Strain-Based Quantification of Ductility Reserve in Eurocode 2 Minimum-Reinforced Singly Reinforced Concrete Beams

Abstract

Eurocode 2 (EC2) minimum longitudinal reinforcement provisions for singly reinforced concrete beams are widely applied to ensure crack control and avoid brittle failure; however, compliance with these requirements is often assumed to imply adequate ductility without explicit quantification. This paper presents a strain-based parametric assessment of the sectional ductility reserve of singly reinforced concrete beams designed at and modestly above the EC2 minimum reinforcement level. Ductility is quantified using a ductility reserve ratio (DRR), defined as the normalized post-yield tensile strain capacity of the reinforcement between first yield and the onset of concrete crushing. Sectional analyses within the EC2 framework examine the influence of effective beam depth, concrete strength class (C25/30, C30/37, and C40/50), and reinforcement ratio expressed relative to the EC2 minimum requirement (ρ/ρ_{min} = 1.0–1.50). Results show that effective depth has no influence on strain-based sectional ductility, while increasing reinforcement ratio systematically reduces ductility reserve. Higher concrete strength increases ductility at a fixed reinforcement level; however, beams with lower-strength concrete at the EC2 minimum reinforcement level may exhibit greater ductility reserve than higher-strength concrete beams with modestly increased reinforcement. The findings provide quantitative insight into ductility behavior relevant to deformation-controlled design.

Keywords: Ductility reserve; Eurocode 2; Minimum reinforcement; Singly reinforced concrete beams; Strain-based sectional analysis

1. Introduction

Singly reinforced concrete beams designed in accordance with Eurocode 2 (EC2) (EN 1992-1-1, 2004) are required to satisfy minimum longitudinal tension reinforcement provisions to ensure adequate crack control and to avoid sudden brittle failure. These minimum reinforcement limits are widely applied in structural practice and frequently govern the design of lightly loaded beams. While compliance with the EC2 minimum reinforcement requirement is commonly taken to imply the presence of adequate ductile behavior at the ultimate limit state, the deformation capacity and post-yield strain reserve associated with EC2 minimum-reinforced singly reinforced concrete beams is not explicitly quantified in routine design, nor directly addressed within the predominantly strength-based framework of the code. The EC2 minimum reinforcement provisions are primarily intended to promote stable cracking and to avoid sudden brittle failure, with no explicit requirement for a quantified level of strain-based or deformation-based ductility (Beeby & Narayanan, 2005).

Plastic hinge theory and moment–curvature relationships provide the basis for curvature-based ductility assessment in reinforced concrete members (Park & Paulay, 1975). Previous research has extensively investigated the flexural and curvature ductility of reinforced concrete beams using section-based strain compatibility analysis and associated moment-curvature relationships (Kwan et al., 2002; Olivia & Mandal, 2005). In this context, ductility is commonly defined in a strain-based manner as the ratio of curvature at ultimate concrete compression strain to curvature at first yielding of the tensile reinforcement, reflecting the post-yield deformation capacity of a reinforced concrete section. Numerous analytical and experimental studies have demonstrated that sectional ductility is influenced by key material and geometric parameters, particularly the longitudinal reinforcement ratio and concrete strength class (Kwan et al., 2002; Olivia & Mandal, 2005). Parametric investigations have further shown that variations in tensile reinforcement ratio and concrete compressive strength significantly affect the moment–curvature response and available curvature ductility, while additional measures such as compression reinforcement may be employed to enhance ductile behavior, particularly in beams constructed with higher-strength concrete (Kwan et al., 2002). The use of higher-strength concretes has also been associated with increased material brittleness, further emphasizing the importance of strain-based assessments of ductility rather than reliance on strength measures alone (Shah & Ahmad, 1994).

Experimental investigations have demonstrated that the flexural ductility of reinforced concrete beams is closely related to the position of the neutral axis at ultimate conditions (Bernardo & Lopes, 2004). The normalized neutral axis depth, commonly expressed as x/d, is widely recognized as a practical indicator of the balance between tensile steel yielding and concrete crushing, and hence of ductile versus brittle sectional behavior.

Studies on both normal- and high-strength concrete beams have shown that deeper neutral axis positions at failure are generally associated with reduced flexural ductility, while shallower neutral axis depths promote higher deformation capacity (Bernardo & Lopes, 2004). Similar trends have been reported for lightweight-aggregate concrete beams, indicating that the relationship between neutral axis depth at failure and flexural ductility remains consistent with that observed in normal-weight concrete beams, despite differences in concrete material properties (Bernardo et al., 2019).

Despite this extensive body of research, existing studies generally examine flexural ductility in relation to absolute reinforcement ratios or broad under- and over-reinforced regimes, without explicitly focusing on sections designed at or near the minimum longitudinal reinforcement levels prescribed by modern design codes. In practice, reinforcement ratios modestly exceeding code-required minimum values are frequently adopted due to conservative design practices rather than structural demand. Field-based investigations of reinforced concrete residential buildings have reported that the reinforcement provided in practice often significantly exceeds code-based design requirements, reflecting conservative design approaches rather than structural necessity (Alnuaimi et al., 2015). Such widespread overdesign indicates that reinforcement ratios adopted in real structures may differ substantially from those implied by minimum code provisions, highlighting the importance of understanding the strain-based ductility characteristics of reinforced concrete sections designed at and modestly above minimum code-prescribed longitudinal reinforcement levels.

In this context, the present study provides a strain-based parametric assessment of ductility reserve in singly reinforced concrete beams designed at and modestly above the EC2 minimum longitudinal reinforcement level. The influence of effective beam depth, reinforcement ratio expressed as ρ/ρ_{min}, and concrete strength class is examined through sectional analysis. Ductility is quantified using a ductility reserve ratio (DRR), defined as the ratio of the absolute strain reserve beyond steel yielding ($\varepsilon_{s,ULS} - \varepsilon_{sy}$) to the steel yield strain. By systematically isolating and combining these parameters within the Eurocode 2 (EC2) design framework, the study clarifies their relative importance in governing sectional ductility and highlights non-intuitive interactions directly relevant to practical structural engineering design. The results provide quantitative insight into how common, code-compliant design choices influence the post-yield deformation capacity of singly reinforced concrete beams, particularly in situations where deformation capacity and post-yield behavior, rather than flexural strength alone, are critical to structural performance.

2. Methodology

2.1 Overview of Analytical Approach

The present study employs a strain-based sectional analysis to quantify the ductility reserve of singly reinforced concrete beams designed at and slightly above the Eurocode 2 (EC2) minimum longitudinal reinforcement level. The analysis is conducted at the cross-sectional level and focuses on post-yield tensile strain capacity of the longitudinal reinforcement up to the onset of concrete crushing.

Ductility is quantified using a ductility reserve ratio (DRR), defined as the ratio of the available tensile steel strain capacity between first yield and ultimate concrete crushing to the steel yield strain. This strain-based metric allows a direct comparison of ductility across different material strengths, reinforcement levels, and effective depth values while remaining independent of member span, loading configuration, and boundary conditions.

All calculations were performed using closed-form expressions derived from EC2 sectional equilibrium and strain compatibility assumptions and implemented in spreadsheet format to ensure transparency, traceability, and reproducibility of the sectional analyses.

2.2 Definition of Ductility Reserve Ratio (DRR)

The ductility reserve ratio (DRR) is defined as:

$DRR = \Delta\varepsilon_{res}/\varepsilon_{sy}$

Where,

- ε_{sy} = Steel yield strain
- $\Delta\varepsilon_{res} = \varepsilon_{s,ULS} - \varepsilon_{sy}$
- $\varepsilon_{s,ULS}$ = Steel strain at ultimate limit state

This definition isolates the available post-yield strain reserve in the reinforcement and provides a normalized, dimensionless measure of sectional ductility suitable for parametric comparison. DRR is the main interpretation parameter, to allow for comparison across beam depths, reinforcement ratios, and concrete classes considered in this paper.

2.3 Parametric Study Design

A structured parametric study was conducted to investigate the influence of three primary parameters on the ductility reserve ratio (DRR):

1. Effective depth (d)
2. Concrete strength class
3. Longitudinal reinforcement ratio expressed relative to the EC2 minimum reinforcement

Each parameter was examined at three discrete levels, resulting in a total of:- 3 * 3 * 3 = 27 distinct section configurations.

The parametric study was structured such that only one primary parameter was varied at a time while the remaining parameters were held constant in any given configuration. For example, the influence of concrete strength class was assessed by varying the concrete class while keeping the effective depth and reinforcement ratio (ρ/ρ_{min}) fixed. Similarly, the influence of reinforcement ratio was examined by varying ρ/ρ_{min} at fixed concrete strength and effective depth, while the influence of effective depth was assessed by varying the effective depth at fixed concrete strength class and reinforcement ratio. This approach ensured that the isolated and combined effects of each parameter on the sectional ductility reserve could be clearly identified.

2.3.1 Effective Depth

Three effective depths (300mm, 500mm, and 700mm), representative of typical reinforced concrete beam dimensions, were considered. These values were selected to investigate whether absolute member size influences sectional ductility when reinforcement is defined relative to the EC2 minimum requirement.

2.3.2 Concrete Strength Classes

Concrete strength classes C25/30, C30/37, and C40/50 were selected to represent conventional normal-strength concrete commonly used in reinforced concrete design. The selection was intentionally limited to this range to maintain focus on typical design applications. In accordance with EC2, the characteristic cylinder compressive strengths (f_{ck}) adopted for concrete classes C25/30, C30/37, and C40/50 were 25 MPa, 30 MPa, and 40 MPa respectively.

2.3.3 Reinforcement Ratio

The longitudinal reinforcement level is expressed in normalized form as the ratio ρ/ρ_{min}, where $\rho = A_{s,provided}/(b*d)$ is the reinforcement ratio provided and ρ_{min} corresponds to the

EC2 minimum longitudinal tension reinforcement. This normalization enables a consistent comparison of ductility reserve across different configurations.
The longitudinal reinforcement ratios are:

- **ρ/ρ_{min} = 1.0 (EC2 minimum)**
- **ρ/ρ_{min} = 1.25**
- **ρ/ρ_{min} = 1.50**

Where,

- $\rho/\rho_{min} = (A_{s,provided})/(A_{s,min})$
- $A_{s,min}$ is the minimum longitudinal tension reinforcement required by the EC2 Clause 9.2.1.1
- $A_{s,provided}$ is the area of the longitudinal tension reinforcement provided
- ρ/ρ_{min} = 1.0 represents the EC2 minimum required longitudinal reinforcement. Also, ρ/ρ_{min} = 1.25 represents 25% above the EC2 minimum, and ρ/ρ_{min} = 1.50 represents 50% above the EC2 minimum

For example:- for a reinforcement ratio of $\rho/\rho_{min} = 1.25$, the $A_{s,provided} = A_{s,min} * 1.25$
Similarly, for a reinforcement ratio of $\rho/\rho_{min} = 1$, the $A_{s,provided} = A_{s,min} * 1.0$

This range was chosen to examine the effect of modest increases above the EC2 minimum reinforcement level, which are commonly encountered in practice due to detailing constraints, constructability considerations, or conservative design choices.

2.4 Computational Procedure

For each section configuration, the following steps were performed in accordance with Eurocode 2 (EC2) (EN 1992-1-1, 2004) sectional equilibrium and strain compatibility principles:

1. The EC2 minimum reinforcement ratio was calculated for the given concrete strength class (EC2 Clause 9.2.1.1):

   $A_{s,min}$ (mm^2) = MAXIMUM [$(0.26*(f_{ctm}/f_{yk})*b*d)$; $(0.0013*b*d)$]

   With: $f_{ctm} = 0.30* f_{ck}^{2/3}$

2. The selected reinforcement ratio (ρ/ρ_{min}) was applied to determine the longitudinal steel area:

   $A_{s,provided} = A_{s,min} * (\rho/\rho_{min})$

3. The neutral axis depth was determined using:

   Neutral Axis Depth, x (mm) = $(0.87*fyk*A_{s,provided})/(0.85*f_{ck}*b)$

4. The neutral axis ratio was computed and EC2 x/d limit check was conducted:

   Neutral axis ratio = x/d

   Where,
   x = neutral axis depth
   d = effective depth of the beam
   Also, EC2 x/d limit is x/d = 0.45

5. Steel strain at concrete crushing:

   Steel strain at ULS, $\varepsilon_{s,ULS} = \varepsilon_{cu}*(d-x)/x$

   Where,
   $\varepsilon_{cu} = 0.0035$

6. Yield Check:

   If $\varepsilon_{s,ULS} \geq \varepsilon_{sy} \rightarrow$ Yielded (ductile)

   Where,
   Steel yield strain, $\varepsilon_{sy} = f_{yk}/E_s$
   f_{yk} is the characteristic strength of steel in MPa. In this study, $f_{yk} = 500$
   E_s is the modulus of elasticity of the reinforcing steel, and $E_s = 200000$MPa

7. Absolute ductility reserve:

   Absolute Ductility Reserve, $\Delta\varepsilon_{res} = \varepsilon_{s,ULS} - \varepsilon_{sy}$

   This indicates how much additional steel strain the section can sustain after yielding.

8. The ductility reserve ratio (DRR) was computed using the defined strain-based expression:

   Ductility Reserve Ratio (DRR) = $\Delta\varepsilon_{res}/\varepsilon_{sy}$

3. Results and Discussion

This section presents and discusses the results of the strain-based sectional analyses carried out in this paper. The influence of effective depth, reinforcement ratio (expressed as ρ/ρ_{min}), and concrete strength class on the ductility reserve ratio (DRR) is examined through a parametric investigation. To aid clarity, the discussion is structured to first assess the influence of individual parameters, followed by an evaluation of their combined effects and practical implications for design.

3.1 Influence of Effective Depth

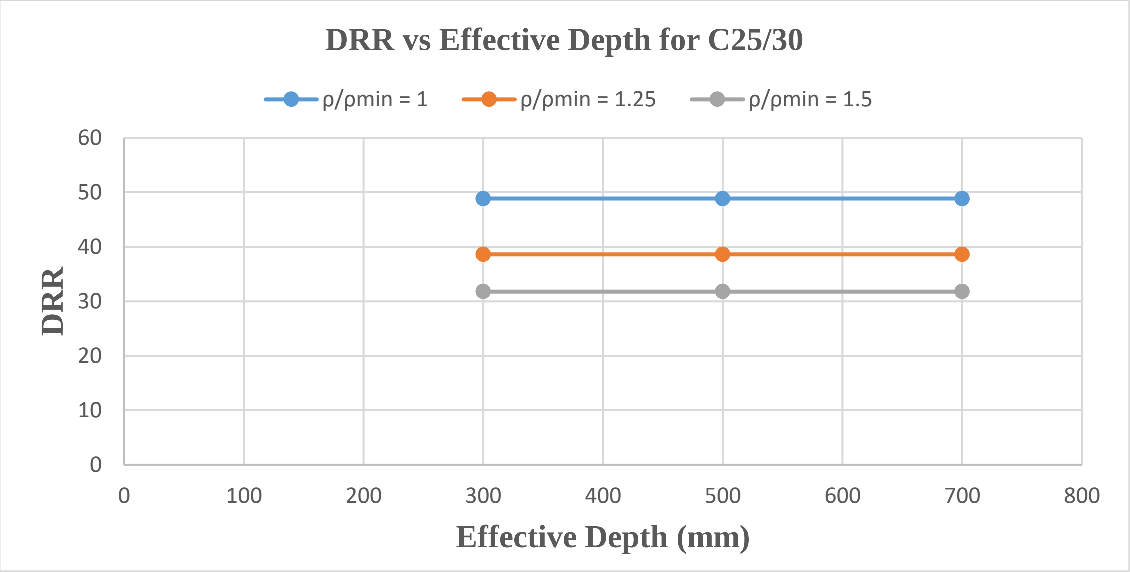

Fig. 1. Variation of ductility reserve ratio (DRR) with effective depth for concrete class C25/30.

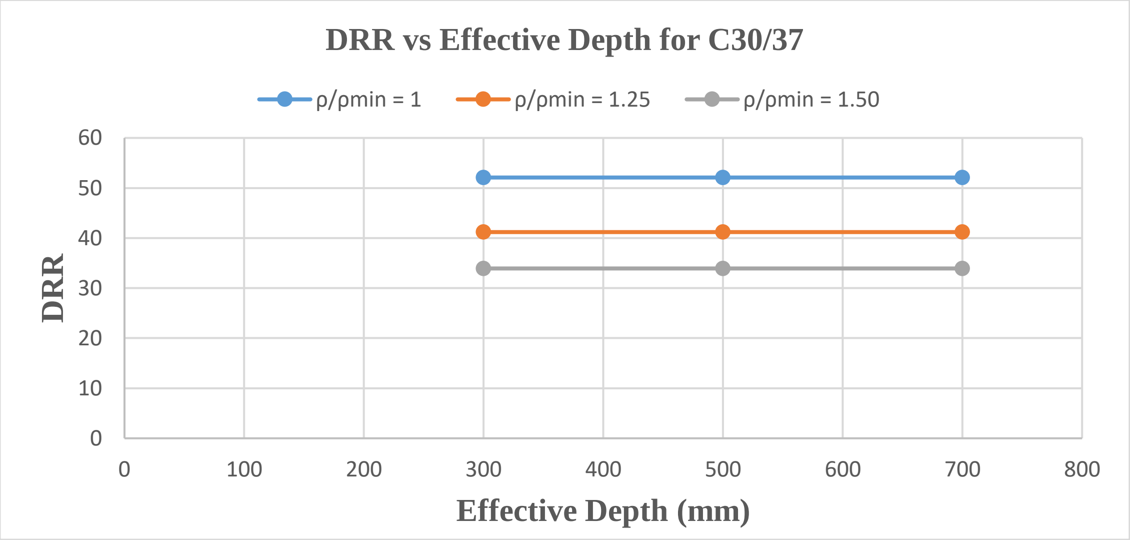

Fig. 2. Variation of ductility reserve ratio (DRR) with effective depth for concrete class C30/37.

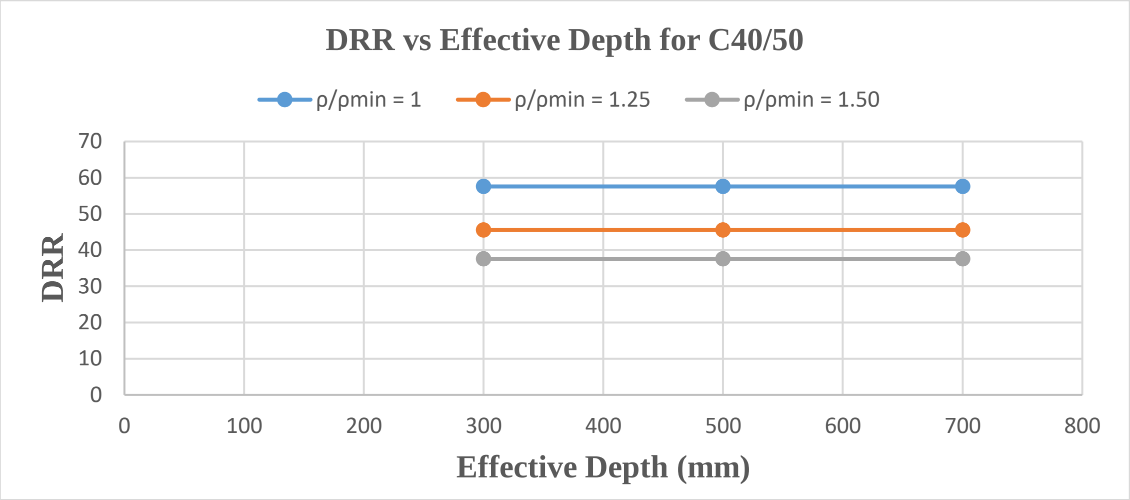

Fig. 3. Variation of ductility reserve ratio (DRR) with effective depth for concrete class C40/50.

Figs. 1-3 present the variation of the ductility reserve ratio (DRR) with effective depth for beams designed using concrete classes C25/30, C30/37, and C40/50 at reinforcement ratios corresponding to ρ/ρ_{min} = 1.0, 1.25, and 1.50, where ρ/ρ_{min} = 1.0 represents the EC2 minimum longitudinal tension reinforcement requirement.

The results show that changes in effective depth within the investigated range do not influence the computed ductility reserve ratio (DRR). For a given concrete strength class and reinforcement ratio, identical DRR values are obtained irrespective of beam effective depth. This outcome arises because, when reinforcement is expressed relative to the EC2 minimum requirement, the normalized neutral axis depth (x/d) remains constant for a given material and reinforcement combination. As a result, the steel strain at the onset of concrete crushing depends on the relative position of the neutral axis within the section (x/d), rather than on the absolute value of the effective beam depth.

This finding is consistent with fundamental sectional analysis principles and demonstrates that, for beams designed at the EC2 minimum reinforcement level and at modest multiples of it (ρ/ρ_{min} = 1.0–1.50), sectional strain-based ductility is governed by concrete strength class and reinforcement proportion rather than by beam effective depth. It is emphasized that the ductility examined in this study is a sectional, strain-based measure quantified from steel yielding up to the ultimate limit state (concrete crushing).

Given the absence of any influence of effective depth on DRR, subsequent results are presented without further reference to beam depth, focusing instead on the influence of concrete strength class and reinforcement ratio.

3.2 Influence of Reinforcement Ratio (ρ/ρ_{min}) on Ductility Reserve

Figs. 4-6 illustrate the variation of the ductility reserve ratio (DRR) with reinforcement ratio expressed as ρ/ρ_{min} for concrete classes C25/30, C30/37, and C40/50. A value of $\rho/\rho_{min} = 1.0$ corresponds to the EC2 minimum longitudinal reinforcement, while ρ/ρ_{min} = 1.25 and 1.50 represent modest increases above the EC2 minimum level.

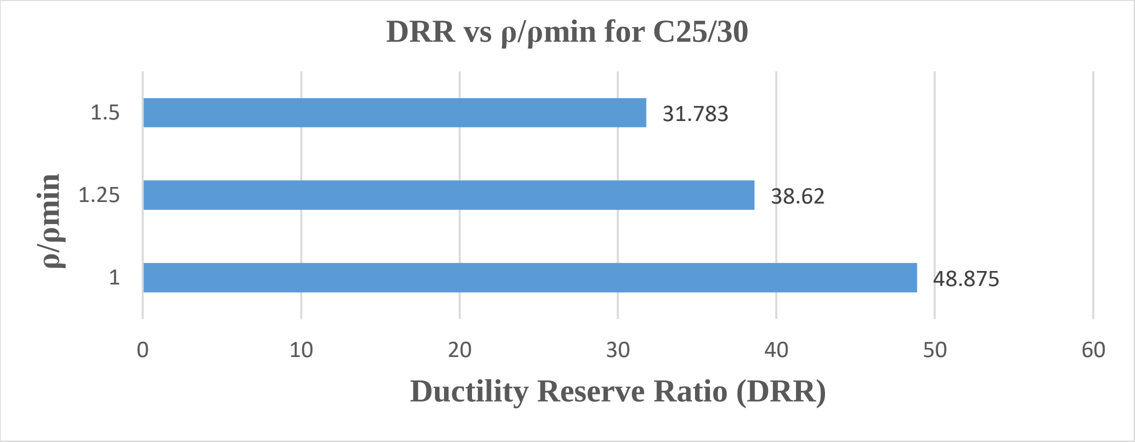

Fig. 4. Variation of ductility reserve ratio (DRR) with reinforcement ratio (ρ/ρmin) for C25/30.

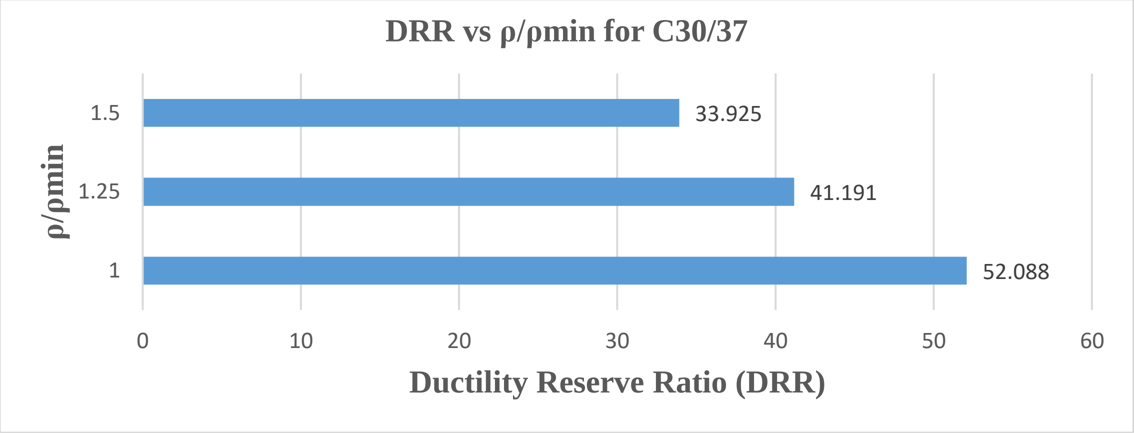

Fig. 5. Variation of ductility reserve ratio (DRR) with reinforcement ratio (ρ/ρmin) for C30/37.

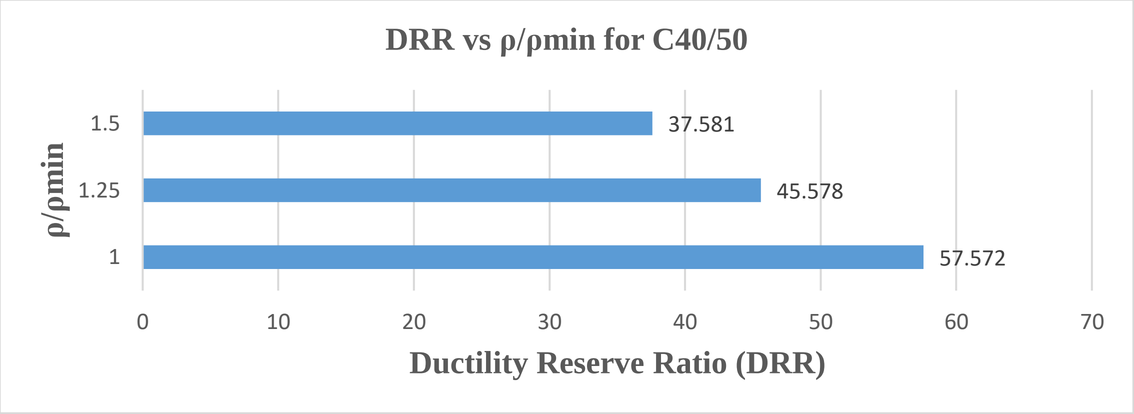

Fig. 6. Variation of ductility reserve ratio (DRR) with reinforcement ratio (ρ/ρ_{min}) for C40/50.

For all the concrete strength classes considered, an increase in reinforcement ratio leads to a consistent reduction in DRR. This trend reflects the shift of the neutral axis toward the compression zone with increasing steel area, which reduces the steel strain capacity available between the first yield and the onset of concrete crushing. Despite this reduction, all examined configurations remain comfortably and clearly within the ductile response range.

For concrete class C25/30 (fig. 4), the DRR decreases from 48.875 at the EC2 minimum reinforcement level to 38.62 and 31.783 at reinforcement ratios of $\rho/\rho_{min} = 1.25$ and 1.50 respectively. A similar trend is observed for C30/37 (fig. 5), where the DRR reduces from 52.088 at minimum reinforcement (as per EC2) to 41.191 and 33.925 as the reinforcement ratio increases. For the higher strength concrete C40/50 (fig. 6), the corresponding DRR values decrease from 57.572 to 45.578 and 37.581 over the same ρ/ρ_{min} range.

Although the relative reduction in DRR with increasing reinforcement ratio is broadly similar across the considered concrete classes, the absolute decrease in ductility reserve ratio with increasing reinforcement ratio becomes progressively larger as concrete strength increases. When the reinforcement ratio is increased from $\rho/\rho_{min} = 1.0$ to 1.50, the reduction in DRR increases from approximately 17.1 for C25/30 to approximately 18.2 for C30/37 and to approximately 20 for C40/50. Although the numerical differences are modest, the trend is systematic and indicates that higher-strength concretes are more sensitive, in absolute strain terms, to increase in longitudinal reinforcement above the EC2 minimum level. Nevertheless, even at $\rho/\rho_{min} = 1.50$, the computed DRR values remain very large (DRR ≈ 30-38), indicating that all the investigated sections retain substantial post-yield steel strain reserve prior to concrete crushing and therefore exhibit strongly ductile sectional behavior, with post-yield steel strain reserves exceeding 30 times the steel yield strain.

3.3 Influence of Concrete Strength Class

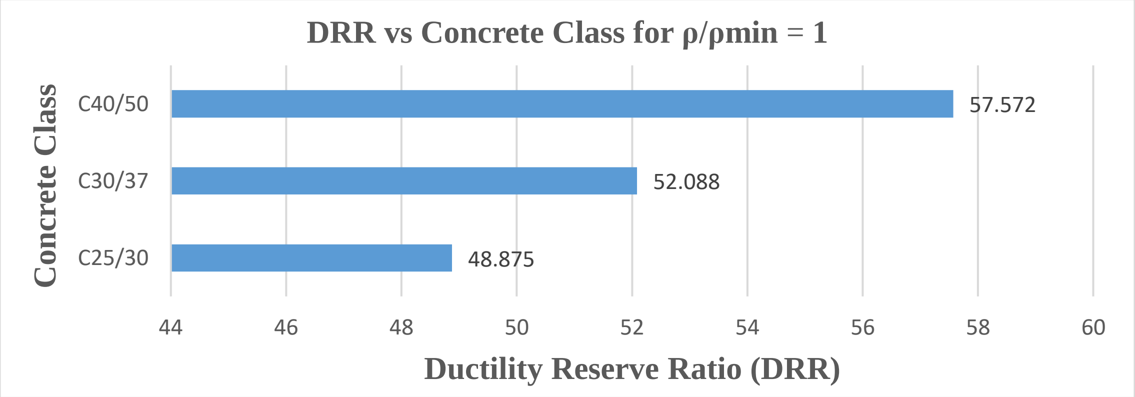

Fig. 7: Variation of ductility reserve ratio (DRR) with concrete strength class for $\rho/\rho_{min} = 1.0$.

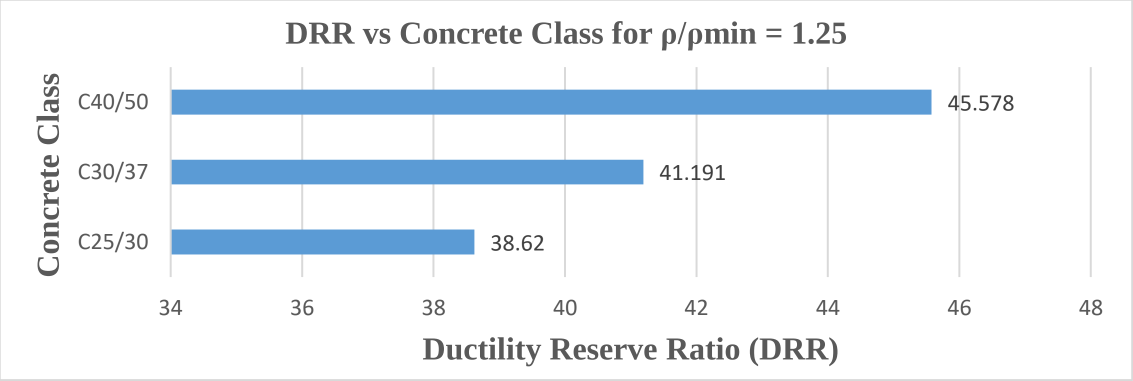

Fig. 8: Variation of ductility reserve ratio (DRR) with concrete strength class for ρ/ρ_{min} = 1.25.

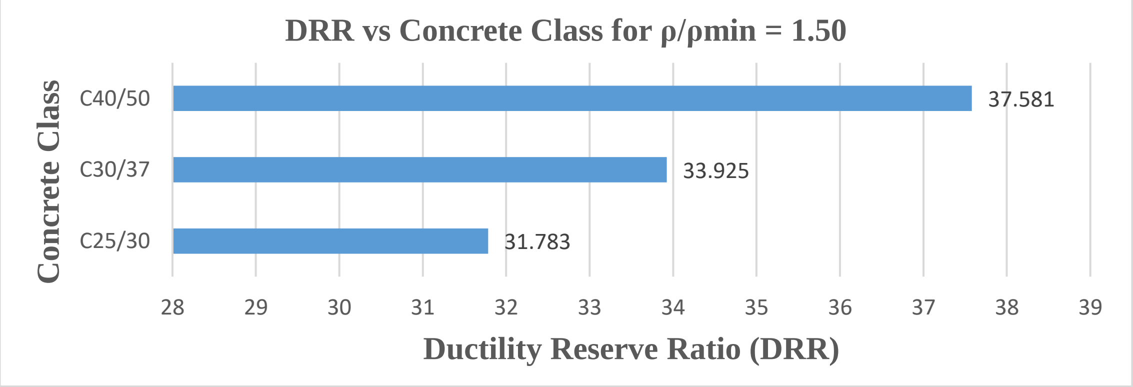

Fig. 9: Variation of ductility reserve ratio (DRR) with concrete strength class for ρ/ρ_{min} = 1.50.

Figs. 7-9 illustrate the variation of the ductility reserve ratio (DRR) with concrete strength class for beams designed at reinforcement ratios corresponding to ρ/ρ_{min} = 1.0, 1.25, and 1.50. For each reinforcement level, an increase in concrete strength class results in a systematic increase in the computed DRR.

At the EC2 minimum reinforcement level (ρ/ρ_{min} = 1.0), DRR increases from 48.875 for C25/30 to 52.088 for C30/37 and 57.572 for C40/50. A similar trend is observed for higher reinforcement ratios. At ρ/ρ_{min} = 1.25, DRR increases from 38.62 (C25/30) to 41.191 (C30/37) and 45.578 (C40/50), while at ρ/ρ_{min} = 1.50, DRR values of 31.783 for C25/30, 33.925 for C30/37, and 37.581 for C40/50 are obtained.

This behavior shows that higher-strength concretes develop a shallower compression zone for a given reinforcement ratio, resulting in lower neutral axis depths relative to the effective depth. As a consequence, the tensile reinforcement experiences a larger strain increment between first yield and the onset of concrete crushing, leading to an increased strain-based ductility reserve.

It is noted that this increase in DRR with concrete strength is observed consistently across all reinforcement ratios considered. However, the beneficial effect of higher concrete strength on ductility reserve is progressively reduced as the reinforcement ratio increases above the EC2 minimum level.

3.4 Combined Influence of Concrete Strength and Reinforcement Ratio

While sections 3.2 and 3.3 examined the individual influence of reinforcement ratio and concrete strength class on the ductility reserve ratio (DRR), their combined effect reveals an important and non-intuitive trend relevant to practical design.

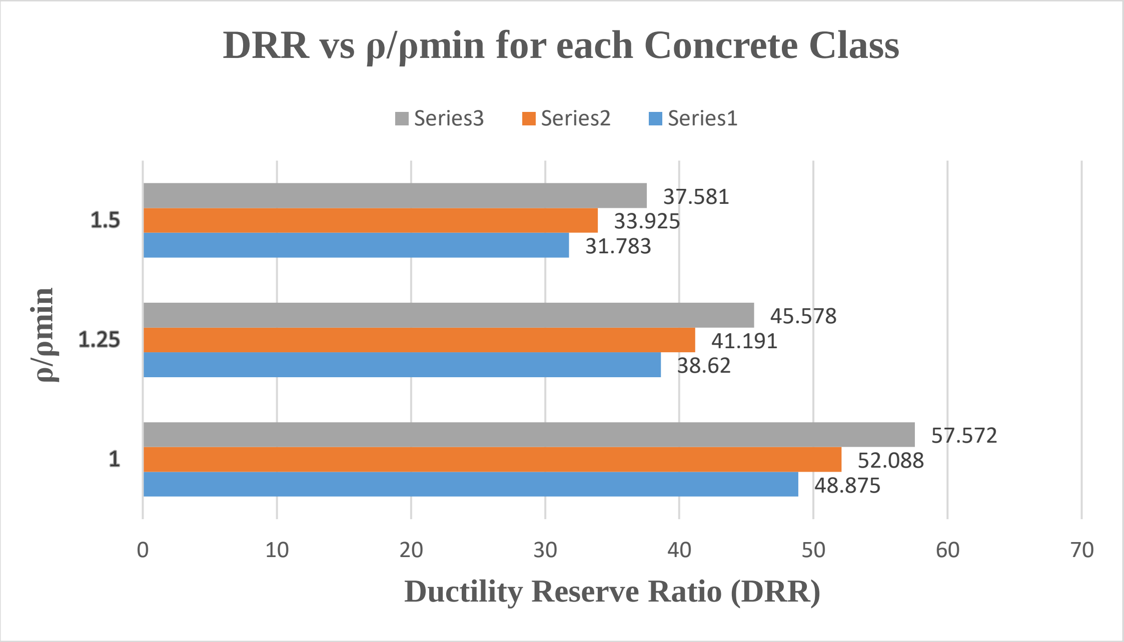

Fig. 10. Combined influence of concrete strength class and reinforcement ratio (ρ/ρ_{min}) on the ductility reserve ratio (DRR) of EC2 minimum- and near-minimum-reinforced singly reinforced concrete beams.

Fig. 10 illustrates the combined influence of concrete strength class and reinforcement ratio on the ductility reserve ratio (DRR). A key and non-intuitive outcome of the present study is that higher concrete strength and higher reinforcement ratio do not necessarily correspond to greater sectional ductility when considered together.

For beams designed at the EC2 minimum longitudinal reinforcement level ($\rho/\rho_{min} = 1.0$), the ductility reserve ratio increases with concrete strength: from 48.875 for C25/30 to 52.088 for C30/37 and 57.572 for C40/50. This trend is directly reflected in the computed ductility reserve ratios obtained from the sectional analysis, indicating that for a given reinforcement ratio, higher concrete strength classes consistently exhibit a greater post-yield tensile strain reserve.

However, when modest increases in reinforcement are introduced, this trend is reversed in a comparative sense. Beams designed using lower-strength concrete at the EC2 minimum reinforcement level exhibit a higher ductility reserve than beams designed using higher-strength concrete with modestly increased reinforcement ratios. From fig. 10, the C25/30 beam at ρ/ρ_{min} = 1.0 exhibits a DRR of 48.875, which is 1.30 times higher than the DRR of 37.581 obtained for the C40/50 beam at ρ/ρ_{min} = 1.50, and 1.07 times higher than the DRR of 45.578 obtained for the C40/50 beam at ρ/ρ_{min} = 1.25.

This behavior arises because increase in reinforcement ratio shifts the neutral axis deeper into the section, as reflected by the increase in the normalized neutral axis depth (x/d) with increasing ρ/ρ_{min} (fig. 11), thereby reducing the available post-yield tensile strain capacity prior to concrete crushing. As a result, the beneficial effect of higher concrete strength on sectional ductility can be partially or fully offset by relatively small increases in longitudinal reinforcement above the EC2 minimum level.

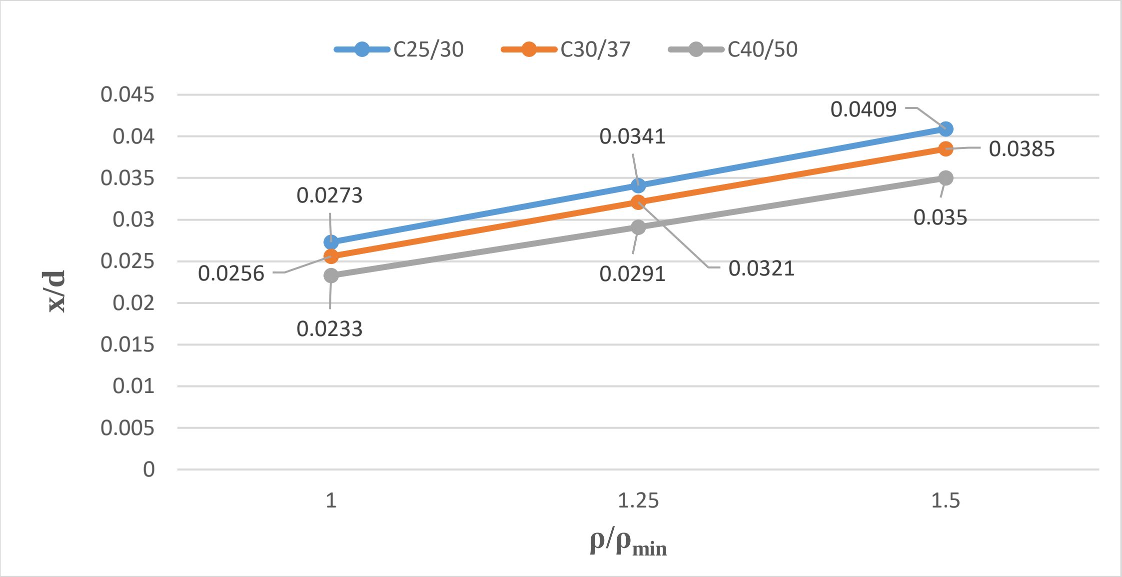

Fig. 11. Variation of normalized neutral axis depth (x/d) with reinforcement ratio (ρ/ρ_{min}) for concrete classes C25/30, C30/37, and C40/50.

From a design perspective, these findings demonstrate that sectional ductility is controlled by the interaction between concrete strength and reinforcement proportion, rather than by material strength alone. In lightly loaded members designed close to the minimum reinforcement requirements, increasing reinforcement in higher-strength concrete may reduce ductility without providing a proportionate benefit in structural performance. This insight is directly relevant to deformation-controlled design situations where post-yield strain capacity governs structural behavior.

4. Conclusions

This paper has presented a strain-based quantification and comparative assessment of the ductility reserve of Eurocode 2 (EC2) minimum-reinforced singly reinforced concrete beams. Based on the results of the parametric analysis, the following conclusions are drawn:

a. Effective beam depth was found to have no influence on the computed ductility reserve ratio (DRR) within the investigated parameter range. For beams designed at the EC2 minimum reinforcement level ($\rho/\rho_{min} = 1$) and at modest multiples of it ($\rho/\rho_{min} = 1.25$ and 1.50), the ductility reserve ratio (DRR) remained invariant with respect to effective depth, indicating that sectional ductility is governed by strain compatibility rather than absolute member size.

b. Reinforcement ratio exerts a dominant influence on sectional ductility. Increasing the reinforcement ratio above the EC2 minimum level leads to a systematic reduction in ductility reserve across all the considered concrete classes. This reduction is associated with increased compression zone depth and a corresponding decrease in available post-yield tensile strain capacity prior to concrete crushing.

c. Concrete strength class, when considered independently at a fixed reinforcement ratio, has a beneficial effect on sectional ductility. For a given value of ρ/ρ_{min}, higher concrete strength results in increased ductility reserve ratios, reflecting the enhanced strain capacity available before ultimate compression failure.

d. A key outcome of this study is the identification of a non-obvious interaction between concrete strength and reinforcement ratio. Beams designed with lower-strength concrete at the EC2 minimum reinforcement level can exhibit greater ductility reserve than beams designed with higher-strength concrete but with modestly increased reinforcement ratios ($\rho/\rho_{min} = 1.25$–1.50), despite all sections remaining under-reinforced and code-compliant. This demonstrates that increases in longitudinal reinforcement, even modestly above the EC2 minimum, can offset or outweigh the ductility benefits associated with higher concrete strength.

e. These findings clarify that increasing concrete strength does not automatically guarantee higher ductility. In lightly loaded members, where strength demand does not control design, increasing reinforcement in higher-strength concrete may lead to reduced ductility while providing additional flexural strength that is not required to satisfy the governing design demand. This is particularly relevant in deformation-controlled regions and performance-based assessments, where post-yield strain capacity is a key design consideration.

Overall, the findings provide a quantitative, strain-based perspective on ductility reserve that is not explicitly addressed within the strength-based framework of Eurocode 2. By operating entirely within the EC2-compliant design limits, the study clarifies how common design choices, particularly concrete strength class and reinforcement level relative to the EC2 minimum, govern the available post-yield strain capacity of singly reinforced concrete beams. The results offer practical insight for engineers seeking to balance strength and ductility in lightly loaded, flexure-governed members, particularly in deformation-controlled situations where post-yield deformation capacity, rather than flexural strength, governs structural performance.

References

Alnuaimi, A. S., Mohsin, M. A., Hago, A., & Gamal, S. E. (2015). Overdesign of villa structures in Oman. *The Journal of Engineering Research*, *12*(2), 68-76.

Beeby, A. W., & Narayanan, R. S. (2005). *Designers' Guide to EN 1992-1-1 Eurocode 2: Design of Concrete Structures: General Rules and Rules for Buildings and Structural Fire Design* (Vol. 17). Thomas Telford.

Bernardo, L. F. A., & Lopes, S. M. R. (2004). Neutral axis depth versus flexural ductility in high-strength concrete beams. *Journal of Structural Engineering*, *130*(3), 452-459.

Bernardo, L., Nepomuceno, M., & Pinto, H. (2019). Neutral axis depth versus ductility and plastic rotation capacity on bending in lightweight-aggregate concrete beams. *Materials*, *12*(21), 3479.

EN 1992-1-1 (2004): Eurocode 2 – Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings, European Committee for Standardization.

Kwan, A. K. H., Ho, J. C. M., & Pam, H. J. (2002). Flexural strength and ductility of reinforced concrete beams. *Proceedings of the institution of civil Engineers-Structures and Buildings*, *152*(4), 361-369.

Olivia, M., & Mandal, P. (2005). Curvature ductility of reinforced concrete beam. *Journal of Civil Engineering*, *6*(1), 1-13.

PARK, R., & PAULAY, T. (1975). REINFORCED CONCRETE STRUCTURES. John Wiley & Sons.

Shah, S. P., & Ahmad, S. H. (1994). High performance concretes and applications. Edward Arnold.

Statements & Declarations

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Competing Interests

The author declares that no competing interests exist.

Author's Contribution

The author solely conceived the study, developed the analytical framework, performed the calculations, analysed and interpreted the results, and prepared the manuscript.

Data Availability

All data generated or analysed during this study is included in this paper. The analytical procedure and governing equations are fully described in the Methodology section, allowing the results to be reproduced.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

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