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Determination of Moment Parameters of Rectangular Stress Block for High-Strength Prestressed Concrete

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ABSTRACT

Various structural design codes for reinforced and prestressed concrete propose different equations and recommendations for the parameters of the rectangular stress block. However, these formulations are often valid only for a specific ultimate strain and are primarily based on concrete with a compressive strength below 50 MPa. In this study, with the aim of evaluating the accuracy and adequacy of these parameters for high-strength prestressed concrete, the stress-strain curve and equivalent stress block parameters were calculated throughout the entire loading process. To achieve this, a simplified third-degree polynomial stress-strain relationship was proposed and compared with experimental data for both compressed (high-strength) and non-compressed (normal-strength) concretes. The results demonstrated that the proposed model has acceptable accuracy in predicting the actual behavior of both compressed and non-compressed concretes, and it can be used to derive instantaneous parameters of the stress block. The obtained stress block parameters were compared with code-based relationships and previous studies, revealing that certain code assumptions require modification when applied to high-strength concrete.

Nomenclature

A_s: Area of steel under tension
b: Section width
C: Compressive force
c: Depth of neutral axis
d: Effective depth of the concrete section
F_s: Area under the stress–strain curve
f'_c: Compressive strength of concrete
f_y: Yield stress of steel
k: $\frac{\varepsilon_c}{\varepsilon_0}$
T: Tensile stress in the reinforcement
α_1, β_1: Parameters of the rectangular stress block
ε_c: Strain in concrete
ε_0: Strain at peak stress
ε_{cu}: Ultimate strain of concrete
ε_s: Steel strain
σ_c: Stress in concrete
RC: Reference concrete
CC: Compressed concrete

1. Introduction

The assumption of linear strain distribution across the depth of a flexural section leads to a compressive stress profile that resembles the uniaxial stress–strain curve of concrete. However, this curve is influenced by numerous variables, making it impractical to propose a universal stress–strain model for concrete. In reinforced concrete design, the stress distribution area and its centroid are more critical for equilibrium equations than the precise geometry of the stress profile [1-6]. Consequently, the rectangular stress block is preferred for its computational simplicity in evaluating area, centroid, and related parameters. The

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rectangular stress block concept, originally introduced by Whitney [7], has been widely adopted in design codes, typically calibrated for a specific maximum strain. For instance, ACI 318 [8] defines parameter $\varepsilon_{cu} = 0.003$ to represent conventional concrete strength. Whitney proposed a rectangular stress block as an alternative to the allowable stress design theory and validated it using experimental data. In his model, the width of the stress block was defined by 0.85 f'_c, while its depth varied with the reinforcement ratio of the beam. Mattock et al. [9] introduced parameters for the rectangular stress block currently used in the ALBDS code for concrete compressive strengths below 10 ksi. Their findings indicated that the stress block width remains constant at 0.85 for all compressive strengths, while the depth equals 0.85 for strengths below 4 ksi and decreases with increasing strength, but not below 0.65. Li [10] reported that the actual compressive stress distribution in high-strength concrete (HSC) resembles a triangular shape, with peak stress occurring at a strain of approximately 0.003. Conservatively, he assumed the peak stress in the triangular stress block for HSC to be f'_c, and derived equivalent rectangular block parameters $\alpha_1 = 0.75$ and $\beta_1 = 0.67$ accordingly. Oztekin et al. [11] developed a new stress–strain model for high-performance concrete (HPC) based on experimental curves, and proposed equivalent rectangular stress block parameters consistent with their model. These parameters showed good agreement with those derived from experimental stress–strain data. Ozbakkaloglu and Saatcioglu [12] introduced a new rectangular stress block applicable to a wide range of concrete strengths (20–130 MPa), and validated their model against experimental data with high accuracy. Mertol et al. [13] investigated the stress–strain behavior and stress block parameters for HSC, concluding that parameter α_1 in the ALBDS formulation requires revision for high-strength concrete, while parameters β_1 and the ultimate strain remain valid. Ho and Peng [14] proposed a strain-gradient-dependent equivalent rectangular stress block for reinforced concrete members, and based on this, developed a new flexural strength design method for normal-strength concrete (NSC) columns that incorporates strain gradient effects. Van Zijl and Mbewe [15] presented models for predicting the flexural capacity of steel fiber-reinforced concrete (SFRC) beams, with and without conventional steel reinforcement, using equivalent rectangular stress blocks for both tensile and compressive zones. Their models demonstrated satisfactory agreement with existing models and experimental results. Prachasaree et al. [16] derived stress–strain relationships, equivalent stress block parameters, and flexural strength predictions for fly ash-based geopolymer concrete members. Their proposed parameters showed good correlation with experimental data, while the nominal strength calculated using standard code parameters was approximately 1.43 times higher than that obtained using their proposed design parameters. In this study, the stress block parameters at any strain level and at ultimate strain are determined using a proposed stress–strain relationship. The parameters proposed by other researchers and design codes are also reviewed and evaluated.

The stress block is a cornerstone concept in reinforced and prestressed concrete design, forming the basis for calculating flexural strength, ductility, and safety margins in structural members. While several design codes provide equations for rectangular stress block parameters, these formulations are generally limited to concretes with compressive strengths below 50 MPa and are tied to specific assumptions about ultimate strain. With the increasing use of high-strength concrete in modern infrastructure driven by the demand for slender, efficient, and sustainable structures, there is a pressing need to re-examine the adequacy of code-based stress block parameters for this class of materials. Previous studies and existing code provisions have not sufficiently captured the nonlinear behavior of high-strength concrete under compression, especially throughout the entire loading process. This gap may lead to over-conservative or unsafe design outcomes when conventional parameters are directly applied to high-strength concrete. The present study addresses this limitation by proposing a simplified third-degree polynomial stress–strain model, which is validated against experimental results for both high-strength and normal-strength concretes. Unlike traditional formulations, the proposed approach allows the derivation of instantaneous stress block parameters, enabling a more accurate representation of the actual material response. By systematically comparing the obtained stress block parameters with those prescribed in international codes and prior research, this work highlights critical discrepancies and identifies areas where code assumptions require modification. The findings not only provide a more reliable foundation for the design of high-strength concrete structures but also contribute to the long-term evolution of design standards. Ultimately, the study bridges the gap between empirical code provisions and the actual behavior of concrete across a broader strength range, thereby advancing both structural safety and efficiency in modern engineering practice.

2. Determination of stress block parameters

The actual stress distribution of concrete in the compression zone of reinforced concrete members subjected to flexure is illustrated in Fig.1. For design simplification, an equivalent rectangular stress block, also depicted in Fig. 1, is adopted. This block is defined by two parameters: α_1 and β_1 The parameter α_1 represents the ratio of the average compressive stress in the equivalent block under flexure to the cylindrical compressive strength (f'_c) or cube strength (f_{cu}) of concrete. The parameter β_1 denotes the ratio of the depth of the equivalent rectangular compressive stress block to the distance from the extreme compression fiber to the neutral axis (c). This simplified stress block model has been endorsed by various design codes, which define the parameters α_1 and β_1 as functions of concrete strength alone, facilitating its application in ultimate limit state design.

In the present study, to obtain the parameters of the equivalent rectangular stress block, an easily integrable stress-strain relation for concrete is required. For this purpose, a third-degree polynomial that satisfies the four boundary conditions mentioned in the previous section is proposed based on Eq. 1.

$$y = mx + (3 - 2m)x^2 + (m - 2)x^3$$
$$x = \frac{\varepsilon_c}{\varepsilon_0}, y = \frac{\sigma_c}{f'_c}, m = \frac{\varepsilon_0}{f'_c} \times \left(\frac{d\sigma_c}{d\varepsilon_c}\right)_{\varepsilon_c=0}, \quad (1)$$

To evaluate the accuracy of the proposed stress–strain relationship, the model curves were compared with experimental results.

Figs. 2 and 3 illustrate the comparison between the proposed model and experimental data for unconfined and confined concrete specimens, respectively.

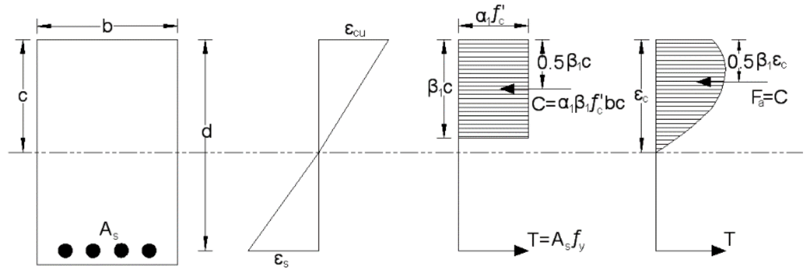
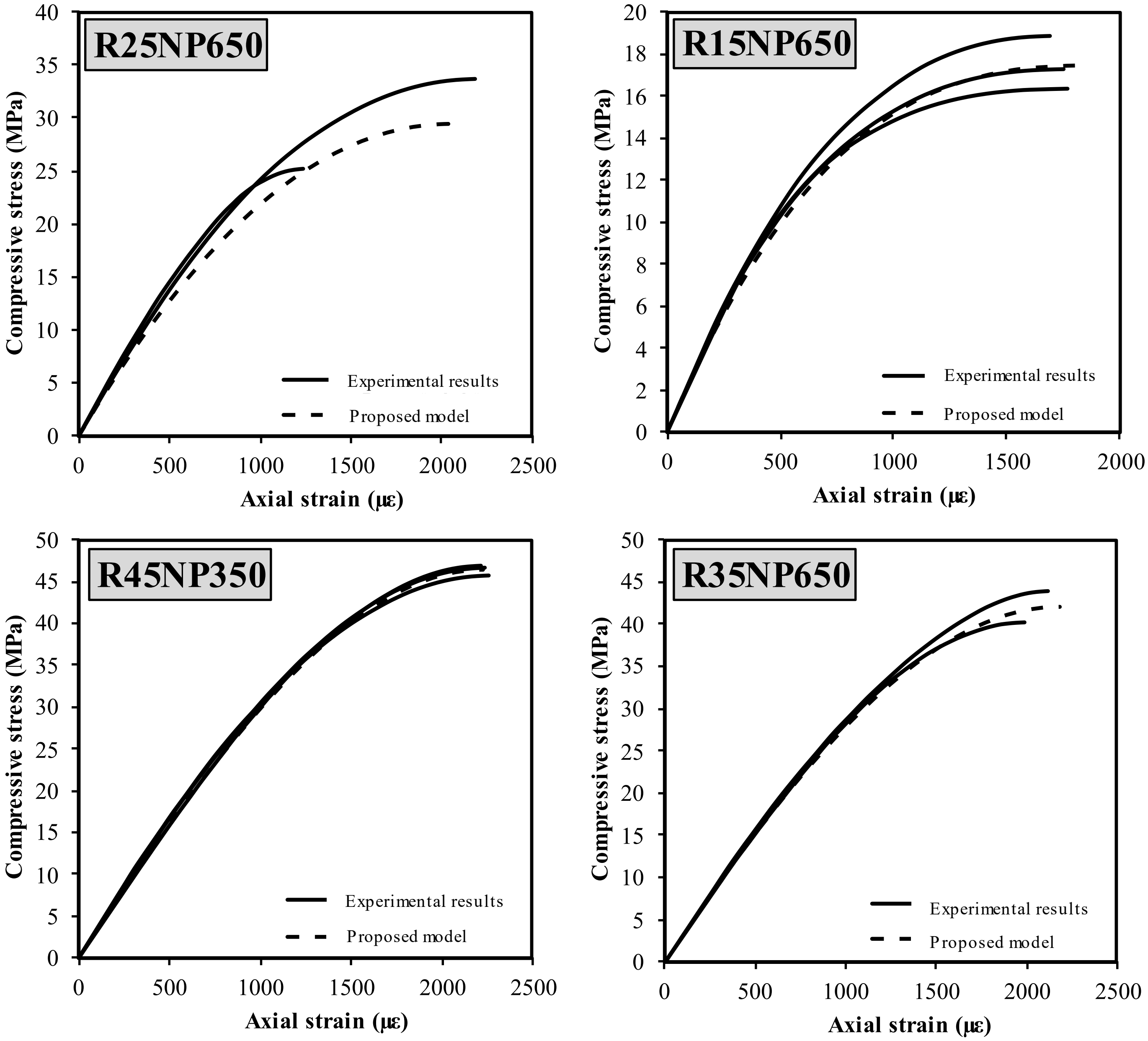


Fig. 1. Experimental and equivalent stress blocks and linear strain distribution [17].

A total of 60 experimental data points related to the research provided by Nematzadeh and Naghipour [18] were used in this study. In the nomenclature for identifying experimental specimens, the first letter represents the type of the specimen (R represents the reference concrete (uncompressed concrete), S represents the compressed concrete. The first number represents the value of the target compressive strength of the corresponding uncompressed concrete in MPa. The letter P, along with the second number in the compressed concretes, demonstrates the primary lateral pressure (expressed in terms of lateral strain) which is going to be applied to the fresh concrete in microstrain, while the two letters NP in the reference concretes indicate the lack of pressure; however, the preceding number is used to distinguish it from other reference concretes. As evident from the figures, the proposed model demonstrates strong agreement with the experimental data. Therefore, it can be reliably employed for determining the parameters of the equivalent rectangular stress block.



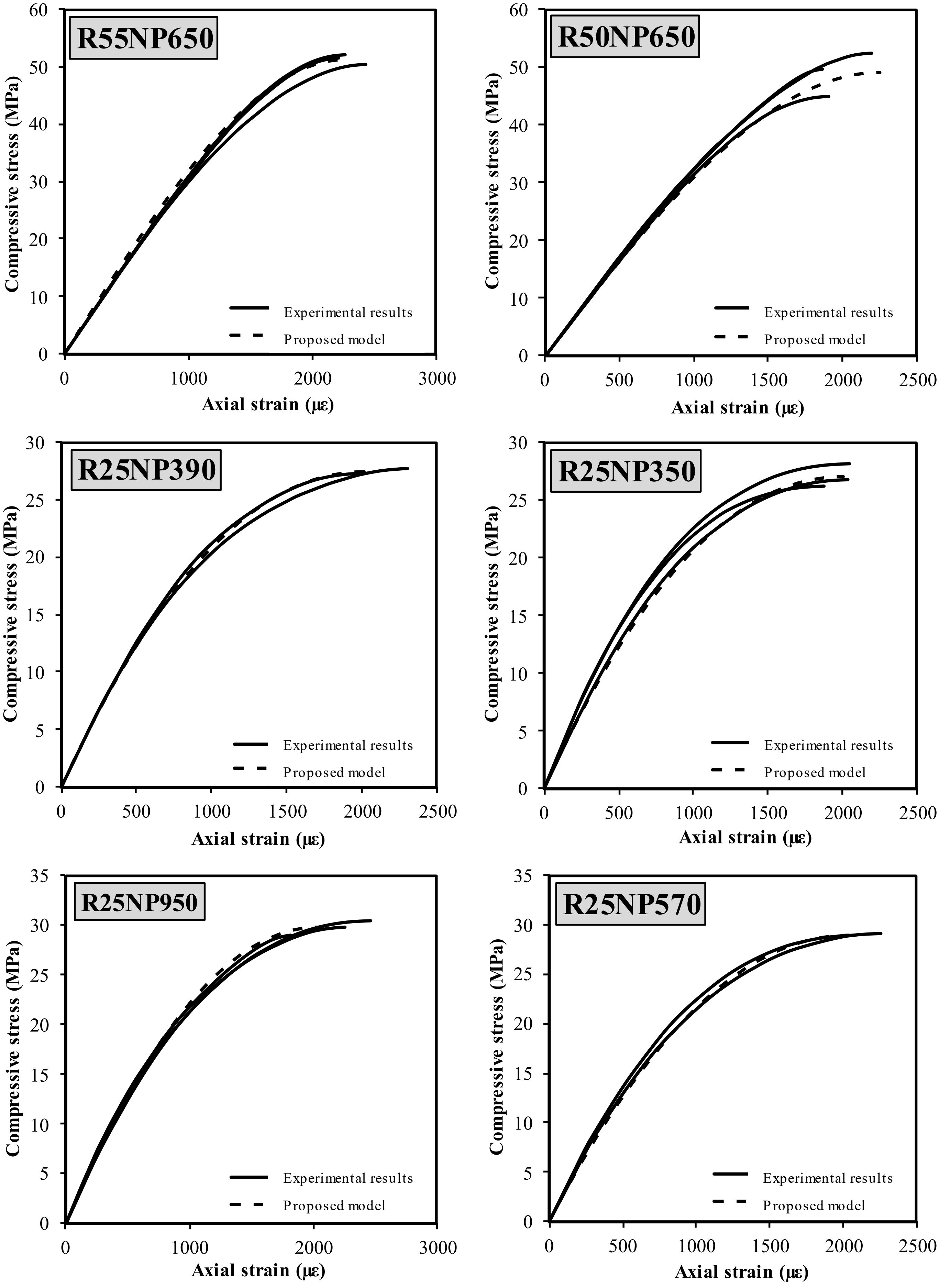
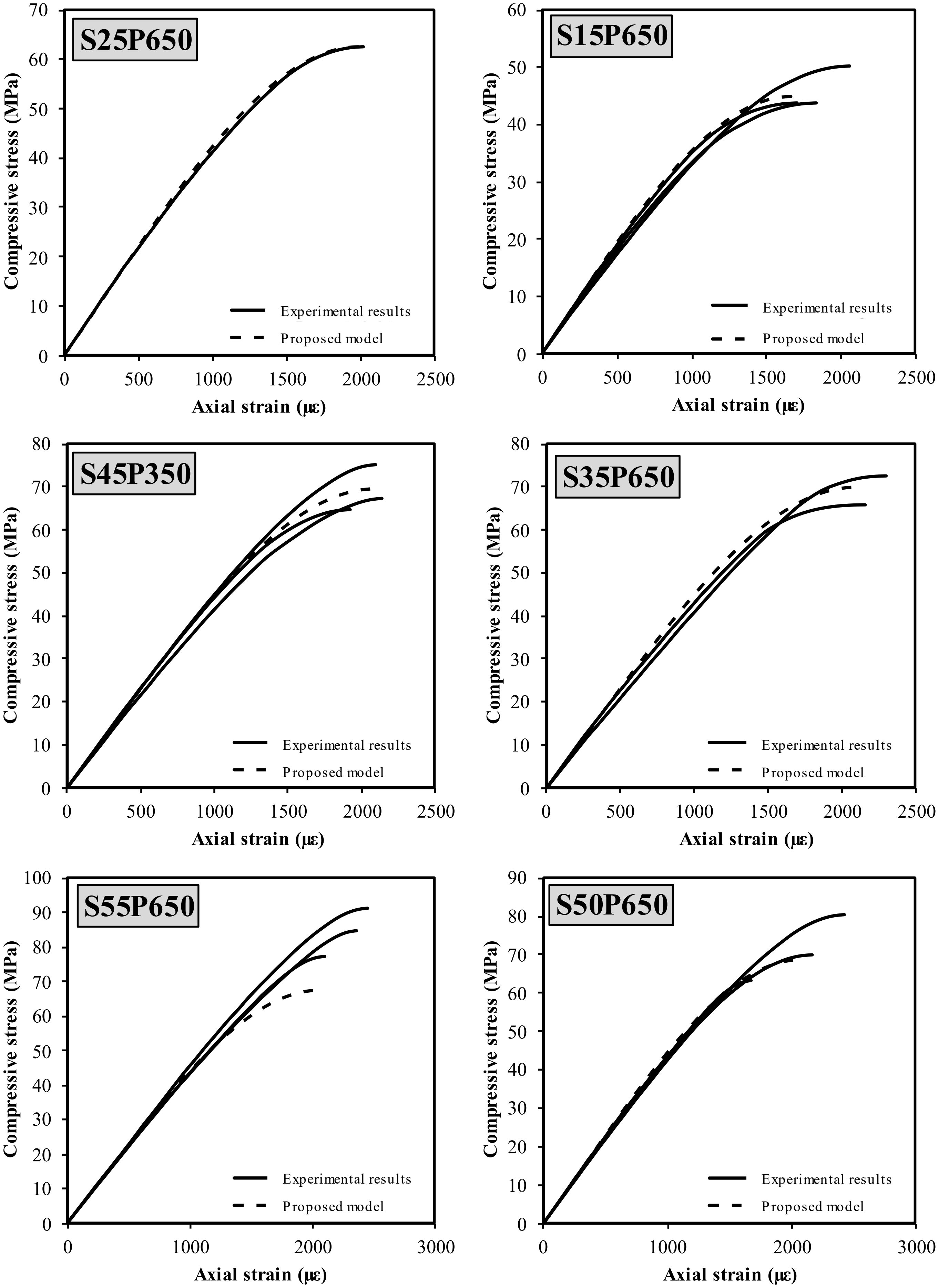


Fig. 2. Experimental stress-strain curve and proposed model for non-compressed specimens.


S25P650
S15P650
S45P350
S35P650
S55P650
S50P650
Compressive stress (MPa)
Axial strain (με)
Experimental results
Proposed model

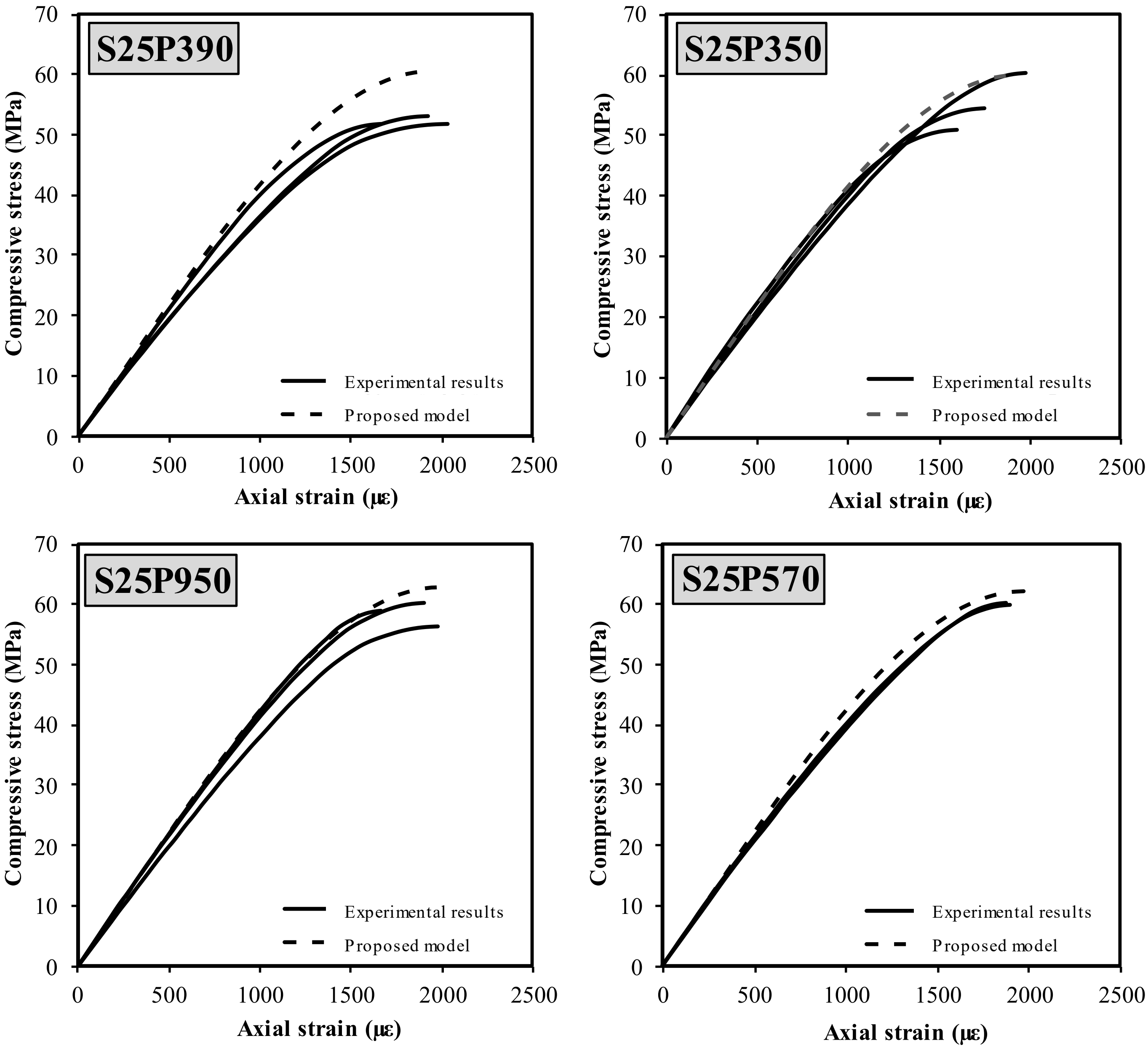


Fig. 3. Experimental stress-strain curve and proposed model for compressed specimens.

The parameters of the stress block can be readily determined using Eq. 1. For a given strain level, the internal force in the concrete can be expressed in terms of the equivalent stress block parameters α_1 and C, where $C = \alpha_1 f'_c \beta_1 c\ b$ denotes the depth of the neutral axis measured from the extreme compression fiber, and b represents the width of the cross-section. The stress block parameters can be derived from the first and second moments of area based on the stress–strain relationships, leading to the following results:

$$\alpha_1\beta_1 = \frac{\int_0^{\varepsilon_c} \sigma_c \, d\varepsilon_c}{f'_c \varepsilon_c} \tag{2}$$

$$\beta_1 = 2 - 2\frac{\int_0^{\varepsilon_c} \sigma_c \, \varepsilon_c \, d\varepsilon_c}{\varepsilon_c \int_0^{\varepsilon_c} \sigma_c \, d\varepsilon_c} \tag{3}$$

3. Results and discussion

By integrating Eqs. 2 and 3 and using stress-strain Eq. 1, the stress block equations at any instant will be as follows:

$$\alpha_1\beta_1 = \frac{mk}{2} + \frac{(3-2m)\,k^2}{3} + \frac{(m-2)\,k^3}{4} \tag{4}$$

$$\beta_1 = \frac{20\,mk^3 + 10\,(3-2m)k^4 + 6(m-2)k^5}{30\,mk^3 + 20\,(3-2m)k^4 + 15(m-2)k^5} \tag{5}$$

In the above equations, $k = \varepsilon_c/\varepsilon_0$, while ε_0 and ε_c represent, respectively, the strain at maximum stress and the strain of concrete at any arbitrary point along the stress–strain curve.

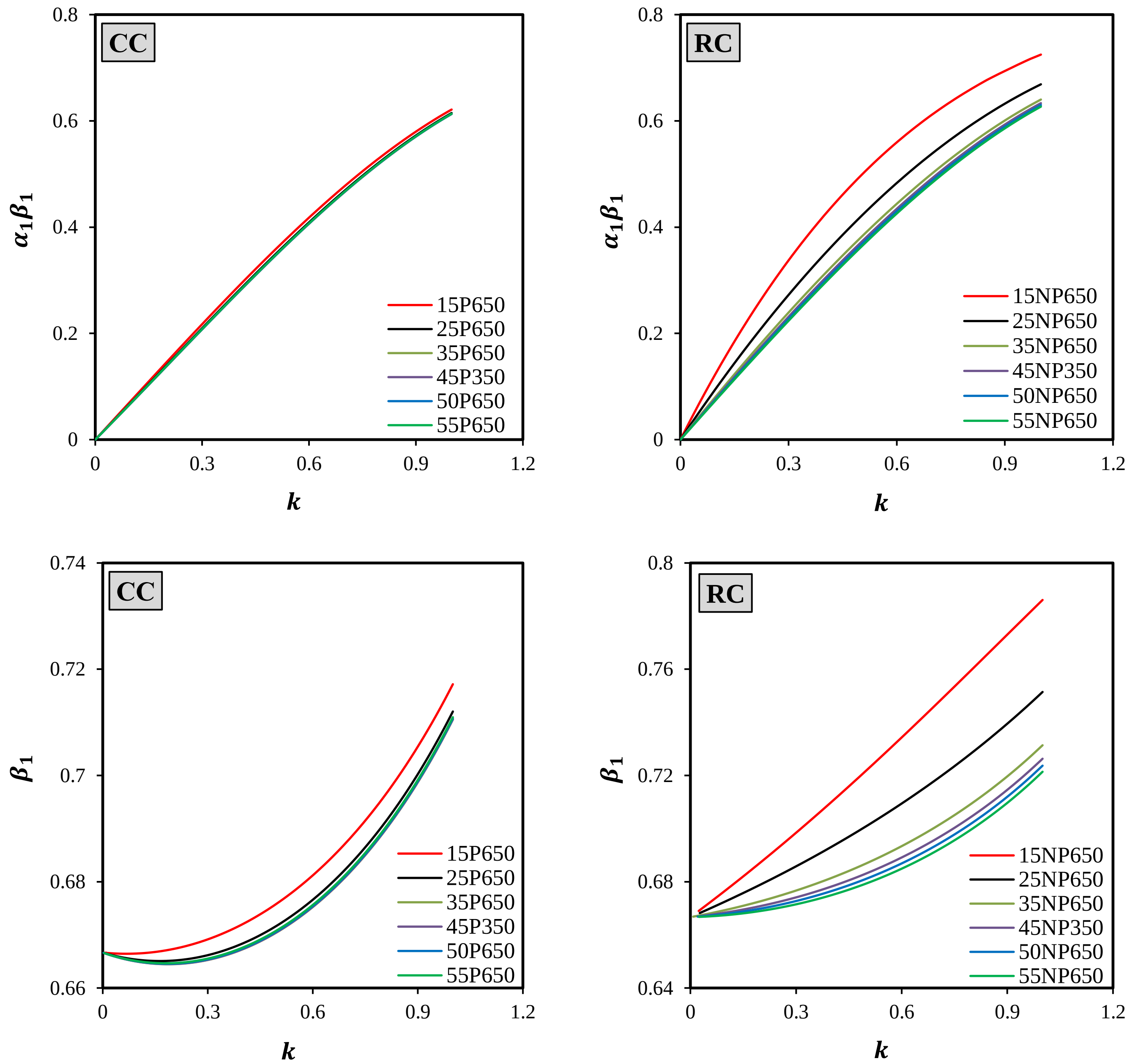


Fig. 4. Stress block parameters for RC and CC.

The stress block parameters at each instant for both compressed and non-compressed specimens are illustrated in Fig. 4. This figure shows the effect of β_1 and $\alpha_1\beta_1$ on k. As evident from the figure, the stress block parameters decrease with increasing compressive strength of the specimens. If, in Eqs. 4 and 5, the value of k is replaced with 1, then the stress block parameters at the peak point can be obtained as follows:

$$\alpha_1\beta_1 = \frac{m+6}{12} \quad (6)$$

$$\beta_1 = \frac{6m+18}{5m+30} \quad (7)$$

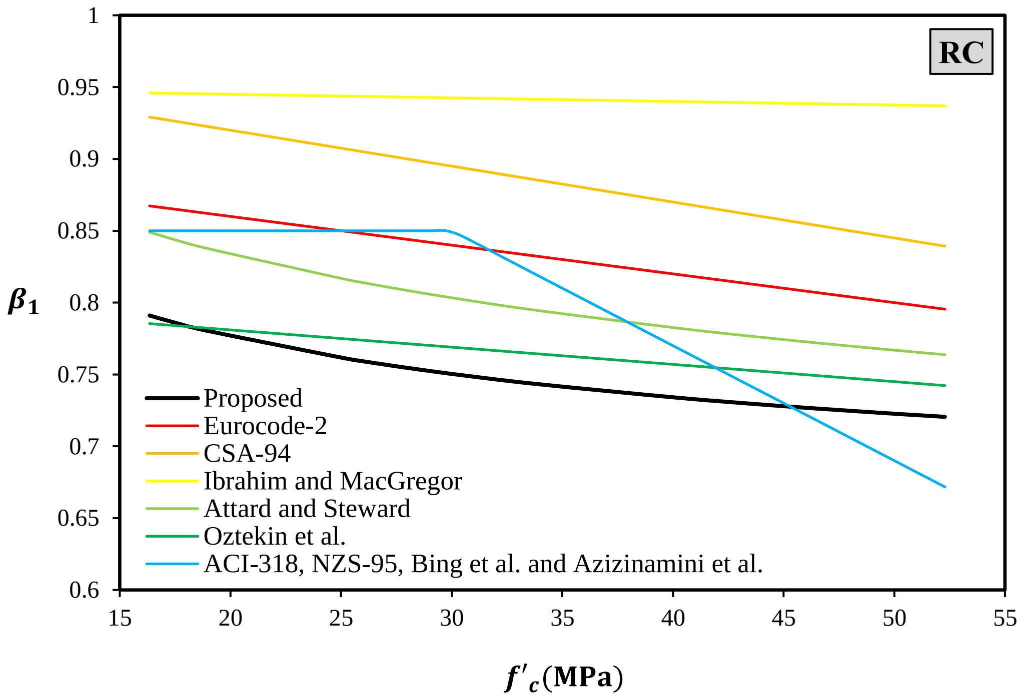
Table 1 presents the rectangular stress block parameters proposed by various design codes and researchers. Fig. 5 illustrates a comparative analysis between the rectangular stress block parameters proposed in this study and those suggested by other researchers. In the present investigation, at the ultimate strain level, the parameter α_1 for RC and CC specimens was found to range between 0.86 to 0.93 and 0.86 to 0.87, respectively. Similarly, the parameter β_1 for these specimens was obtained in the range of 0.72 to 0.80 for RC and 0.71 to 0.72 for CC.

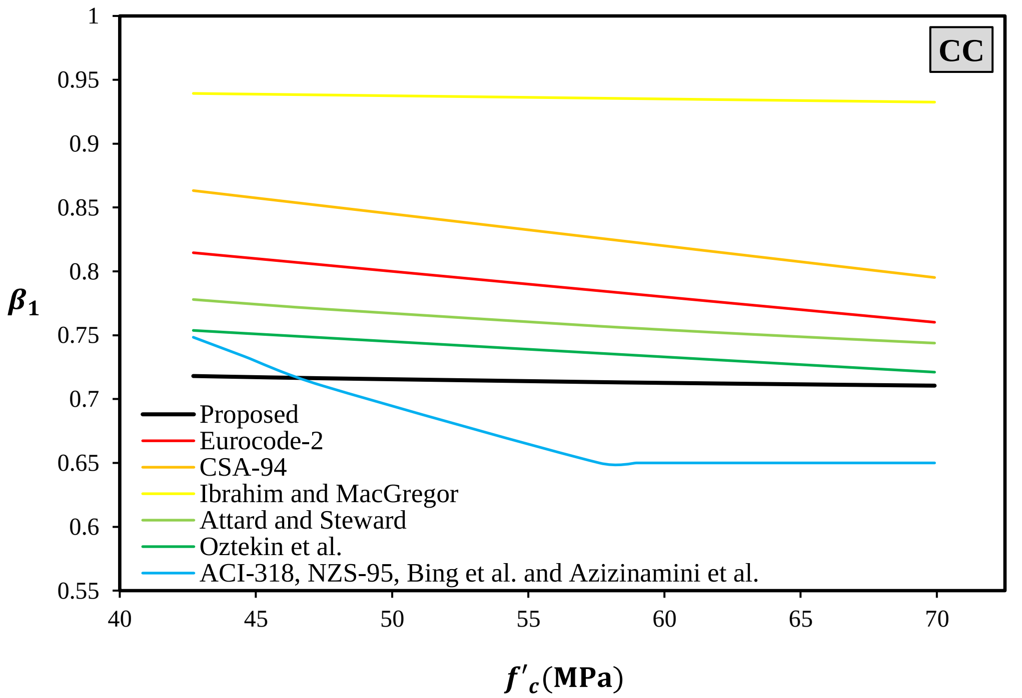
4. Conclusions

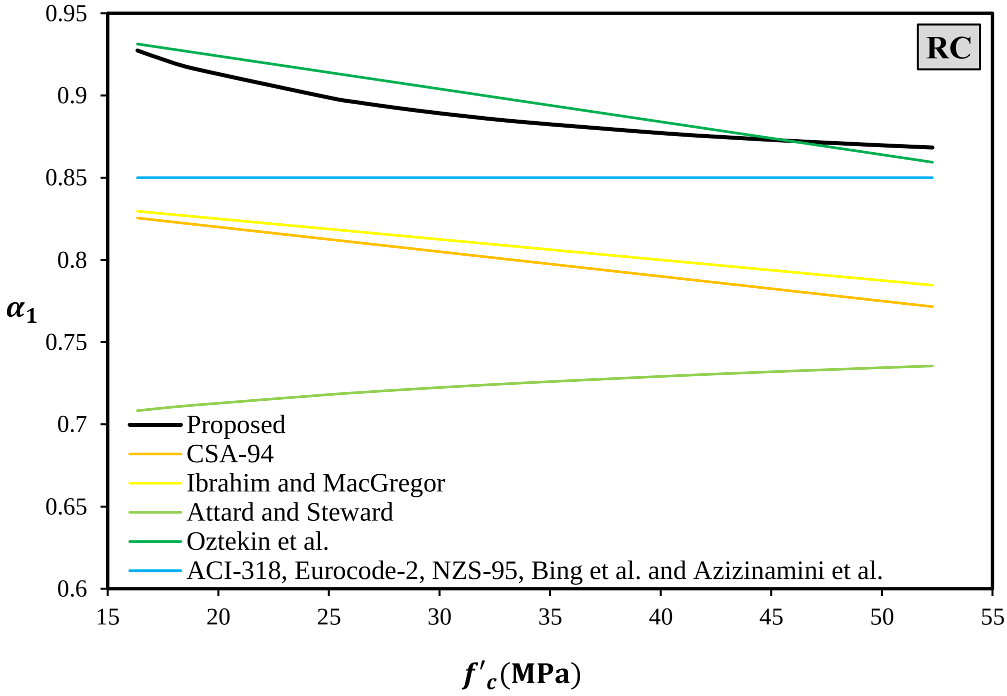
In this study, the adequacy and accuracy of rectangular stress block parameters for high-strength prestressed (freshly compressed) concrete were investigated through analytical modeling and experimental comparison. A simplified third-degree polynomial stress–strain relationship was proposed to represent the entire loading process, and its predictions were validated against experimental data for both non-compressed and compressed concretes. The findings of this research can be summarized as follows.

Table 1. Rectangular stress block parameters.

Reference	α_1	β_1
ACI-318 [8]	0.85	$1.09 - 0.008f'_c$, $(0.85 \geq \beta_1 \geq 0.65)$
Eurocode-2 [19]	0.85	$0.9 - f'_c/500$
CSA-94 [20]	$0.85 - 0.0015f'_c \geq 0.67$	$0.97 - 0.0025f'_c \geq 0.67$
NZS-95 [21]	$1.07 - 0.004f'_c$, $(0.85 \geq \alpha_1 \geq 0.75)$	$1.09 - 0.008f'_c$, $(0.85 \geq \beta_1 \geq 0.65)$
Attard and Stewart [22]	$0.6470f'^{0.0324}_c \geq 0.58$	$0.948f'^{-0.091}_c \geq 0.67$
Ibrahim and MacGregor [23]	$0.85 - f'_c/800 \geq 0.725$	$0.95 - f'_c/4000 \geq 0.7$
Li et al. [24]	$0.85 - 0.004\,(f'_c - 55) \geq 0.75)$	$1.09 - 0.008f'_c$, $(0.85 \geq \beta_1 \geq 0.65)$
Azizinamini et al. [25]	$0.85 - 0.0073\,(f'_c - 69) \geq 0.6)$	$1.09 - 0.008f'_c$, $(0.85 \geq \beta_1 \geq 0.65)$
Oztekin et al. [11]	$0.964 - 0.002f'_c$	$0.805 - 0.0012f'_c$







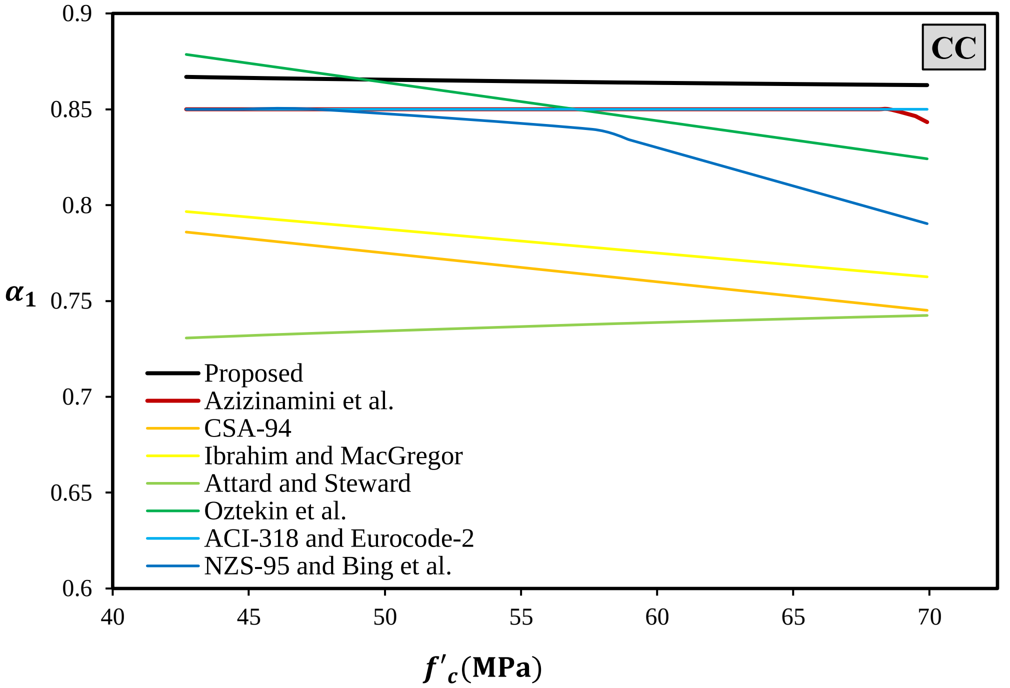


Fig. 5. Relationships between stress block parameters and concrete strength.

- Developed model satisfies four critical boundary conditions, including the stress and strain values at key points along the curve, and was benchmarked against validated experimental data for both compressed and non-compressed concrete specimens. The results demonstrated that the proposed model predicts the actual behavior of concrete with a satisfactory level of accuracy and is suitable for analyzing the parameters of the rectangular stress block.
- The primary parameters of the rectangular stress block, namely α (the ratio of equivalent compressive stress to the concrete compressive strength) and β (the ratio of stress block height to the depth of the neutral axis), were evaluated throughout the loading process, particularly at the ultimate strain level. Analytical results indicated that both α and β decrease with increasing concrete compressive strength, and this reduction can significantly influence the flexural capacity of structural members as well as the prediction of their failure modes. In particular, for high-strength prestressed concrete, conventional code-based models may lack sufficient accuracy, and their direct application could lead to non-conservative or overly conservative outcomes.
- A comparison between the results of this study and the stress block parameters presented in various design codes and by other researchers indicates that current code-based formulations require revision, particularly when applied to concrete with

compressive strengths exceeding 60 MPa. The instantaneous parameters proposed in this research may serve as a foundation for the development of more accurate and safer design methodologies for reinforced concrete members.

- Overall, the implementation of the proposed stress–strain model and its derived parameters offers a reliable approach for enhancing the accuracy of engineering design and performance analysis of structural members, particularly in high-strength prestressed concrete structures. These findings may serve as a foundation for revising existing design codes and advancing innovative design methodologies in future practice.

Statements & declarations

Author contributions

Shahram Maghsodian: Conceptualization, Investigation, Methodology, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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