element analysis were comparable to the outcomes of these tests. In order to assess the extent to which the eccentricity and reinforcement ratio impacted the final strength of the column, as well as its deformation and failure processes, investigations were carried out. The results demonstrated that there was a substantial level of concordance between the experimental data and the analytical data. Furthermore, the findings brought to light the relevance of the reinforcement ratio in terms of boosting the column's ductility. In addition, Rao and Rajamane carried out study on the behaviour of reinforced concrete columns when they were exposed to eccentric stress. With the purpose of investigating this behaviour, they used both experimental and analytical methods. The authors conducted a series of tests on full-scale columns in order to compare the results obtained from analytical models with those obtained from full-scale columns with several eccentricities and concrete strengths. This was done in order to make a comparison between the two sets of data. It was determined that eccentricity, concrete strength, and confinement all had an effect on the ultimate strength and deformation of the column, and an examination into these factors was carried out. According to the results, the confinement level had a significant influence on both the ductility and the energy absorption capacity of the column. This was discovered to be the case.

For the purpose of investigating the behaviour of thin reinforced concrete columns when subjected to eccentric stress,

S. A. Ghannad and his colleagues made use of finite element analysis. In order to investigate the effects that eccentricity, slenderness ratio, and concrete strength had on the behaviour of a thin column, the authors developed a computer model of the column that was three-dimensional. It was concluded, on the basis of the data, that the degree of eccentricity had a significant influence on the final strength of the column as well as the deformation of the column. Furthermore, it was shown that the failure modes were influenced by the degree of slenderness as well as the strength of the concrete. The behaviour of reinforced concrete columns with a range of cross-section geometries was investigated by Silva, Barros, and Rocha (2017). They used both experimental and computational methods to investigate the behaviour of these columns when they were exposed to eccentric stress. A variety of tests were conducted by the authors using full-scale columns that had cross-sections that were circular and rectangular. These columns were used in the experiments. It was determined whether or not the conclusions obtained using finite element analysis were comparable to the outcomes of these studies. An examination was carried out in order to ascertain the manner in which the cross-section geometry, eccentricity, and slenderness ratio facets influenced the behaviour of the column. According to the results, the geometry of the cross-section had a significant influence on the final strength of the column, as well as its deformation and failure processes. This was particularly true for the column's failure mechanisms.

Cheng and Lu investigated the behaviour of reinforced concrete columns by using both experimental and computational methods in their research. They focused on the behaviour of the columns when they were subjected to eccentric force as well as axial loading. After conducting a series of tests on full-scale columns that had a wide range of eccentricities and reinforcement ratios, the authors contrasted the results of these experiments with the conclusions that were obtained via the use of finite element analysis. An analysis was carried out with the purpose of determining the extent to which the eccentricity and reinforcement ratio had an impact on the ultimate strength, deformation, and energy absorption capacity of the column. This indicates the relevance of the reinforcement ratio in boosting the ductility of the column as well as its capacity to absorb energy. The results revealed that there was a good agreement between the experimental data and the numerical data, which suggests that the numerical data was more accurate than the experimental data.

3. Theoretical Concepts

Reinforced concrete columns experience both axial loads and bending moments, leading to intricate stress patterns and potential failure modes. When the applied load doesn't align with the centroid of the cross-section, the column undergoes eccentric loading, inducing bending moments that can prompt failure through bending or a combination of bending and axial compression (Silva et al., 2017). The extent of this eccentricity can be quantified as the distance between the centroid of the cross-section and the line of action of the applied load, as expressed by Equation 1 (Cheng & Lu, 2020):

$$e = \frac{M}{N} \times \frac{h}{2} \qquad (1)$$

Here, 'e' signifies eccentricity, 'M' stands for the applied moment, 'N' represents the axial load, and 'h' denotes the height of the cross-section. The resultant bending moment can then be computed using Equation 2 (Cheng & Lu, 2020):

$$M = e \times N \tag{2}$$

etermining the ultimate strength of a concrete column under eccentric loading involves utilizing an interaction diagram, which illustrates the maximum axial load and bending moment the column can endure without failing. This diagram is derived through equilibrium equations and considers the stress-strain behavior of both concrete and steel. Concrete typically exhibits nonlinear stress-strain relationships, approximated by a parabolic curve until reaching peak stress, beyond which it enters the post-peak stage and experiences significant softening. On the other hand, the stress-strain relationship of steel is generally linear until reaching the yield stress. The load-carrying capacity of a concrete column under eccentric loading can then be computed using Equation 3 (Silva et al., 2017):

$$Pc = Ag \times f'c + As \times fy \tag{3}$$

Here, 'P_c' represents the load-carrying capacity, 'A_g' denotes the gross area of the concrete column, 'f'_c' signifies the compressive strength of concrete, 'A_s' stands for the area of steel reinforcement, and 'f_y' represents the yield strength of the steel.

In addition to the load-carrying capacity, considerations for the deformation capacity and ductility of the column are crucial. Ductility, a key aspect, can be evaluated by determining the curvature ductility factor, reflecting the ratio of curvature at ultimate load to yield curvature. This factor is calculated using Equation 4 (Cheng & Lu, 2020):

$$\mu_c = \kappa_u / \kappa_y \tag{4}$$

Here, μc represents the curvature ductility factor, κu denotes the ultimate curvature, and κy signifies the yield curvature.

In this investigation, the Todeschini method is employed to model the nonlinear compressive strength of concrete in finite element analysis (FEA). This method entails defining the stress-strain relationship for concrete using an analytical function, such as a polynomial or hyperbolic function. Calibration of the function coefficients is achieved through experimental data, such as compression tests conducted on concrete specimens (see Figure 1).

In the depicted relationship, $'fc'$ denotes compressive strength, ε represents strain corresponding to stress, and $0\varepsilon 0$ signifies strain corresponding to maximum strength.

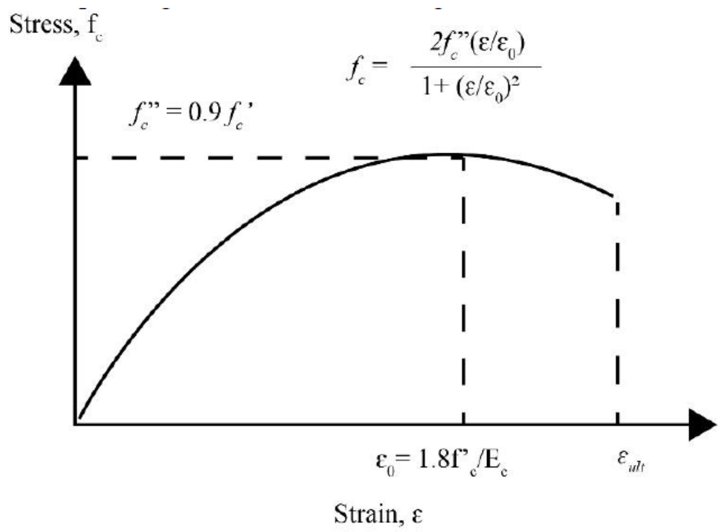

Fig. 1 Todeschini compressive strength model

In the field of finite element analysis (FEA), it is feasible to produce more accurate predictions about the behaviour of the concrete column when it is loaded by simulating the compressive strength of concrete using the Todeschini approach. The reason for this is because the Todeschini approach takes into account the nonlinear behaviour of the concrete, which is highly vital for the proper prediction of the column and the fracture propagation that it undergoes.

4. ABAQUS-Based Finite Element Analysis of Reinforced Concrete Column

The component of this research that dealt with numerical modelling involves the use of the Abaqus software in order to mimic the behaviour of concrete columns when they were subjected to eccentric loading. It is possible to create accurate models of complicated structures and simulate how they behave under a variety of loading circumstances with the help of the Abaqus programme, which is a strong finite element analysis tool. In this investigation, we used the Todeschini technique to simulate the nonlinear compressive strength of the concrete in the Abaqus programme. Additionally, we integrated other significant material characteristics into the model, such as the tensile and shear strengths of the concrete as well as the reinforcing steel. The consequences of concrete cracking and the link between the concrete and the steel reinforcement were also taken into consideration when we were working on this project. This numerical modelling was evaluated using a laboratory investigation that was carried out by Jin et al. (2016) on the size effect in eccentrically loaded stocky reinforced concrete (RC) columns (figure 2). This allowed us to more accurately assess the findings of the numerical modelling. This work offered experimental data on the behaviour of concrete columns when subjected to eccentric loading, which we were able to compare with the outcomes of numerical models developed by other researchers. We were able to evaluate the correctness of the modelling technique and identify areas in which more improvement may be required as a result of this. The researchers conducted their experiments using a total of thirty RC columns that were cast from the same batch of concrete. This was done in order to reduce the statistical dispersion of the data and to guarantee that the material qualities of all of the specimens were nearly identical. The concrete was provided by a ready-mix plant located in the area. The maximum size of the fine aggregate was 5 millimetres, while the maximum size of the coarse aggregate was 30 millimetres. For the purpose of determining the compressive and splitting tensile strengths, the typical plain concrete cube samples,

ISSN: 2454-1435 (Print) | 2454-1443 (online)
Volume 9 Issue 1, April – June. 2023 - www.ijrmmae.in – Pages 16-28

which were measured to be 150 × 150 × 150 mm, yielded a value of 30.7 MPa and 2.4 MPa, respectively. This concrete has a measured elastic modulus of thirty gigapascals (GPa). Ribbed bars with an average yield strength of 335 MPa were used to construct the longitudinal reinforcement that was used in the red concrete columns. Smooth bars with an average yield strength of 235 MPa were used to construct the transversal reinforcement in the corbel. This reinforcement was solely intended to prevent local damage from occurring. An illustration of the longitudinal and transverse rebars of the columns may be seen in Figure 2.

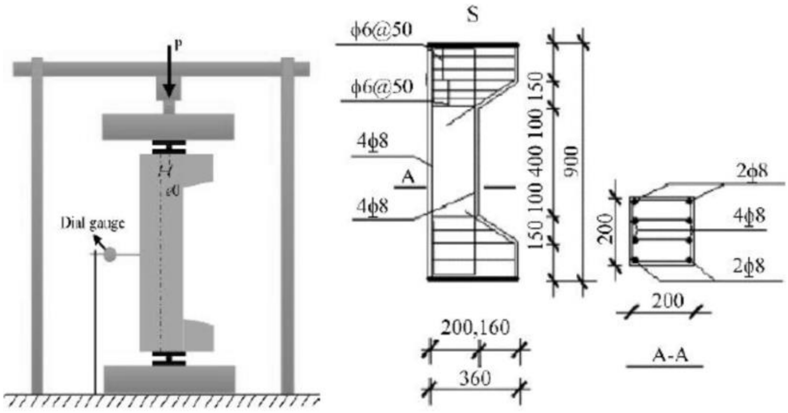

Fig. 2 Loading arrangement and reinforcement detail of columns –Jin et al. (2016)

A total of three RC columns that are geometrically related and have dimensions of 200 × 200 × 900 mm were chosen for the purpose of numerical modelling. These columns were chosen because they share similar dimensions. We selected these columns with eccentricities of 0.1h0, 0.25h0, and 0.9h0, where h0 is the effective cross-sectional height. These eccentricities were chosen because they were selected. For the purpose of this inquiry, we used the Todeschini method to simulate the nonlinear compressive strength of the concrete inside the Abaqus software. In addition, we included a number of other critical material parameters into the model. These included the tensile and shear strengths of the concrete, as well as the materials that were used to reinforce the concrete. When we were working on this project, we also took into account the repercussions of concrete cracking as well as the connection that exists between the concrete and the steel reinforcement. Figure 4 depicts the stress-strain curve that is described as the non-linear compressive behaviour of concrete in Abaqus. This curve may be observed in the figure. In addition, the model has to have a definition of the material properties of the reinforcement as well as the components that make up the concrete. Either an elastic-plastic material model or a more complicated model that encompasses nonlinear behaviour such as cracking and crushing may be used to simulate the concrete. Both of these models are both possible possibilities. There is a choice between using any of these two models. It is feasible to express the reinforcement by using either a linear-elastic or a nonlinear material model, depending on the level of accuracy that is needed. Both of these modes of representation are viable.

A failure criterion that is often utilised is known as the Concrete Damage Plasticity (CDP) failure criterion. This failure criterion is employed in finite element analysis (FEA) software for the aim of simulating the behaviour of concrete when subjected to complex loading circumstances. These two instances of the nonlinear behaviour of concrete are taken into account by the continuum damage model known as CDP. Cracking and crushing of concrete are two examples of the nonlinear behaviour of concrete. According to the definition that was supplied by CDP (Han et al., 2020), the two components that may be considered to be the components that make up concrete failure are concrete deformation and damage accumulation. As a consequence of the formation of micro-cracks and the propagation of cracks when the material is loaded, the model takes into account the degradation of the elastic modulus, tensile strength, and compressive strength of concrete. This occurs as a result of the material being loaded. In addition to this, the CDP criterion takes into consideration the creation of fracture patterns in concrete. These patterns occur as a result of the opening and closing of cracks, as well as the frictional sliding of the crack surfaces (Figure 3).

As part of our analysis, we simulated the response of concrete columns to eccentric stress by using the Concrete Damage Plasticity (CDP) criterion. our allowed us to determine how concrete columns would respond to the incident stress. We were able to simulate the formation and spread of cracks in concrete by including the CDP criteria into finite element analysis (FEA) simulations. This allowed us to successfully replicate the cracking process. Because of this, we were able to accurately portray the complex behaviour of concrete under a wide range of stress conditions. This allowed us to create more accurate predictions regarding the behaviour of the column to eccentric loading, as well as to estimate its ultimate capacity and failure mechanism, as stated by Lee et al. (2017). In addition, this made it feasible for us to estimate the column's capacity. Table 1 displays the values that are defined in ABAQUS for the major parameters that are being taken into account in this criterion.

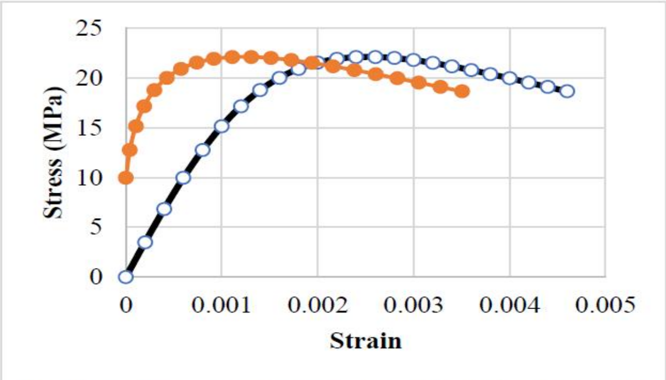

Fig. 3 Concrete compressive stress-strain behavior (Inelastic strain shifted)

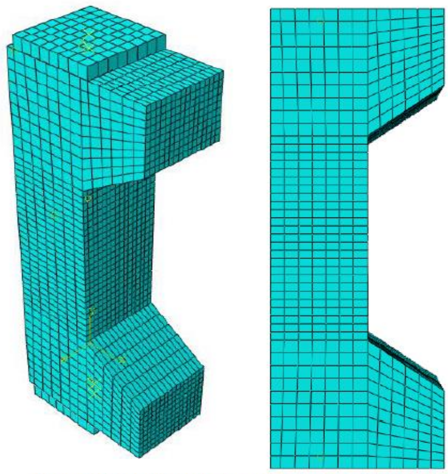

Fig. 4 Concrete column geometry - Meshed for FEA

5. Results and Discussion

To this investigation, we carried out numerical simulations of three concrete columns with varying eccentricities, namely 0.1, 0.25, and 0.9, in relation to the effective section height (h0). The software Abaqus was used in order to carry out the finite element analysis. A laboratory model was used to compare the results of a finite element analysis (FEA) with the findings of an investigation into the effects of eccentric loading on the behaviour of concrete columns. pictures 5 through 7 were given during the first portion of the talk. These pictures contrasted the concrete fractures and damages that were caused by these simulations to the patterns that were seen in the laboratory. As a result of the comparison, it was discovered that the numerical simulations were in excellent agreement with the laboratory model, which is evidence that the numerical technique is accurate. The results of the simulations demonstrated that the compressive behaviour of the column is more accurate when the h0 coefficient is smaller. This finding is in line with the behaviour that was seen in the laboratory model (figure 5 and 6). The bending behaviour of the column got more evident and eventually overtook the tensile behaviour when the eccentricity was raised, which is another way of saying that the h0 coefficient was increased. It was noticed that this behaviour occurred in each of the three columns, and the columns that had larger eccentricity had a more significant bending behaviour (Figure 7).

Through the use of simulations, we were also able to investigate the development and spread of fractures in the various concrete columns. We made the observation that the fractures appeared more often in areas of the column that were subjected to a high concentration of stress, such as the corners of the column. It was noticed that the creation of greater fractures in the concrete column occurred when the eccentricity was high. The frequency of tensile cracks as well as their size increased as the eccentricity rose. Furthermore, the findings demonstrated that the column had a tendency to exhibit bending behaviour at greater eccentricities, whilst the compressive behaviour of the column was shown with the highest degree of accuracy at lower eccentricities. When attempting to get a comprehensive understanding of the behaviour of concrete columns when subjected to eccentric loading, it is essential to evaluate the bearing and ultimate capabilities of the construction. Utilising a force-displacement curve is a crucial instrument for carrying out this study. In relation to the effective cross-sectional area of the columns (h0), the bearing and ultimate capacities are shown in Figures 8 through 10. These capacities are shown for eccentricities of 0.1, 0.25, and 0.9 respectively.

According to the findings, one of the most significant observations is that the bearing capacity decreases with increasing eccentricity. This is something that was precisely anticipated by both the laboratory models and the numerical models. The maximum capacity drops from 1377 KN and 920 KN to 161 KN when the eccentricity grows from 0.1h0 to 0.9h0, as illustrated in figures 8 to 10. This is the case whenever the eccentricity increases. This loss in capacity is a consequence of the higher bending moment that is brought about by eccentric loading. The Todeschini behavioural model properly predicts the behaviour of the column when the eccentricity is low, which is another major finding that has been made. However, when the eccentricity is increased to 0.9h0, the model is unable to effectively estimate the forces that correspond to the principal displacements. This is despite the fact that it is able to correctly anticipate the existence of cracks and the position of those cracks. It is possible that the increasing intricacy of the behaviour of the column as it gets closer to failure is the cause of this mismatch. In spite of this disparity, the model forecasts the column's ultimate capacity with a high degree of precision. In conclusion, the findings suggest that the eccentricity of the load has a significant impact on the bearing and ultimate capacities of concrete columns when they are subjected to eccentric loading. Furthermore,

ISSN: 2454-1435 (Print) | 2454-1443 (online)
Volume 9 Issue 1, April – June. 2023 - www.ijrmmae.in – Pages 16-28

while the Todeschini behavioural model is capable of effectively forecasting the behaviour of the column when the eccentricity is low, it may not be enough when it comes to predicting the forces that correspond to primary displacements when the eccentricity is large.

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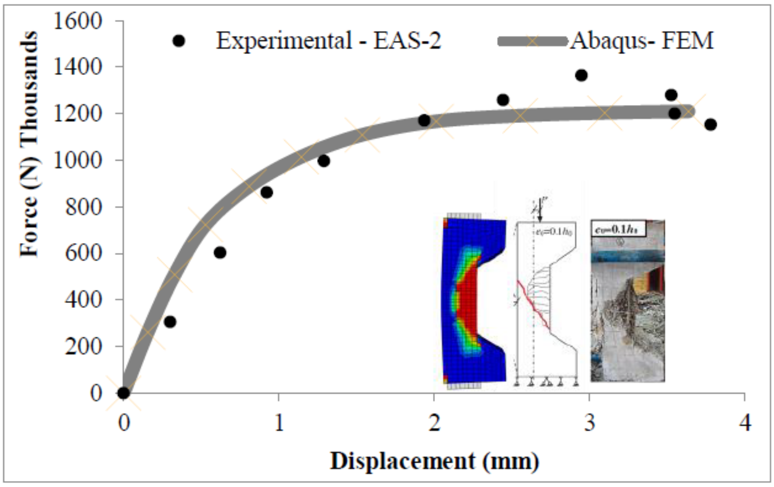

Fig. 8 Load-displacement curve (e_0= 0.1h_0).

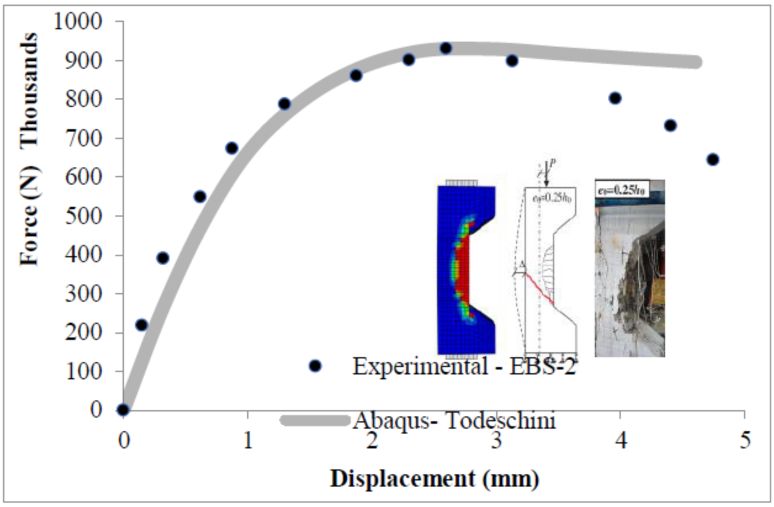

Fig. 9 Load-displacement curve (e_0= 0.25h_0)

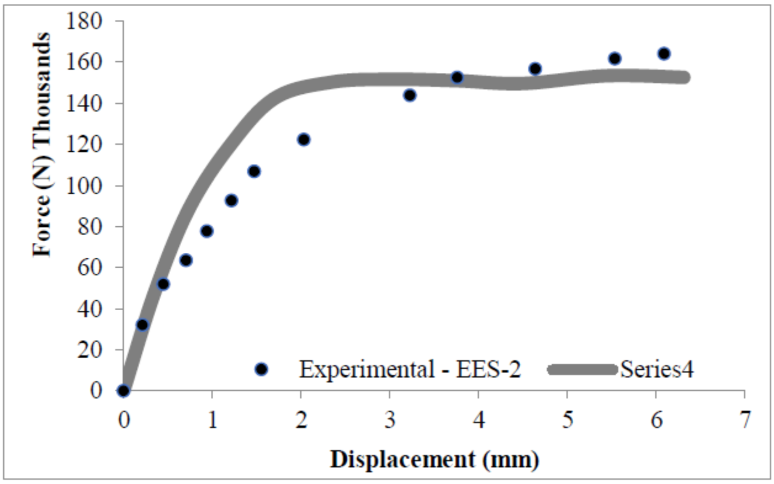

Fig. 10 Load-displacement curve (e_0= 0.9h_0)

Conclusion

It is possible to draw the conclusion, on the basis of the findings of this numerical modelling carried out with the Abaqus software, that the behaviour of concrete columns subjected to eccentric loading can be accurately predicted by employing the Concrete Damage Plasticity (CDP) criterion in conjunction with the Todeschini method for nonlinear compressive strength. The findings of this research demonstrated that the carrying capacity of the column falls as the eccentricity of the load grows, and the column's behaviour changes to become more like to that of a beam column. In addition, a comparison with a laboratory research that was carried out by Jin et al. (2016) demonstrated that the findings of the numerical modelling were in excellent agreement with the data that was obtained from the experiments. The findings of this research have practical consequences for the design of concrete columns that are subjected to eccentric loading. These findings emphasise the significance of taking into account the eccentricity of the load throughout the design phase in order to guarantee the safety and stability of the structure. Furthermore, this modelling technique and the findings might be helpful for engineers and academics who are interested in further investigating the behaviour of concrete columns under a variety of loading scenarios. The findings of this study, taken as a whole, provide significant insights into the behaviour of concrete columns when subjected to eccentric loading and show the efficacy of numerical modelling in forecasting the behaviour of concrete structures.

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