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A comparative study of the load-deflection behaviour of plain and reinforced blended concrete beams Experimentally and Analytically using Abaqus

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Abstract:

Load-deflection behaviour is a key indicator of structural performance in reinforced concrete (RC) and plain concrete beams. This study is carried out both by experimental and analytical method to compare the load-deflection response of RC and plain blended concrete beams. The literature survey discusses previous findings on load deflection behaviour, stiffness, ductility, and failure mechanisms, highlighting the role of reinforcement in enhancing load-bearing capacity. Experimental studies involving three-point bending tests, as well as analytical study through numerical simulations in Abaqus by models, are examined. The comparison of results demonstrates significant differences in structural response due to reinforcement, varying a/d ratio and dimensions of the beams. Beams with deeper notches showed a drastic reduction in strength and FEM simulations closely matched experimental data validating it.

Keywords: Load-Deflection Behaviour, Experimental, Abaqus modelling, Structural performance, Numerical simulation, a/d ratio

1. Introduction:

A lot of study has been done on the use of fly ash and ground granulated blast furnace slag (GGBS) as supplemental cementitious materials (SCMs) in concrete. Lower carbon emissions, greater durability, and easier workability are just a few of their benefits for the environment and performance. Smith et al. (2015) demonstrated that the addition of fly ash enhances the workability of fresh concrete due to its spherical particle form. Mixing GGBS improves flowability and reduces the need for water or superplasticizers (Patel and Kumar, (2017)). Roy et al. (2018)) found that a 50% fly ash and GGBS mixture provides a balanced strength growth profile. When it comes to durability, blended concrete has remarkable qualities. Gupta et al. (2019) found that fly ash and GGBS improve resistance to chloride ion penetration and sulphate assault. Additionally, Yang and Zhao (2020) found that concrete compositions containing 40% GGBS and 20% fly ash had enhanced freeze-thaw resistance.

The load-deflection behaviour of concrete beams is a critical parameter that illustrates their response under applied loads, including stiffness, ductility, and failure mechanisms. Plain concrete beams and reinforced concrete (RC) beams demonstrate distinct load-deflection characteristics due to their structural composition and mechanisms of load resistance.

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Plain concrete beams typically exhibit a brittle load-deflection behaviour. As the load increases, the deflection remains linear till it reaches to the point where the tensile strength of blended concrete is exceeded, resulting in the formation of a crack. Beyond this point, the beam fails abruptly with minimal additional deflection, as plain concrete lacks the ductility to sustain further deformation (Bazant & Planas (1998)).

In contrast, the reinforced beams exhibit a more ductile load-deflection behaviour due to the inclusion of reinforcement. Initially, the behaviour of an RC beam is like that of a plain concrete beam, with a linear response as the load increases. However, after the concrete cracks, the reinforcement bars take over the tensile stresses, allowing the beam to sustain higher loads while undergoing significant deflections. This results in a nonlinear load-deflection curve characterized by a post cracking phase where the beam remains functional until the reinforcement yields and eventually fails (Hognestad, (1951)).

The ductility of RC beams, reflected in their ability to undergo large deflections without immediate failure, is a vital characteristic for structural safety, as it provides warning before collapse. Factors such as the reinforcement ratio, concrete strength, and beam dimensions influence the shape and the load-deflection curve. Bažant and Planas (1998), investigated the fundamental differences in load-deflection behaviour between RC and plain concrete beams. Their study revealed that reinforcement significantly altered crack development and post cracking stiffness, resulting in higher load-carrying capacity and enhanced ductility in RC beams. Carpinteri et al. (2010), conducted many tests of three-point bending tests on RC and plain beams to compare the experimental results with analytical- finite element method (FEM) simulations. Their findings indicated that FEM models accurately predicted load-deflection responses, validating their use for structural analysis.

Jirásek and Bažant (2002), explored the effects of reinforcement ratios on load-deflection curves. They found that increasing reinforcement content enhances load resistance and alters failure modes, transitioning from brittle fracture in plain beams to ductile behaviour in RC beams. Shah et al. (1995), utilized ABAQUS simulations to analyse the load-deflection characteristics of RC and plain beams. Their numerical models successfully captured the stiffness variations and deflection limits, providing a reliable tool for predicting structural performance. RILEM (2004), conducted wedge splitting and bending tests to examine crack propagation in RC and plain beams. The study revealed that reinforcement controls crack width and improves post-cracking stiffness, leading to smoother load-deflection transitions in RC beams. Petersson (1981), performed experimental tests on different beam configurations to compare load-deflection responses. The research demonstrated that RC beams exhibit higher energy absorption and improved deflection control compared to plain concrete beams. Singh, H., & Singh, S. P , provide both analytical and experimental insights into the load-deflection behaviour of shallow-beam supported reinforced concrete slabs, highlighting the influence of support conditions on deflection characteristics.(2010).

Oktaviani, W. N. et.al.(2020) investigate how RCC beams that have 15% fly ash added in place of cement behave flexurally. According to the study, fly ash beams had a 22% higher load-bearing capacity and more deflection than beams manufactured with regular Portland cement. Both Response-2000 software and manual computations yielded analytical predictions that agreed well with experimental results. Babu, K. G., & Rao, G. S. N.(1996) evaluate the efficiency of GGBS as a partial replacement for cement in concrete and its impact on the load-deflection behaviour of concrete beams. GGBS as a partial cement replacement enhances the flexural strength and modifies the load-deflection behaviour of concrete beams, contributing to increased ductility.

Siddique, R.(2004),focuses on the performance characteristics, including load-deflection behaviour, of concrete mixtures with high volumes of Class F fly ash. High-volume Class F fly ash concrete exhibits comparable load-deflection behaviour to conventional concrete, with improved long-term performance due to pozzolanic reactions. Poon, C. S and et.al. (2000)showed that, Utilizing large volumes of low-calcium fly ash in high-strength concrete enhances workability and results in favorable load-deflection characteristics, with increased energy absorption capacity. Ganesan, N. (2007) demonstrated that High-performance concrete beam-column joints incorporating fly ash and GGBS display improved load-deflection behaviour, attributed to enhanced material properties and joint integrity. Partial replacement of cement with metakaolin and GGBS in reinforced concrete beams leads to enhanced flexural strength and improved load-deflection behaviour, indicating increased stiffness and ductility was the finding of Suresh, S., & Nagaraju, K.(2015). Adding fly ash to reinforced concrete beams enhances flexural capacity and modifies load-deflection behaviour, contributing to increased energy absorption and improved crack resistance , Marthong, C., & Agrawal, T. P. (2012).

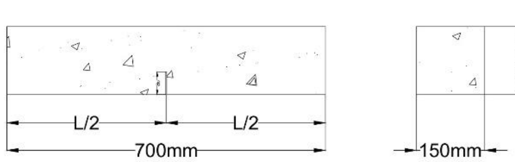
2. Methodology

2.1 Materials and Mix Design

The typical concrete mix had a w/c ratio of 0.5. In the current study, blended concrete containing 20% FA and 10% GGBS is used in place of cement. The M25 concrete mix was designed in accordance with IS 10262. Ordinary Portland cement (OPC) 43 grade, with verification number 8112-1983, is the type of cement utilized in this investigation. To increase workability and slump, super plasticizer is used throughout the experimental work in the current study. To evaluate their effect on load-deflection behaviour, Steel bars were used to reinforce RC mixed beams. For the M25 grade design mix, the concrete mix's 28-day compressive strength was 32.86 N/mm2, and its slump was 80 mm. High yield strength deformed (HYSD) bars that satisfy 1786 and 1985 requirements are used. 415 N/mm2 is their yield strength, often known as their characteristic strength. Here, the main bars are 12 mm in diameter, while the stirrups are 8 mm.

2.2 Specimen Preparation

Blended Concrete Plain beams as well as RC beams of varying lengths i.e 700mm, 1200mm and 1500mm, breadth 150mm and varying depth of 150mm, 250mm and 350mm were cast. Refer Fig. 1, Fig. 2 and Fig. 3 for the details. Each beam contained a controlled notch to facilitate fracture analysis. The notch depth was fixed based on the a/d ratio viz. 0.25, 0.33 and 0.5 for plain concrete blended beams. In case of RCC beams the notch, depth was equal to the cover provided upto the face of the reinforcement. Refer Fig. 4, Fig. 5 and Fig.6 for the RC beam details with notch at centre. Three-Point bending test was Conducted to assess stiffness and deflection characteristics. A displacement-controlled Flexure testing equipment and a real-time data gathering system make up the experimental setup. A strain-controlled test is one in which the strain is increased at a constant, uniform pace and the test is carried out in that manner. The tests are carried out on the specimens under CMOD control at a consistent pace of 0.02 mm/min. To measure CMOD, a clip gauge is used. To measure the downward displacement at mid-span, a linear variable displacement transducer (LVDT) is employed. The energy is computed as the area under the load-deflection curve up to the failure point. The load and deflection are recorded while applying a load steadily until the specimen fails. The Finite Element Modelling and simulations was performed for the same set of RC and Plain blended beams using ABAQUS software.



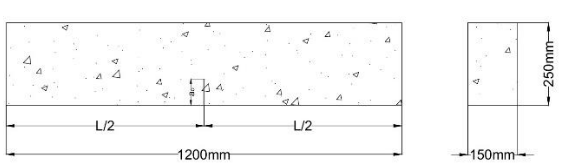


Fig. 1 : Plain Concrete beam with Notch at L/2 of length 1200mm

Fig. 2 : Plain Concrete beam with Notch at L/2 of length 700 mm

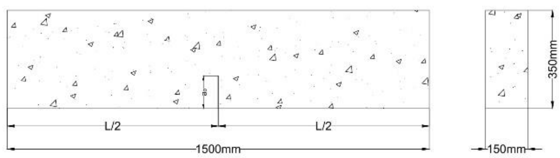
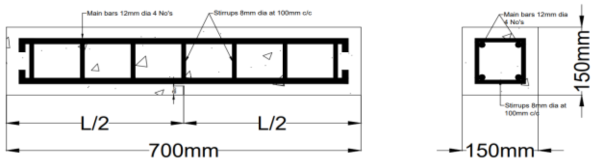


Fig. 3 : Plain Concrete beam with Notch at L/2 of length 1500mm



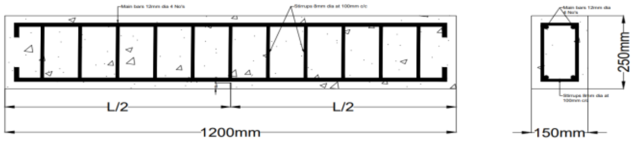


Fig.4 : RC Beam of length 700mm with notch at L/2 Fig.5: RC Beam of length 1200mm with notch at L/2

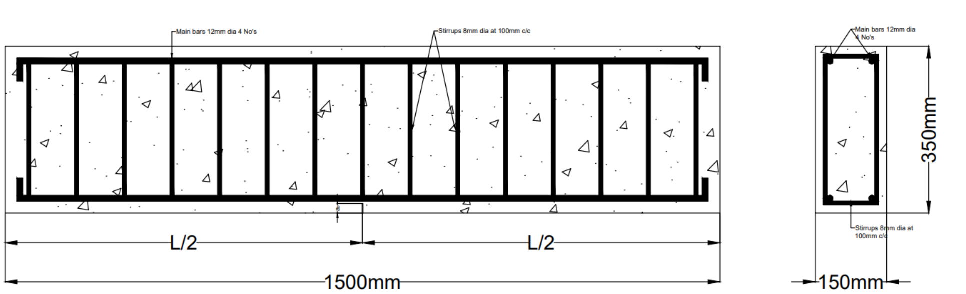
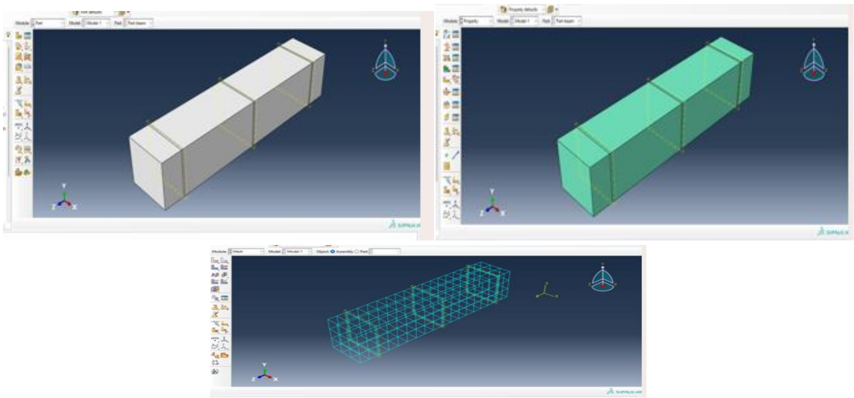


Fig.6: RC Beam of length 1500 mm with notch at L/2

2.3 Analytical study using Abaqus

The numerical simulation of Plain Blended concrete as well as Reinforced concrete structure necessitates a precise model of the structural components and their constituent members, which function as a composite of concrete and steel. Each section (Fig. 1 to Fig.6) is individually modelled using ABAQUS, allowing for extrusion in any direction. Consequently, a 3D solid element was developed in the "modelling space," utilizing a deformable type for the beam. This element is designed to accommodate plastic deformation, cracking in three orthogonal directions, and crushing. Three-dimensional Finite Element models of the reinforced concrete beam have been established, addressing various aspects of modelling, including element types, material properties, section assignments, step definitions, interactions between elements, boundary conditions, loading, meshing, job assignments, and result evaluation. All the beams of lengths 700mm, 1200mm and 1500mm with their varying depth of 150mm, 250mm and 350 mm and a constant width of beam which is 150mm are modelled in Abaqus along with notches at centre. In case of Plain blended concrete beam, for each of beam a varying a/d ratio of viz. 0.33, 0.25 and 0.5 was incorporated to fix the notch depth. For Rc blended Concrete beams, The depth of notch was upto the face of reinforcement provided i.e. the cover provided.



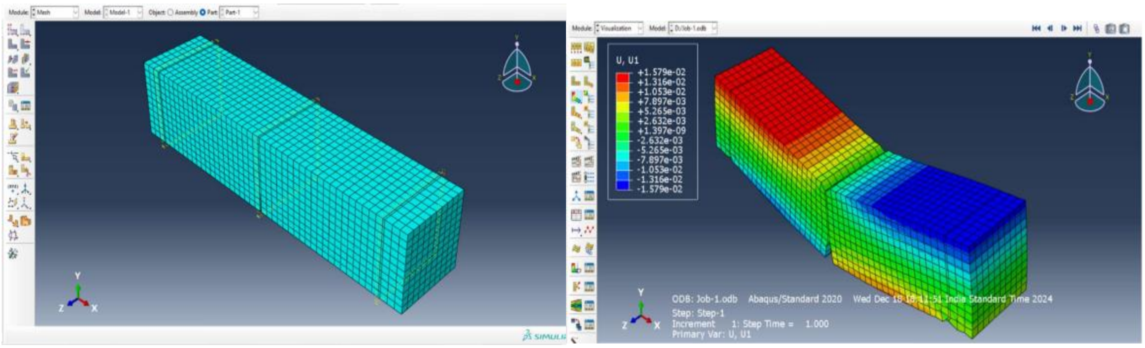


Fig.7 – Simulation of Blended Plain & RC Beam i.e. Modelling, Meshing and Analysis of Beam with notch at the centre under three point bending tests in Abaqus.

3. Results and Discussion

It is evident that from the present study we can see the Reinforcement significantly enhances load-carrying capacity and alters failure modes. Experimental and numerical methodologies provide balancing insights to structural behaviour. The following are the graphs plotted and discussions for Load v/s deflection of RCC and blended plain concrete for various lengths of beam and depths of beams with different a/d ratios both through experimental and Analytical tool – Abaqus.

Table 1: Reinforced Blended Cement Concrete P-δ values

Length (mm)	**a/d ratio**	**Pu (Max. Load) KN**	**Deflection (mm)**
			Experimental
700	No Notch	75.8	3.89
	0.33	62.5	5.04
1200	No Notch	84.26	4.32
	0.1	72.2	6.81
1500	No Notch	106.1	5.9
	0.071	85	7.2

Table 2: Plain Blended Cement Concrete P-δ values

Length (mm)	**a/d ratio**	**Pu (Max. Load) kN**	**Deflection (mm)**
			Experimental
700	No Notch	9.9	0.59
	0.25	9.25	1.73
	0.33	8.15	4.35
	0.5	7.96	4.19
1200	No Notch	15.74	0.5
	0.25	13.51	0.96
	0.33	11.31	3.08

	0.5	10.66	5.2
1500	No Notch	17.5	0.07
	0.25	15.36	0.29
	0.33	13.82	1.82
	0.5	12.43	1.86

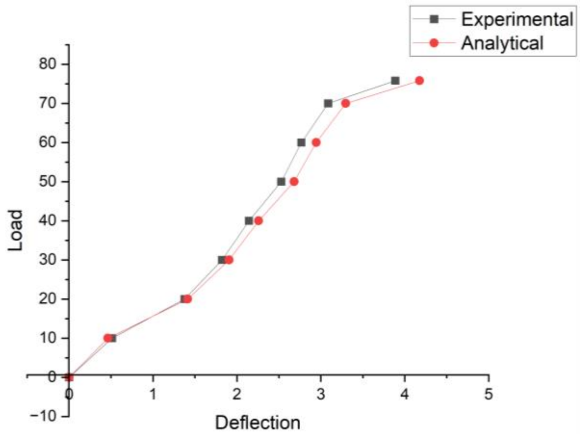


Fig. 8 Load deflection curve for RC Beam of length 700mm by Experimental and analytical study.

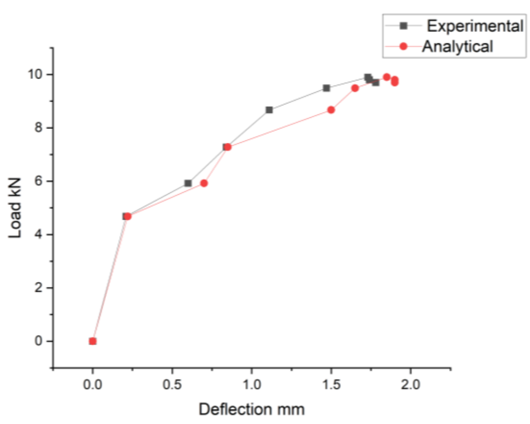
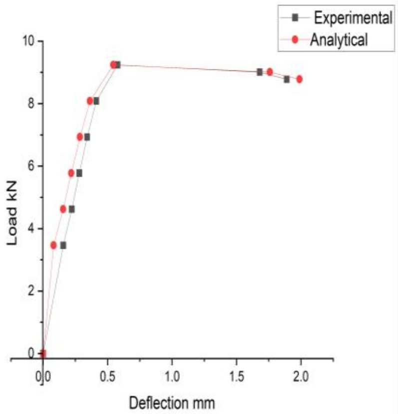
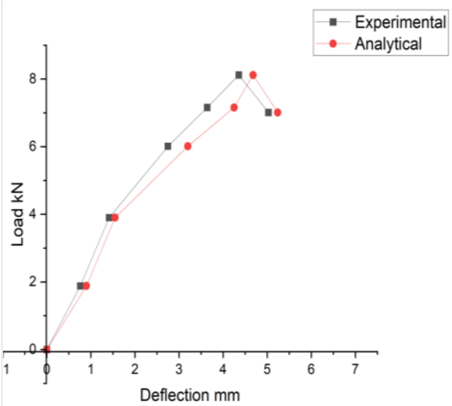


Fig. 9 –Load deflection curve for Plain beam of length 700mm by Experimental and analytical study





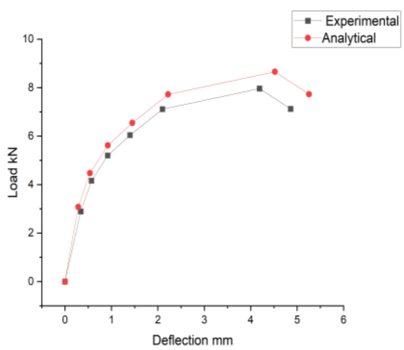


Fig. 10: P-δ curve for L=700mm   Fig.11: P-δ curve for L=700mm   Fig.12: P-δ curve for L=700mm

and $\frac{a}{d} = 0.25$ and $\frac{a}{d} = 0.33$ and $\frac{a}{d} = 0.5$

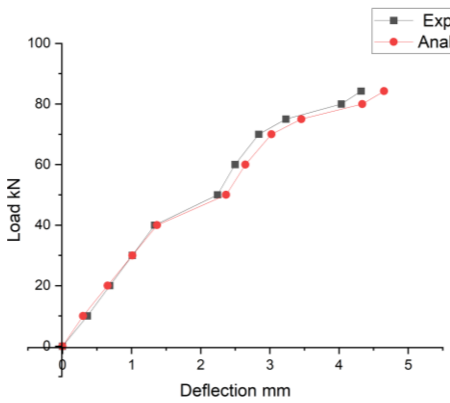


Fig. 13 Load deflection curve for RC Beam of length 1200mm by Experimental and analytical study.

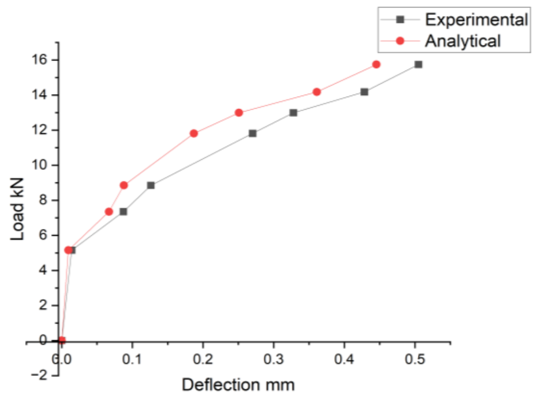
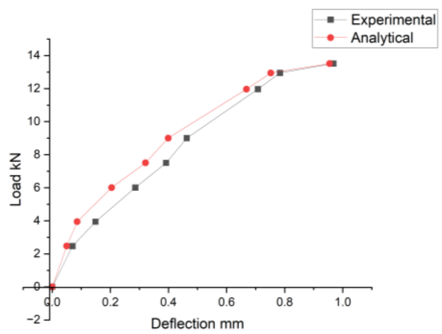
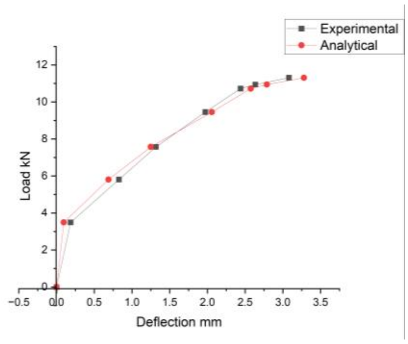


Fig. 14 –Load deflection curve for Plain beam of 1200mm by Experimental and analytical study





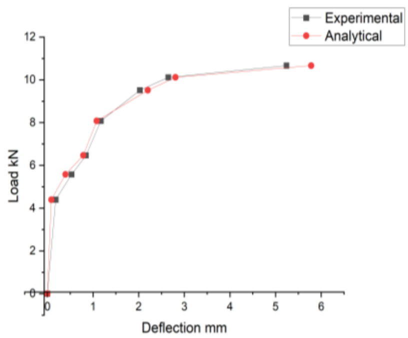


Fig.15: P-δ curve for L=1200mm and $\frac{a}{d} = 0.25$

Fig.16: P-δ curve for L=1200mm and $\frac{a}{d} = 0.33$

Fig. 17: P-δ curve for L=1200mm and $\frac{a}{d} = 0.5$

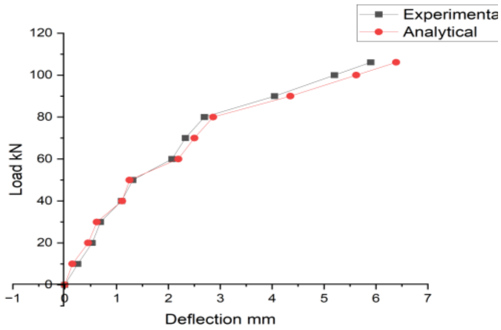


Fig. 18 Load deflection curve for RC Beam of length 1500mm by Experimental and analytical study.

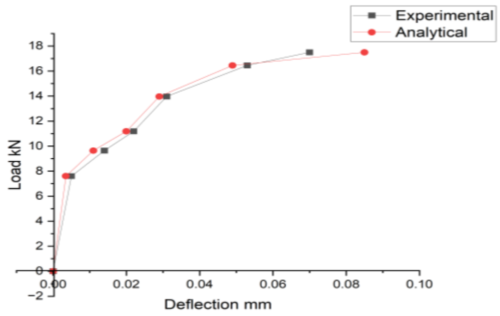


Fig. 19 –Load deflection curve for Plain beam of 1500mm by Experimental and analytical study

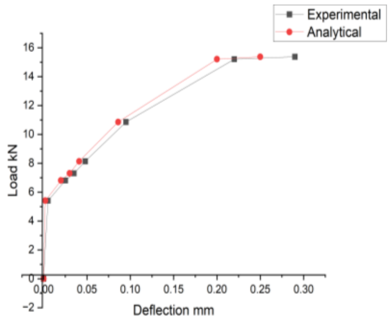


Fig. 20:P-δ curve for L=1500mm and $\frac{a}{d} = 0.25$

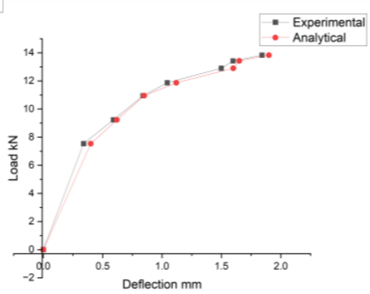


Fig. 21: P-δ curve for L=1500mm L=1500mm and $\frac{a}{d} = 0.33$

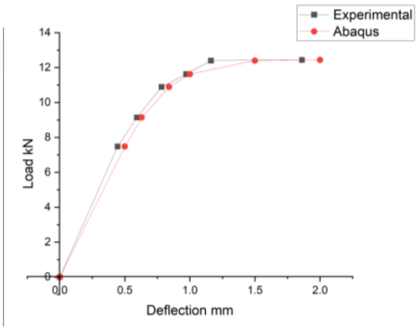


Fig.22: P-δ curve for and $\frac{a}{d} = 0.5$

3.1 Discussions:

The load-deflection curve of RCC beams followed a nonlinear trend, with an initial elastic phase followed by yielding and strain hardening, whereas plain beams exhibited a nearly linear-elastic response until sudden failure.

1. It is observed that from Fig. 8, 9, 13, 14, 18 & 19, Because reinforcing is essential for increasing tensile strength and flexibility, reinforced cement concrete (RCC) beams have a substantially larger load-carrying capacity than plain blended concrete beams. Experimental and analytical investigations that assess the flexural performance of beams containing fly ash and ground granulated blast furnace slag (GGBS) corroborate this finding.
2. When compared to conventional mixed concrete beams, RCC beams have superior crack distribution and spacing. According to experimental research, RCC beams can withstand greater loads even after first cracking, whereas plain concrete beams collapse quickly because of their low post-cracking strength.
3. Because reinforcement yields before ultimate failure, RCC beams maintain serviceability at increased loads, according to deflection patterns captured by linear variable differential transformers, or LVDTs.
4. Both plain and RCC beams benefit from fly ash and GGBS's long-term strength growth, while RCC beams benefit more from their use since reinforcing lessens early-age deficiencies.
5. ABAQUS simulations verify that RCC beams have greater load-carrying capacity because they more effectively disperse stresses.
6. While ordinary blended concrete beams fail at lower loads because of their limited tensile resistance, RCC beams exhibit a more uniform strain distribution transition from elastic to plastic behaviour.
7. RCC beams have a nonlinear but predictable load-deflection response, according to analytical models. Higher ultimate loads before failure result from the reinforcement's ability to dissipate energy.

8. The load capacity of reinforced beams is 40–60% higher than that of unreinforced plain concrete beams, according to comparisons with experimental data.
9. In confirming that deflections rise dramatically with greater spans, there is remarkable agreement between experimental deflection data and theoretical predictions. Because reinforcement can withstand tensile stresses, RCC beams deflect less than plain concrete beams, yet the pattern is the same for both material types.
10. When compared to plain blended concrete beams, RCC beams with blended cementitious materials show reduced early-stage deflections and increased stiffness.
11. It has been observed that longer beams demonstrated greater deflections under equivalent loads due to the proportional increase in bending moment and reduced stiffness in both Experimental and Analytical method.
12. Beams with notches exhibited lower load-bearing capacity and higher deflections as stress concentrations developed at the notched sections, leading to premature failure validated by both Experimental and Analytical method.
13. Test-generated load-displacement graphs show that, in comparison to unnotched beams, notched beams fail at a significantly lower applied load.
14. Stress concentration at the notch tip, which serves as a crack initiation location and causes early brittle failure before the beam can fully utilize its flexural capacity, is the cause of the strength drop.
15. Notched beams deflect more than their unnotched counterparts under the same applied load, according to deflection measurements made with linear variable differential transformers (LVDTs). More flexibility and deflection result from a decrease in the moment of inertia (I) caused by the notch's reduction of the effective cross-section.
16. Experimental findings demonstrating that notched beams achieve their maximal deflection earlier than unnotched beams, leading to decreased ductility and serviceability, further support the deflection increase.
17. Beams with deeper notches showed a drastic reduction in strength and stiffness, indicating that notch depth plays a critical role in determining structural performance by both methods.
18. The Experimental results when compared to analytical results from AQBAUS are almost similar answers with a maximum difference betw the two is between 3% - 10%.

4. Conclusion

This study provides a comprehensive review of the comparison between RC and Blended plain concrete beams load-deflection behaviour. The results emphasize how the reinforcement is important in improving structural performance. Further scope of research can focus on optimizing reinforcement design and exposure to machine learning techniques for predictive modelling.

1. RC beams exhibited higher stiffness and reduced deflection compared to plain beams. In RC beams Deflection grows linearly at the beginning of loading, however nonlinearity is shown at greater loads because of reinforcing yielding and cracking. Where as Plain concrete beams fail suddenly due to the material’s low tensile strength, leading to abrupt cracking and collapse.
2. FEM simulations closely matched experimental data, validating numerical approaches.
3. Because RC beams are ductile, the reinforcement gradually yields before failing completely, giving for warning indicators such increased deflection before to collapse.
4. Beams with deeper notches showed a drastic reduction in strength and stiffness, indicating that notch depth plays a critical role in determining structural performance.
5. In RCC beams, cracks were controlled by reinforcement, allowing a more ductile failure. In contrast, plain beams experienced brittle failure with rapid crack propagation.

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