Analytical study on the behaviour of beam-column joints made of electric arc furnace concrete

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Abstract: The advancement of the construction industry towards using recycled materials has substantially reduced the consumption of natural resources. Electric Arc Furnace (EAF) slag is the by-product obtained from the production of steel and is procured after the separation of molten steel from impurities. In this paper, the impact of EAF concrete on the structural behaviour of beam-column joints and the resisting mechanism of these joints are evaluated using ANSYS software. One joint made with conventional concrete and two joints made with EAF concrete were analysed subjected to incremented loading. The results indicate that EAF concrete exhibits better structural performance than conventional concrete in terms of the ultimate load attained by the joint in the failure condition.

1. Introduction

In Indian practice, a beam-column joint is not distinctively designed mainly due to economic considerations. Beam-column joints are indispensable zones in the analysis of moment resisting reinforced concrete frames, especially under combined loading condition [1]. The most important part of composite beam-column structures is the connection [2, 3]. This is better understood during earthquakes when the failure of reinforced concrete frames occurs primarily due to shear in joints resulting in the total breakdown of structure. Joint design can be conveniently avoided if the structure is solely subjected to gravity load. Adequate detailing and design of joints should be ensured to improve the strength and ductility to resist large deformations caused due to earthquakes. Since sufficient guidelines on joint design are not specifically provided in Indian codes of practice, adequate lapping of main reinforcement satisfies the strength criteria.

India is the world’s second largest producer of crude steel. According to the World Steel Association, India’s crude steel production in 2019 was at 111.2 million tons which accounted to 12 million tons of steel slag. This leaves a question as to what happens to this enormous quantity of slag produced. In contrast to certain other nations, steel slag is discarded and is becoming a problem due to paucity of land. Currently, there are no specific regulations or norms to control the slag generation or disposal. EAF slag is obtained as a by-product of steel production process when Electric Arc Furnace is used instead of Basic Oxygen Furnace (BOF) [4, 5, 6]. Although EAF slag has relatively low hydraulicity, its chemical composition can be controlled by adjusting the steel making process [7]. Correctly manufactured EAF concrete has good mechanical properties and high density [8]. It is desirable to use EAF instead of BOF due to the following
reasons: (i) energy consumption of BOF process is 2.8 times greater than that of EAF process, (ii) material consumption of BOF process is 11 times greater than that of EAF process, (iii) carbon emission is low when steel is produced through EAF and (iv) cost of production is lower for EAF compared to the blast furnace route [4].

Worldwide industrial waste generation and quarry exploitation are becoming a major environmental problem. EAF is currently used for asphalt concrete pavements in many countries but however, huge quantities of this material are still land filled [4]. Reusing the slag as a recycled material in construction industry not only helps in the reduction of the amount of waste disposed off but it can also bring down the consumption of natural aggregates.

Current Indian codes like IS 1893:2002, IS 13920:1993 and IS 456:2000 is not equipped well enough to design a beam-column joint under seismic conditions. It fails to shed light on the assessment of shear demand and detailing of shear reinforcement. This lack of information may be due to the disparities among different countries in terms of the occurrence of earthquakes. In this study, an exterior beam-column joint is designed based on [10, 11] which provides codal recommendations on structural concrete and beam-column joint design in RC structures respectively. The designed joint is used for the analytical study on its behaviour under combined loading condition. Also, a comparative study is conducted on the joints made with EAF concrete and conventional concrete based on load-deflection plot, energy absorption capacity and crack propagation results. Analysis is done using ANSYS software. This study also brings to light the urgent need for updating the Indian codes of practice considering the critical joints in a moment resisting structure.

2. Design approach

An exterior beam-column joint is designed using ACI 352R-02 and ACI 318M-02 which apply only to structures using normal weight concrete with a compressive strength less than 100MPa. Based on the loading state and the expected deformation of the fastened frame members when resisting lateral loads, beam-column joints are classified into two categories – Type 1 and Type 2 respectively [11]. Type 2 connection is preferred for the joint since the frame members are required to dissipate energy and they have sustained strength when subjected to deformation reversals in the inelastic range [11]. Joint dimensions along with reinforcement details are given in Figure 1 below and all dimensions are given in millimeters. Clear cover of 25 mm is provided for beams and columns. The design shear force and the concrete shear capacity of the joint is obtained as 354 kN and 2.32 MPa respectively.

![Figure 1. Reinforcement details of the beam-column joint.](#)
3. Finite element modelling and meshing

A finite element model is created as shown in Figure 2 using ANSYS, widespread Finite Element modelling and analysis software.

![Figure 2. Model of the joint.](image1)

Solid 65 element is used for modelling concrete (Figure 3). Solid 65 is a 3D structural RC solid element which can indicate cracking and crushing [12]. It has eight nodes with three translational degrees of freedom at each node. It also exhibits non-linear material properties.

![Figure 3. Solid 65 element.](image2)

Reinforcements are modelled using bilinear kinematic hardening properties where translation of the yield surface is allowed. Excessive number of stirrups is provided in beams and columns to initiate more shear cracks within the joint area than along the beam or column. This helps in the study of beam-column joint mechanism. Since the beam-column joint region is given utmost importance, full length of a beam or column is not considered. Hence beam or column is considered mid-length from the support. Due to this reason, all beam ends and bottom region of the column are provided with simple supports. Top portion of the column is allowed to move freely in the direction of applied loads and constrained in the remaining directions.

For meshing, hex dominant method is adopted for the entire body by using all quadrilateral elements. Body sizing and face meshing is also done with an element size of 30mm.
4. Material properties
Concrete is a quasi-brittle material and shows different behaviour in tension and compression. The mechanical properties of both concrete materials are provided in Table 1. The reinforcement is characterized with a yield stress of 250MPa and tangent modulus of 1450.

Table 1. Material properties of concrete (Rajasekhar et al. 2017) [13].

| Type of concrete                     | Conventional | EAF   |
|--------------------------------------|--------------|-------|
| Open shear transfer coefficient      | 0.3          | 0.3   |
| Closed shear transfer coefficient    | 1            | 1     |
| Uniaxial cracking stress            | 3.35 MPa     | 3.77 MPa |
| Uniaxial crushing stress            | 27.85 MPa    | 33.11 MPa |
| Poisson’s ratio                      | 0.2          | 0.2   |
| Elastic modulus                      | 26386 MPa    | 29155 MPa |

5. Non-linear static analysis
- A constant vertical load of 400kN is applied on top of the column corresponding to the gravity load induced by upper floors.
- Horizontal load is applied on top of the column corresponding to the quantified movement of the joint to the inter-story drift of a whole frame. A 2mm displacement is provided in the first step which lies within the elastic range. The successive displacements have values between 1.25 and 1.5 the preceding one.
- According to ACI 318-2011, allowable story drift is 3.5% for joints [14].
- Maximum principal stress, total deformation and force reaction in the direction of deformation are obtained as results from Ansys. Crack and crushing results are obtained from Ansys Parametric Design Language commands.
- Maximum principal stress theory is used for the analysis of brittle materials. In this case, failure occurs when maximum principal stress for complex loading in the joint at any point reaches equal or more than the maximum principal stress of simple tension test.

6. Results and discussion
Non-linear static analysis is used as an efficient tool to assess the performance of EAF concrete and conventional concrete. Non-linear static methods are improving day to day for evaluating the seismic analysis with more accuracy in a simple way. Load deflection graphs are developed out of the results obtained from non-linear static analysis. In Finite Element Analysis (FEA), it is recommended to use nonlinear static analysis as nonlinear dynamic time history analysis is very complex and time consuming. The main objective of this study is to evaluate the effect of EAF concrete on an exterior beam-column joint and to assess the performance by developing force-displacement graph. A non-linear quasi static analysis study of the considered joint model is conducted to assess the effect of constant axial load and incremented displacement on the top of column. Non-linear studies are conducted mainly to determine the yield point and the ultimate load of the joints. The significance of beam-column joints becomes more evident especially in high seismic prone areas. Most of the building collapse during earthquake is majorly caused due to the shear failure occurring in joints.
6.1. Study on failure criterion and load-deflection curve

The main purpose of this analysis is to evaluate the effect of concrete properties on the overall performance of the joint. Joint shear cracks are developed at the ultimate drift ratio ($\theta = 3.5\%$) from the crack and crush results using APDL commands. Cracks also developed along the beam near the column. This failure mode is known as $BJ$ type failure where a mixed cracking is observed in which shear cracks in the joint occurs along with flexural damage in the beam [14]. Figure 4 shows the results referring to the force-displacement envelope curves of EAF and conventional concrete joints.

Joints made with EAF concrete is marked by higher ultimate loads achieved at lesser displacement than in conventional concrete. Hence, they showed greater stiffness than the joint made with conventional concrete due to higher elastic modulus values. As a result of $B\cdot J$ failure mode, deformation capacity and strength reduction of the elements occurred as an outcome of cracking of joints.

![Figure 4. Load-deflection plot obtained from analysis.](image)

The conventional concrete joint is less stiff compared to the EAF joint. Ultimate load achieved by the joint made of EAF concrete is 2057.93 kN and that of conventional concrete is 1897.08 kN. Maximum drift value attained by the joint is about $\theta = 3.7\%$ which is greater than the allowed limit $\theta = 3.5\%$. After reaching the ultimate load, the stiffness of joints is seen to be suddenly reduced which typically characterizes a shear failure mechanism [14].

According to [15], there are three major points in the load-deflection graph of exterior beam-column joints failing by $B\cdot J$ failure mode representing the major stiffness changes. These key points (Figure 5) are obtained as follows: (i) a tangent line is drawn from origin until a point A that sets off another tangent line, (ii) another tangent line is drawn from A until it reaches a point B that sets off another line, (iii) point C is placed at the ultimate load attained by the joint.

![Figure 5. Plot showing the key points of stiffness change.](image)
Point A stands for first stiffness change due to shear cracks in the joint. Point B stands for reinforcement yielding and point C stands for concrete crushing within the joint. It can be concluded that EAF concrete attains maximum load compared to conventional concrete and also at reduced applied displacement.

The displacement is 28.24 mm for EAF concrete at ultimate load whereas the displacement for conventional concrete is 32.52 mm at ultimate load. The shear values at point A are 1331.39 kN and 1280.66 kN for EAF and conventional concrete at 13.93 mm and 20.807 mm displacement respectively. The first stiffness change for EAF takes place at greater force and smaller displacement. The shear values at point B are 1947.68 kN and 1618.09 kN for EAF and conventional concrete at 24.06 mm and 25.55 mm displacement respectively. In the second stiffness change, an increase of total load attained by EAF concrete is observed. Also, the increase in shear force and displacement for EAF concrete in the stiffness change is much greater than that for conventional concrete.

6.2. Crack results
Crack results can be used to identify damage progression during the loading. In RC structures, the rigid joint assumption is a coarse concept and since concrete has low tensile strength, cracks are developed even at the early stages of loading. Crack occurs when the stress evolving on a portion of the structure match up with a point in the principal stress space situated outside the surface which defines the failure criterion and this, in turn results in localized material failure. This failure is evidenced by crack formation which results in the loss of load carrying capacity in the direction normal to the plane of crack. Crack results for EAF and conventional concrete in step 2 of loading are shown in Figures 6-9.

![Crack results for conventional concrete](image)

**Figure 6.** Front view of crack results for conventional concrete.
Figures 6 and 7 show the front and side view of conventional concrete joint. It can be seen that first crack and second cracks are formed at the joint portion. As each step of loading progresses, cracks continue to grow in number. But no sign of cracks were found along the beam length or column length. Hence, in this case, the majorly affected area is the beam-column joint region. Figures 8 and 9 show the front and side view of crack and crush results obtained for EAF concrete. Here, same as the conventional concrete, second step observation is taken in order to make comparison more solid. Crack has not yet developed in the joint region in this step for EAF concrete. But first and second cracks are developed in the top half portion of the column. As the load step progresses, crack continues to grow in number along the column portion as well as in the joint region.
There are 3 directions of principal stresses for finding cracks in a 3D solid 65 element. If the value of the maximum principal stress attains the value of the material strength, the first crack forms; if the value of the average principal stress attains the value of the material strength, the second crack forms and if the value of the minimum principal stress attains the value of the material strength, the third crack forms. Last load step showed all three cracks in the beam-column region as well as along the length of column. But the number of cracks developed is less in EAF compared to the conventional concrete even during the last step of loading.

6.3. Energy absorption capacity

Load-deflection plot of both the concrete materials are given in the previous session. The area under the load–deflection plot characterizes the energy absorption capacity of the joint [16]. Considering the limitations in analysis running condition, the deflection after ultimate loading could not be tracked and hence the area under the load–deflection plot considered in this study constitutes the area under the upward slope portion up to the ultimate load. The energy absorption capacity was calculated for both joints and is shown in Table 2. It may be noticed from Table 2 that the energy absorption capacity of EAF is about 22.8% higher than that of conventional concrete.

Table 2. Comparison of the energy absorption capacity.

| Joint type          | Energy absorption capacity (kNm) | % increment in EAC |
|---------------------|---------------------------------|--------------------|
| Conventional concrete | 38.266                          | ---                |
| EAF                 | 47.001                          | 22.8               |
7. Conclusions
From the analysis results obtained in this study, the following conclusions can be drawn:

- Failure mode of both the materials showed that an increase in shear force and displacement for EAF in the stiffness change is much greater than that for conventional concrete.

- Load attained by EAF concrete is greater than that attained by conventional concrete.

- Cracks are developed in the joint region for conventional concrete in the early stages of loading whereas for EAF concrete joint cracks are developed in the final steps of loading.

- Energy absorption capacity (EAC) for EAF concrete is 22.8% higher than that of conventional concrete.

These results give an indication about the capacity of EAF slag to be used in structural concrete members as a replacement of aggregates. This, in turn will help to reduce the overexploitation of quarries.

8. References
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