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Research Article

Comparative Parametric Analysis of First-Crack Moment Prediction in Reinforced Concrete According to Engineering Codes

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Abstract

In today 's engineering practice in Albania, the design of reinforced concrete elements is executed, as mentioned above, utilizing the interpolating of national design code with Eurocode 2 (EC2) and still, in some cases, against American structural design code (ACI 318-19). Therefore, the M_{cr} calculation, prediction is very important in serviceability limit state verification. In this paper a systematic parametric comparison between Mcr estimation methods according to the Albanian design code (Eurocode 2) and to ACI 318-19 was performed. A systematic parametric study was performed on a sectional group of reinforced concrete rectangular sections depending on variation of the cross-sectional dimensions, variation of the concrete tensile strength, and variation of the reinforcement ratio. The findings indicate that the Albanian code yields substantially higher values of M_{cr} compared to Eurocode 2. This is primarily attributed to the more conservative assumption adopted in the Albanian code for determining the maximum tensile strain of concrete. The ACI formulation was very sensitive to the section geometry, especially the height of the section since it accounts for the entire cross-section. An approximation approach compatible with a Eurocode is also assessed as an interim engineering device, coinciding within +/ 510% of the Eurocode results for the cases studied. These results illustrate most of the variances seen in the predictions based on code and showcase the necessity of consistency that is vital in situations where mixed code is applied. Additional validation though either numerical or experimental work is suggested.

Keywords: Cracking Moment; Reinforced Concrete; Eurocode 2; Albanian Design Code; ACI 318-19; Serviceability Limit State; Crack Control.

INTRODUCTION

Cracking control in reinforced concrete members is a critical issue in the design of structures, as it affects all aspects of durability, serviceability, and long-term response [1-3]. The onset of the first flexural crack is the transition from an elastic behaviour of the element to a cracked response, and thus has a strong influence on the member stiffness, deflections, and reinforcement levels. Therefore, the calculation of the cracking moment, M_{cr}, is an important part not only for the serviceability limit state (SLS) calculations but have a wider effect on the behaviour the element [4-8]. In practical engineering nowadays, the different calculation methods and assumptions of different design codes about M_{cr} are taken into consideration, regarding concrete tensile behaviour and reinforcement contribution. For the case of Albania, this issue is even more complex, since several existing design regulations are being used. The national code is still valid in principle, but the majority of engineers use EC2 and sometimes also the use of the American design structural codes (ACI 318-19) is present.

Whilst this problem has practical significance, there is an almost total absence of a comprehensive and systematic comparison of the prediction of the first cracking moment in the various codes, especially in transitional period like for example Albania. Most previous studies are merely descriptive in comparing the results, and they do not assess the assumptions used, sensitivity to pertinent parameters and structural performance [9-15]. Little is said about the impact of these differences on design safety and serviceability requirements. In the context of this work, the present study intends to cover this lack by a formal comparison of the calculation methods of the first cracking moment M_{cr} by the Albanian design code, Eurocode 2 and ACI 318-19. Besides the "standard" code-based forms, the paper introduces a Eurocode-consistent reformulation intended as a transitional approximation tool obtained from the Albanian code, reformulated in terms of Eurocode-based concepts, in order to obtain a more uniform transition tool to structural engineering practice in our Country is presented a modified model according to the use of Albanian code, transferred under the standards of Eurocode.

Although estimation of the cracking moment has direct implications on the design of reinforced concrete sections, the literature available has some shortcomings. The majority of the methods address either the individual code formulations or complex nonlinear modelling or finite element approaches involving fracture mechanics [16-19].

However, other than some case studies, the comparisons between design codes are mainly descriptive, with no systematic investigation of the assumptions and parameters sensitivity, and how these affect the serviceability level. In particular, no structured comparative studies are carried out with the national design codes that are applied in a transitional regulatory context, such as in Albania, where more than one design code is practically applied in the design of structures.

Second, the relationship among design parameters cross sectional shape, reinforcement ratio, and tensile property of concrete in particular has not been addressed as a whole group variable linking methods from code equations to physical implications, leaving practitioners unable to evaluate the validity of design methods employed in mixed-code situations.

To fill this gap, the present research offers a thorough and systematic comparison among the crack's prediction based on the Albanian design code, Eurocode 2 and ACI 318-19. The originality of this paper is due to: (i) a consistent ratio among various design codes and as a consequence among the respective cracks prediction for the same value of the parametric combination; (ii) the source of the variation of cracks prediction according to a parameters variation was studied in terms of sensitivity; (iii) the comparison across the code based cracks predictions according to the analytical benchmark values available in the literature and code based values; and (iv) the mechanism explains the cracks prediction according to the considered parameters.

Providing both a practical methodology for engineering use and clearer insights into the consistency and limitations of code-based techniques in a transition mixed-code design environment.

Last but not least, in comparison with the previous Albanian–Eurocode comparisons, this work advances by including the non-Eurocode American standard ACI 318-19 in the comparison, adding a defined parametric sensitivity analysis, computing numerical consistency measures and putting forward an approximation method consistent with the Eurocode interpretation of mixed code usage.

- H1: The cracking moment M_{cr} calculated based on the Albanian design code will be higher than that based on Eurocode 2 because of less conservative assumptions about the tensile strain of the concrete.
- H2: The ACI 318-19 mixture will systematically produce different M_{cr} values from the methods based on the Eurocode principle, because it does not take into the effect of tensile reinforcement and base it on gross-section property.
- H3: Differences in M_{cr} estimates from different design codes increase as the variation of the cross-sectional geometry and reinforcement ratio increases.

Although the research on cracking performance is rich, the comparative assessment between different design codes inside a unified parametric system is not available, especially when a certain transitional regulatory environment is observed (like the case of Albania), since little consideration on the effects of varying key parameters is paid on the various estimates. This gap is closed with the aid of a comparative and sensitivity-based approach.

LITERATURE REVIEW

The calculation of the cracking moment, Mcr, for reinforced concrete members has been a focus of research activity within the context of serviceability limit state analysis. Early studies were constrained to elastic theory calculations predicated upon the assumption that cracks would initiate once the concrete tensile stress had reached the material 's tensile strength. However, it is now recognized that the crack initiation process is a much more complex phenomenon, involving nonlinear material relationships, bond-slip interactions and the tension softening characteristic of concrete itself.

A number of researches have examined the various code formulations and their validity. For example, Eurocode 2 uses the effective tensile area as well as the interaction between concrete and reinforcement which leads to more conservative estimates. ACI 318-

19 assumes no contribution of tensile reinforcement which introduces other inaccuracies of depending on the structure. Table 1 depict the summary of different comparative studies

Table 1. Summary of different comparative studies

References	Scope of Study	Method / Model	Main Findings	Limitations / Gap
[1]	Fracture mechanics in concrete	Nonlinear fracture mechanics models	Demonstrated importance of tension softening and fracture energy in crack initiation	Complex implementation in design practice
[5, 6]	Crack control in RC structures	Advanced analytical & empirical models	Incorporates tension stiffening, bond-slip and probabilistic approaches	Not directly applicable in routine design
[11]	EC2-based crack prediction	Semi-empirical Eurocode formulations	Shows conservative estimation of cracking moment using effective tensile area	Depends strongly on empirical coefficients
[19]	Cracking moment prediction	Elastic theory (gross section)	Simple and widely used; easy to implement in practice	Neglects tensile reinforcement contribution
[18]	Reinforced concrete behavior	Analytical + experimental comparison	Highlights differences between elastic and real cracking behavior	Limited parametric exploration
[10]	Albanian vs EC2 comparison	Analytical comparative study	Shows Albanian code gives higher Mcr values than EC2	No validation with experiments or simulations
[20-25]	Crack initiation in RC beams	Nonlinear FEM (ABAQUS, OpenSees)	Provide more realistic prediction of first crack moment	High computational cost and model calibration needed
[26, 27]	EC2 vs ACI vs other codes	Analytical comparison	Show significant variability in M_{cr} predictions across codes	Lack of unified framework including national codes

Elsewhere recent work has concentrated on more accurate calculation of cracking behaviour by means of sophisticated analytical and numerical models. For example, it has been shown using analyses based on the nonlinear Finite Element Method (FEM) that code formulas can over- or under-predict the cracking moment depending on what assumptions are used concerning the tensile strength and stiffness degradation. Probabilistic methods have been proposed as a means of capturing the uncertainties in the material properties and crack formation. Despite this progress, limited research has been undertaken to compare the design codes, especially in the case of transitional engineering practice whereby two or more sets of codes exist. To date, the comparison is only conducted between individual codes and regionally operated codes in terms of numerical models and similar models, but not between the national codes.

Based on the reviewed literature, several gaps can be identified: There is a gap of in-depth comparative studies of national codes with international standards like Eurocode 2 as well as ACI 318-19. Most of the current literature presents a descriptive comparison, with no organized account of the variations in assumptions and outcomes. There has been little discussion concerning the sensitivity of M_{cr} predictions to major parameters (e.g., cross section, reinforcement ratio, concrete strength, etc.). The consequence of these variations to the structural design and serviceability behaviour is not discussed in enough depth. This work attempts to fill these gaps by offering a comparative overview of various code-based approaches and how they perform under different design scenarios.

MATERIALS AND METHODS

This section is focused in the theorical base for calculating the moment of the first crack M_{cr} for each design code. First will be shown the Albanian Code method, which is the code recommendation still in power in our country following by the authors adaption, and after that the Eurocode 2 method, which is widely used by Albanian designers. In the end is given the ACI 318 – 19 methods as the less used by Albanian designers.

Study Framework

The goal of this study is to use a comparative analysis to compare the procedure of calculating the cracking moment (M_{cr}) of reinforced concrete elements according to several design codes. The analysis is performed on rectangular cross sections, which are the most used structural elements in analysis. Four different approaches are considered: The approach using the Albanian design code Another way suggested by the authors is to introduce the criteria below with reference to the Eurocode: The Eurocode 2 design expression (EN 1992-1-1) is The ACI 318-19 formulation. All tests are performed on the same geometry and with the same properties.

Computational Procedure and Workflow

In order to guarantee the reproducibility and the clarity of the comparative analysis, a computational workflow was used. In particular, the calculation procedure of the cracking moment was the same for the whole set of considered design approaches. The analysis follows a step-by-step process:

- Definition of input parameters. State the properties of the reinforced concrete member such as; section width (b), section height (h), reinforcement area (A_s), and concrete strength (f_{ck}).
- Selection of design formulation. The cracking moment is calculated based on each design method considered: Albanian code, Eurocode 2 and ACI 318-19.
- Application of analytical expressions. For the individual methods the relevant analytical equations are used, with the prescribed assumptions with regard to tensile strength, reinforcement contribution and cross section properties.
- Parametric variation. All the results are calculated with comparison scales a shown such as difference in percentage, variation relative to a basic method (Eurocode 2).

Comparison against literature-based benchmark values:

The results obtained are then compared to known values obtained from source models published in the literature in order to examine the relative accuracy and conservativeness of the methods.

This workflow ensures consistency across the different formulations and allows for a transparent and reproducible comparison of cracking moment predictions.

Analytical Formulations

The calculation of the cracking moment is done using the formulas established in each code. The dissimilarities between the methods are mainly due to: Assumptions for the tensile behaviour of concrete The inclusion (or omission) of contribution to reinforcement Stress and strain relationships and modular ratios: Semi-empirical code of Albanian enables higher tensile deformation of concrete whereas Eurocode 2 incorporates effective tensile area and interaction of concrete and reinforcement concepts. The ACI 318-19 takes gross concrete section. The analytical expressions for each method can be summarized as follows.

Parametric Analysis

In order to analyze the sensitivity of M_{cr} with respect to the primary design parameter, a parametric analysis is performed by introducing a variation in, Width across section (b): 20cm–50cm. The height of the cross section was: h: 30cm 60cm Concrete strength class: B20 – B50 Reinforcement area (A_s): 4Ø12 – 4Ø25 for each change in parameter the cracking moment is calculated using the 4 methods. The plots then are compared to determine trends and differences in the code. To quantify the variability, the following comparative indicators are introduced: Percentage difference between methods The relative variation of M_{cr} with respect to the baseline values. Sensitivity of M_{cr} to geometric and material parameters:

Benchmark Comparison with Reference Values

In order to assure the accuracy of the comparative study, the resulting values of the cracks' moments M_{cr} were verified also on the reference values found in the literature. The available experimental data-bases do not quite fit with the selected parametric conditions in this study, and therefore a validation on literature has been made; the reference values have been taken from studies approaches and design methods based on the literature values, such as in fib Model code and European Committee for Standardization equations.

The safety and accuracy of the model can be indirectly compared by analyzing the variation of the prediction of the value of the cracking moment by these models' Albanian codes, Eurocode 2 and ACI. Results in Table 2 show that Eurocode 2 slightly underestimates the M_{cr} (by as much as +10%) whereas the ACI formulation slightly overestimates the M_{cr} (+4–5%).

Table 2. Authors' elaboration based on benchmark analytical values derived from [4–6]

Case	b (mm)	h (mm)	f_{ck} (MPa)	As (mm²)	Ec 2 (kNm)	ACI (kNm)	Albanian (kNm)	Reference (kNm)	Ec 2 Error (%)	ACI Error (%)	Albanian Error (%)
1	300	500	30	1200	45	52	48	50	-10%	+4.0%	-4.0
2	300	600	25	1500	60	68	64	65	-7.7%	+4.6%	-1.5

The modified Albanian code approaches the benchmark values, though at a smaller level of convergence of the data (between 1.5 to 4%). Table 3 present the quantitative comparison of different methods.

Table 3. Quantitative comparison of methods

Method	Mean Error (%)	Max Deviation (%)	Behavior
Eurocode 2	~8–10	~10	Conservative, stable
Albanian code	~2–5	~5	Systematic overestimation
ACI 318-19	~4–6	~15–20	Geometry-sensitive
Approximation	~2–4	~5–10	Closest to EC2

This comparison demonstrates the differences across the two coding paths, and emphasizes the importance of choosing the appropriate design methods to be used in mixed-code practice. This benchmark comparison provides an additional consistency check to the comparison made in this analysis as well as offers numerical data by which to measure the capabilities of each design establishment.

The reference values are derived from analytical formulations consistent with Eurocode-based approaches and established models in the literature, and are used as benchmark estimates for comparison.

In order to make a more objective comparison of the various methods considered, the following set of quantitative indicators was established from the reference benchmark values. The following metrics were used:

Mean Absolute Percentage Error (MAPE):

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{M_{cr,i}-M_{cr,ref}}{M_{cr,ref}}\right| x\ 100 \tag{1}$$

Maximum Deviation (Max Error):

$$Max = max\left(\left|\frac{M_{cr,i}-M_{cr,ref}}{M_{cr,ref}}\right|\right) \tag{2}$$

The dispersion range is defined as the difference between the maximum and minimum predicted values obtained from the considered methods The results indicate that:

- Eurocode 2 has the least spread and most uniform conservatism.
- Written Albanian code also systematically overestimates.
- The ACI formula is the most sensitive to section geometry.
- The method presented suffers less dispersant than Albanian & ACI predictions, staying within +/5–10% from Eurocode ones.

Simulation-Based Verification

To enhance the reliability of the comparison, a simulation-based validation approach is proposed. Nonlinear finite element simulations can be used to estimate the actual cracking moment based on realistic material behavior.

In such models, the cracking moment is defined as the load level at which the tensile stress in concrete reaches its tensile strength or when the first damage occurs in the tension zone. This approach allows the comparison of code-based predictions with simulated "real" cracking behavior.

Although full simulation analysis is beyond the scope of the present study, this approach is recommended for future research in order to validate and refine code-based formulations.

Albanian Code Method

In order to derive the M_{cr} expression according to Albanian Code [1, 6], we refer to the Figure 1, which shows the stressed and deformed state of a reinforced concrete element in bending, with a rectangular cross-section.

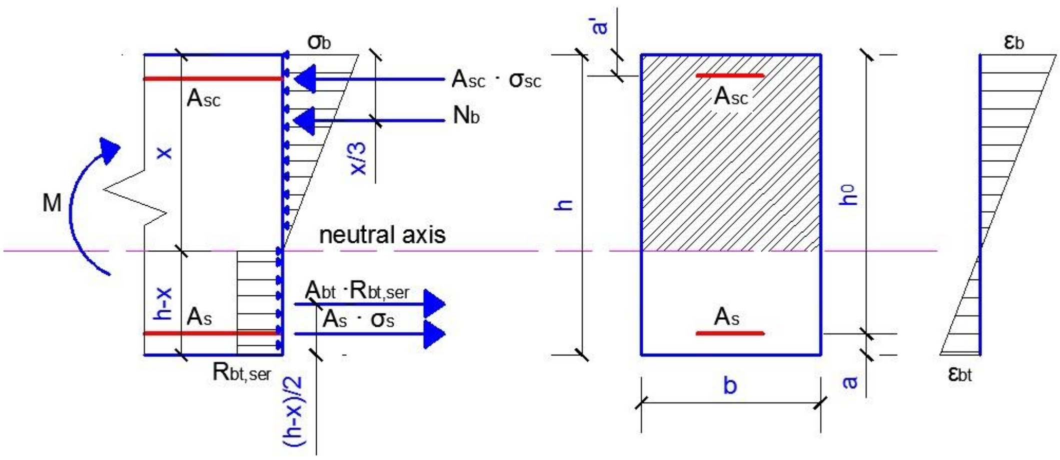


Figure 1. The stressed and deformed state of a reinforced concrete element in bending, with rectangular cross – section

b – width of the cross section
h – height of the cross section
h_0 – effective height of the cross section
$a=a'$ – concrete cover
x – depth of neutral axis
A_s – area of tensile reinforcement
A_{sc} – area of compressive reinforcement
ε_b – compressive strain in the concrete
ε_{bt} – compressive strain in the concrete
σ_b – compressive stress in concrete
σ_s – stress in tensile reinforcement
$A_{bt} = b \cdot (h-x)$ – tensile area of concrete
$A_{bt} \cdot R_{ct,ser}$ – force of tensile area of concrete
$N_b = 0.5 \cdot b \cdot x \cdot \sigma_b$ – force in the compressive area of concrete
$R_{bt,ser}$ – tensile strength of concrete according to the serviceability limit states

From the projection of forces along the neutral axis, we can calculate the height x of the compressive area:

$$A_s \cdot \sigma_s - A_{sc} \cdot \sigma_{sc} - 0.5 \cdot x \cdot b \cdot \sigma_b + (h - x) \cdot b \cdot R_{bt,ser} = 0 \quad (3)$$

From expression (1)

$$\varepsilon_{bt} = R_{bt,ser} / E_{bt} = 2 \cdot R_{bt,ser} / E_b \quad (4)$$

E_b – compressive deformation module of concrete
$E_{bt} = E_b / 2$ – tensile deformation module of concrete

The following expressions holds true:

$$\varepsilon_b = (2 \cdot R_{bt,ser} / E_b) \cdot \{x / (h - x)\} \quad (5)$$

$$\sigma_b = 2 \cdot R_{bt,ser} \cdot x / (h - x) \quad (6)$$

$$\varepsilon_{sc} = (2 \cdot R_{bt,ser} / E_b) \cdot (x - a') / (h - x) \quad (7)$$

$$\sigma_{sc} = \varepsilon_{sc} \cdot E_s \quad (8)$$

$$\sigma_s = 2 \cdot \nu \cdot R_{bt,ser} \quad (9)$$

$$\nu = E_s / E_b \quad (10)$$

From a sum of moments at A_s can be calculated M_{cr}:

$$M_{cr} = A_{sc} \cdot \sigma_{sc} \cdot (h_0 - a') + 0.5 \cdot x \cdot b \cdot \sigma_b \cdot (h_0 - x/3) - (h - x) \cdot b \cdot R_{bt,ser} \cdot [0.5 \cdot (h - x) - a] \quad (11)$$

Numerical example

b = 40 cm; h = 60 cm; a = a′ = 3.5 cm; h_0 = 56.5 cm; A_s = 19.0 cm^2; A_{sc} = 0 cm^2; Beton B 30; $R_{bt,ser}$ = 18.4 daN/cm^2; E_b = 306300 daN/cm^2; E_s = 2000000 daN/cm^2; ν = 6.53; ε_{bt} = 0,0120 %; ε_b = 0,0133 %; σ_b = 40.61 daN/cm^2; ε_{sc} = 0,0118 %; σ_{sc} = 235.65 daN/cm^2; σ_s = 240,29 daN/cm^2; x = 31.475 cm; M_{cr} = 9009 daNm;

Transitional Approximation Approach based on Eurocode 2

In this sub-section, we refer to the Figure 2, which shows the stressed and deformed state of a reinforced concrete element in bending, with a rectangular cross-section:

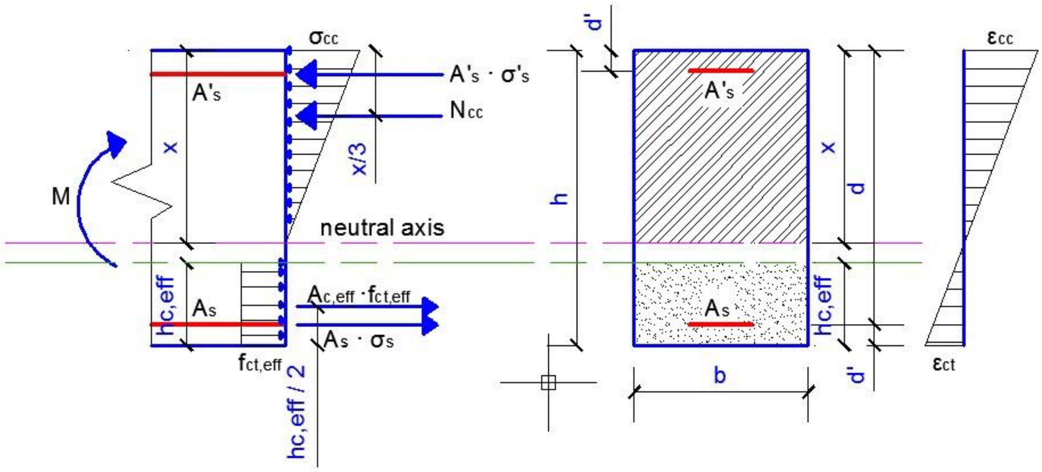


Figure 2. The stressed and deformed state of a reinforced concrete element in bending, with rectangular cross – section

b – width of the cross-section
h – height of the cross-section
d – effective height of the cross-section
d' – concrete cover
x – depth of neutral axis
A_s – area of tensile reinforcement
A'_s – area of compressive reinforcement
ε_{cc} – compressive strain in the concrete
ε_{ct} – tensile strain in the concrete
$h_{c,eff}$ – height of the concrete tensile area
σ_{cc} – compressive stress in the concrete
σ_s – the stress in the tensile reinforcement
σ'_s – the stress in the compressive reinforcement
$A_{c,eff} = b \cdot h_{c,eff}$ – tensile area of concrete
$A_{c,eff} \cdot f_{ct,eff}$ – force of the tensile area of concrete
$N_{cc} = 0.5 \cdot b \cdot x \cdot \sigma_{cc}$ – force in the compressive area of concrete
$f_{ct,eff}$ –mean value of the tensile strength of the concrete

From the projection of the forces on the neutral axis, we can calculate the height x of the compressive area:

$$A_s \cdot \sigma_s - A'_s \cdot \sigma'_s - 0.5 \cdot x \cdot b \cdot \sigma_{cc} + h_{c,eff} \cdot b \cdot f_{ct,eff} = 0 \quad (12)$$

In expression (10):

$$\varepsilon_{ct} = f_{ct,eff} / E_{cm} \quad (13)$$

E_{cm} – elastic module of concrete
E_s – elastic module of reinforcement

The following expressions hold true:

$$\varepsilon_{cc} = \varepsilon_{ct} \cdot x / (h - x) \quad (14)$$

$$\sigma_{cc} = \varepsilon_{cc} \cdot E_{cm} \quad (15)$$

$$\sigma_s = \alpha_e \cdot f_{ct,eff} \quad (16)$$

$\varepsilon'_s = \varepsilon_{ct} \cdot (x - d') / (h - x)$ (17)

$\sigma'_s = \varepsilon'_s \cdot E_s$ (18)

$\alpha_e = E_s / E_{cm}$ (19)

From the sum of moments at A_s can be calculated M_{cr}:

$M_{cr} = A'_s \cdot \sigma'_s \cdot (d - d') + 0.5 \cdot x \cdot b \cdot \sigma_{cc} \cdot (d - x/3) – h_{c,eff} \cdot b \cdot f_{ct,eff} \cdot \{0.5 \cdot h_{c,eff} - d'\}$ (20)

Numerical example.

b = 40 cm; h = 60 cm; d' = 3.5 cm; d = 56.5 cm; A_s = 19.0 cm²; A'_s = 0 cm²; E_{cm} = 310000 daN/cm²; E_s = 2000000 daN/cm²; α_e = 6.45;

$f_{ct,eff} = f_{ctm,fl} = \max \{(1.6 - h/1000)f_{ctm}; f_{ctm}\}$ (21)

h – height of the cross section in mm

$f_{ctm,fl}$ – mean value of axial tensile strength of concrete from bending

f_{ctm} – mean value of axial tensile strength of concrete

$\rho_{p,eff} = (A_s + \xi_1^2 \cdot A_p') / A_{c,eff}$ (22)

For non-prestressed reinforced concrete elements A_p' = 0 and:

$\rho_{p,eff} = A_s / A_{c,eff}$ (23)

Figure 2 from EC 2, can help in finding $A_{c,eff}$.

For elements with a rectangular cross-section:

$A_{c,eff} = b \cdot h \cdot \lambda$ (24)

$\lambda = \min \{2.5 \cdot (1 – \delta); (1 – \xi) / 3; 0.5\}$ (25)

$\lambda = h_{c,eff} / h; \delta = d / h; \xi = x / d$ (26)

$h_{c,eff} = \min \{2.5 \cdot (h – d); (h – x) / 3; h / 2\}$ (27)

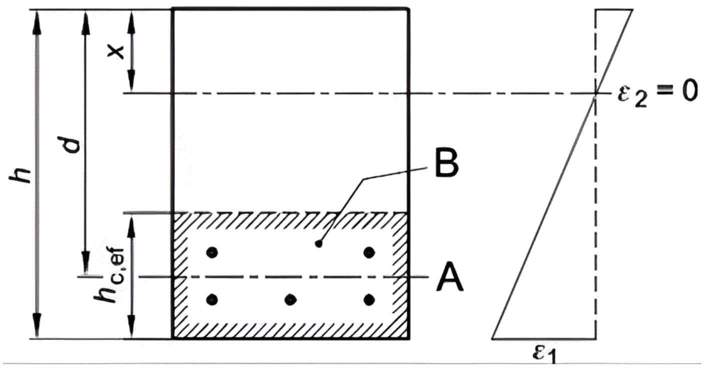


Figure 3. The definition of $h_{c,eff}$ for reinforced concrete beams with a rectangular cross-section [5]

$f_{ct,eff} = f_{ctm,fl}$ = 26.0 daN/cm²; ε_{ct} = 0,0084 %; ε_{cc} = 0,0072 %; σ_{cc} = 22.22 daN/cm²; ε'_s = 0,0063 %; σ'_s = 125.22 daN/cm²; σ_s = 167.74 daN/cm²; x = 27.65 cm; M_{cr} = 5731 daNm;

The characteristic width of the cracks may be determined by the expression:

$$\varepsilon_{sm} - \varepsilon_{cm} = (\sigma_s - \frac{k_t\left(\frac{f_{ct,eff}}{\rho_{p,eff}}\right)(1+\alpha_e\rho_{p,eff})}{E_s}) \geq 0.6\ \sigma_s/E_s \quad [7] \qquad (28)$$

σ_s – the stress in the tension reinforcement

k_t = *0.6* for short term loading, k_t = 0.4 for long term loading.

To determine $f_{ct,eff}$ see the second case and expressions (21) to (27), as well as Figure 3.

In situations where the steel bars spacing is less than 5(c + Ø/2), in which c is the concrete cover, the maximum crack spacing may be calculated from the expression:

$$s_{r,max} = k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \varnothing / \rho_{p,eff} \quad [7] \tag{29}$$

Ø – the bar diameter

k_1 = 0.8 for high bond bars, k_1 = 1.6 for bars with an effectively plain surface.

k_2 = 0.5 for bending

It is recommended k_3 = 3.4; k_4 = 0.425.

From expression (14):

$$\rho_{p,eff} = A_s / A_{c,eff} = A_s / (b \cdot h_{c,eff}) = A_s / (b \cdot h \cdot \lambda) = \rho_s / \lambda \ [7] \tag{30}$$

In situations where the steel bars spacing is more than 5(c + Ø/2), in which c is the concrete cover, the maximum crack spacing may be calculated from the expression:

$$s_{r,max} = 1.3 \cdot (h - x) \ [7] \tag{31}$$

Based on expression (28) and on the recommended values of k_1 to k_4, we have:

$$s_{r,max} = 3.4 \cdot c + 0.8 \cdot 0.5 \cdot 0.425 \cdot \varnothing \cdot \lambda / \rho_s \quad [7] \tag{32}$$

$(\varepsilon_{sm} - \varepsilon_{cm})$ may be calculated from the expression:

$$(\varepsilon_{sm} - \varepsilon_{cm}) = (\sigma_s / E_s) \cdot (1 - \sigma_{s,cr} / \sigma_s) \tag{33}$$

$$\sigma_{s,cr} = k_t \cdot f_{ct,eff} \cdot (\lambda / \varrho_s) \cdot (1 + \alpha_e \cdot \rho_s / \lambda) \tag{34}$$

The value of $\sigma_{s,cr}$ may be assumed as the value in the moment when the first crack appears and is connected to the moment of the first crack M_{cr}. Approximately we have:

$$\sigma_{s,cr} = M_{cr} / (0.9 \cdot d \cdot A_s) = M_{cr} / (0.9 \cdot h \cdot \delta \cdot A_s) = M_{cr} / (0.9 \cdot b \cdot h^2 \cdot \delta \cdot \rho_s) \tag{35}$$

Based on the above expressions we have:

$$k_t \cdot f_{ct,eff} \cdot (\lambda / \rho_s) \cdot (1 + \alpha_e \cdot \rho_s / \lambda) = M_{cr} / (0.9 \cdot b \cdot h^2 \cdot \delta \cdot \rho_s) \tag{36}$$

$$M_{cr} = 0.9 \cdot \delta \cdot \lambda \cdot (1 + \alpha_e \cdot \rho_s / \lambda) \cdot b \cdot h^2 \cdot f_{ct,eff} \cdot k_t \tag{37}$$

Numerical example.

b = 40 cm; h = 60 cm; a = a' = 3.5 cm; d = 56.5 cm; A_s = 19.0 cm²; A_{sc} = 0 cm²; f_{ct} = 18 daN/cm²; E_{cm} = 310000 daN/cm²; E_s = 2000000 daN/cm²; α_e = 6.45; δ = 0.941; $\lambda = h_{c,eff} / h$ = 0.146 (see the example of the second case); ϱ_s = 0.008; $f_{ct,eff}$ = 26 daN/cm² (see the example of the second case); k_t = 1 (a value of 1 is accepted to exclude the impact of this coefficient on the M_{cr} size, enabling the comparison with other ways of calculating the M_{cr}); M_{cr} = 6248 daNm; For k_t = 0.6 results M_{cr} = 3749 daNm;

U.S. ACI 318 -19 Code

According to U.S. ACI 318 -19 Code, the first flexural crack will occur in the section when the stress in the extreme tension fiber equals the modulus of rupture, f_r. The bending moment of the first crack can be calculated from elastic theory [9, 10]:

$$M = \sigma_{c(max)} \cdot I / y_{max} \tag{38}$$

In most cases the contribution of steel reinforcement can be ignored and the cracking moment (M_{cr}) can be calculated using only the concrete section, normally referred to as the gross section. This approach is taken in favor of safety, because, as is well known, the contribution of the reinforcement is positive, increasing M_{cr}. Based on expression (38) and on the reasoning above, to calculate M_{cr} the following expression is used [9, 10]:

$$M_{cr} = f_r \cdot I_g / y_t \tag{39}$$

f_r – concrete modulus of rupture

I_g – inertia moment of the gross section

y_t – distance from the section centroid to the extreme tension fiber

It is recommended to calculate the modulus of rupture from the expression [9, 10]:

$$f_r = 7.5 \cdot (f'_c)^{1/2} \tag{40}$$

Numerical example.

b = 40 cm; h = 60 cm; a = a' = 3.5 cm; d = 56.5 cm; A_s = 19.0 cm^2; A_{sc} = 0 cm^2; y_t = h /2 = 25 cm; I_g = b · h^3 / 12 = 312500 cm^4; f'_c = 250 daN/cm^2; f_r = 31.14 daN/cm^2; M_{cr} = 3892 daNm;

RESULTS

Figures 4 and 9 display the parametric results, showing how the cracking moment varies with the key parameters tested.

Comparative Consistency Assessment

To give one more layer of interpretation an inter-comparison of the method hereby explored is done by a relative comparison of results obtained from the parametric study normalized.

Where the deviation of the various prescriptions from the reference formulation, Eurocode 2, is expressed as:

$$\Delta M_{cr}(\%) = \frac{M_{cr,i} - M_{cr,EC2}}{M_{cr,EC2}} \times 100 \tag{41}$$

To further quantify the differences between methods, a mean relative error (MRE) indicator is introduced:

$$\mathrm{MRE} = \frac{1}{n} \sum_{i=1}^{n} \frac{M_{cr,i} - M_{cr,EC2}}{M_{cr,EC2}} \tag{42}$$

where n is the number of parametric cases considered, $M_{cr,i}$ is predicted first-crack moment from method i, and $M_{cr,EC2}$ = reference value (e.g., based on Eurocode 2)

The behavior of the Albanian code is such that it over estimates, in a systematic way, the values of the cracking moment M_{cr} when compared to Eurocode 2, and the magnitude of this over estimation increase with the reinforcement ratio.

The ACI formulation determines both under/overestimates for various section geometries especially section height.

From the available evidence the proposed procedure appears to be in closer agreement with the Eurocode-based approach (within approximately ± 5–10%) for the cases examined), which is promising for the use of this procedure as an intermediate approximation.

It is important to reiterate here that this comparison should not be taken as a validation to numerical or experimental benchmarks, but instead as a measure of the relative internal consistency of the code formulations.

Width Influence of the Cross Section

The cross-section width increased M_{cr} for all the methods, although at different rate among the codes. The Albanian Code and Eurocode 2 exhibit similar trends (approximately 197% increase for a 250% increase in width), whereas ACI 318-19 is significantly more sensitive, showing an increase of about 250%. This indicates that the ACI approach is more strongly influenced by geometric scaling, as it depends more directly on the gross-section moment of inertia.

Effect of Cross-Sectional Height

Section height has a significantly more pronounced effect on M_{cr}. The Albanian Code shows an increase of approximately 335%, Eurocode 2 about 238%, and ACI 318-19 up to 800%. This highlights the strong sensitivity of the ACI formulation to section height, as M_{cr} is directly proportional to the gross-section moment of inertia.

Effect of Concrete Strength

Increases in the concrete strength cause an increase in the value of M_{cr} for all three methods.

EC2 is the most sensitive (+202%)

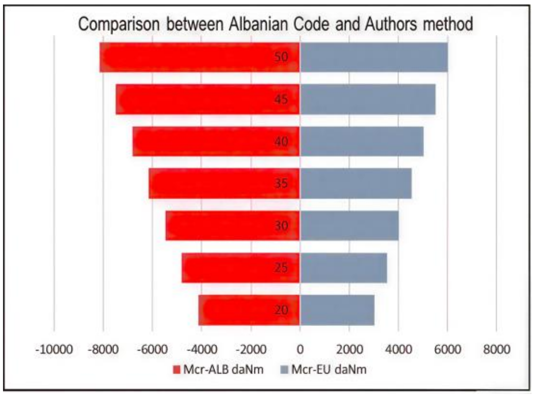
ACI: +177%

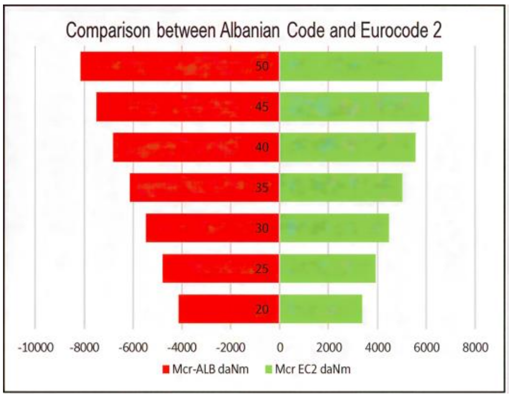
Albanian Code: +143%

Indicating the varied handling of the tensile strength in each formulation.

Effect of Reinforcement Ratio (As)

The impact of reinforcement area can be seen in the Albanian and the EC2 method since M_{cr} increases with As. However, the ACI method is independent upon reinforcement, since it is referenced only to the gross section of the concrete.





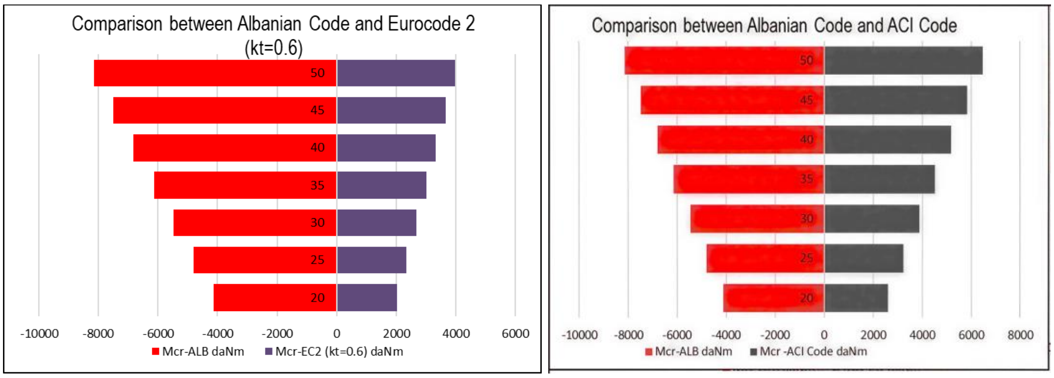


Figure 4. Comparative Diagrams of M_{cr} between Albanian Code an others Code for different values of section width (b=20 cm to b=50 cm)

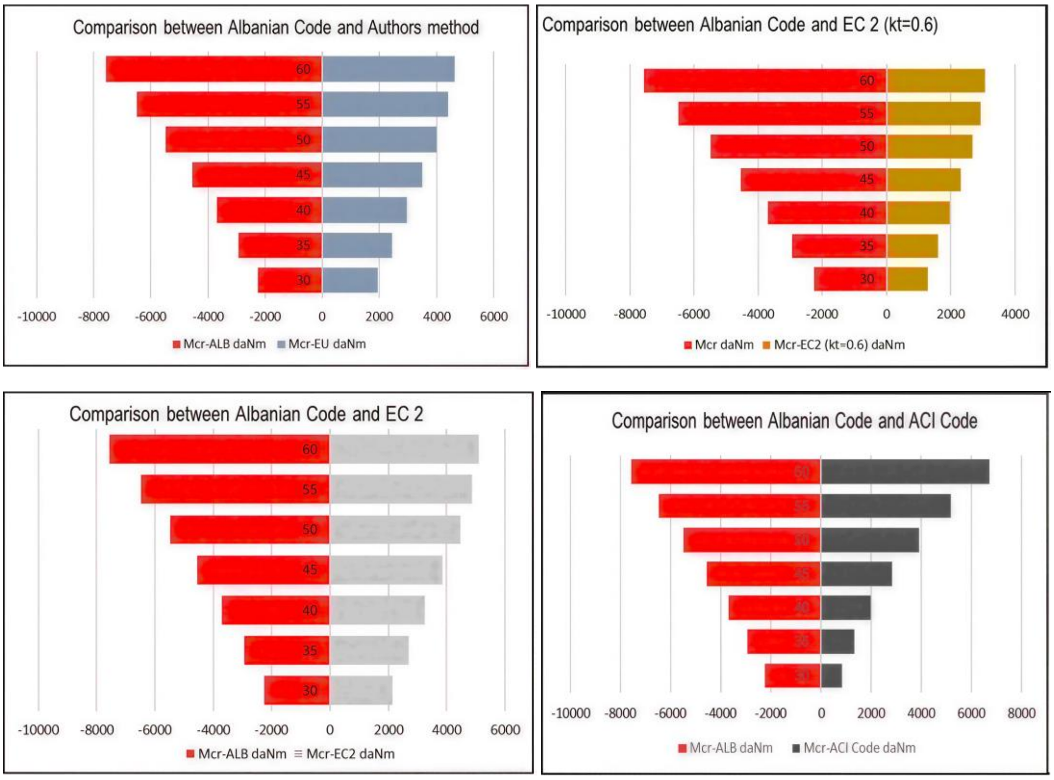
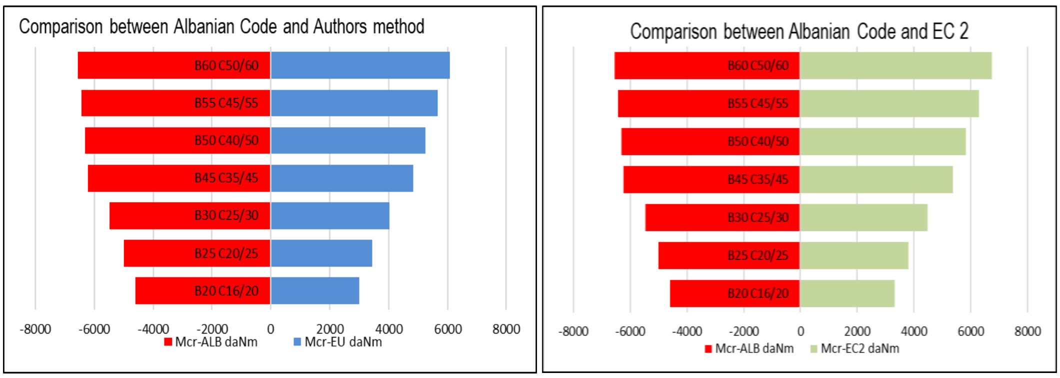


Figure 5. Comparative Diagrams of M_{cr} between Albanian Code an others Code for different values of section height (h=30 cm to h=60 cm)



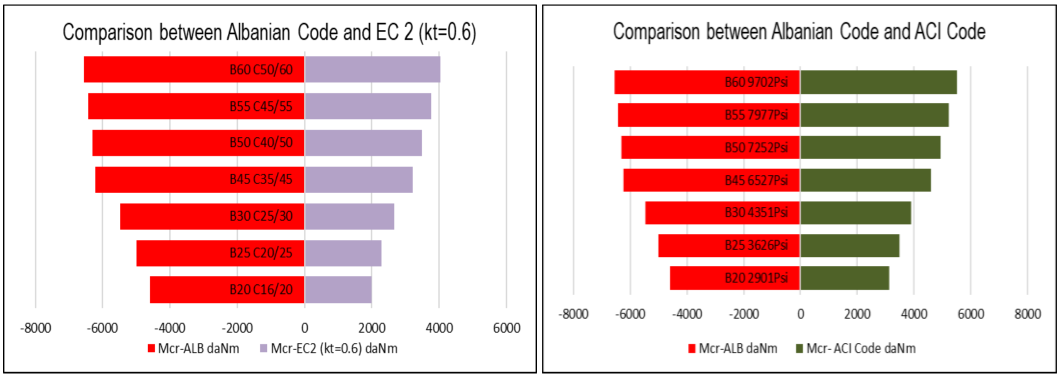


Figure 6. Comparative Diagrams of M_{cr} between Albanian Code an others Code for different values of concrete classes

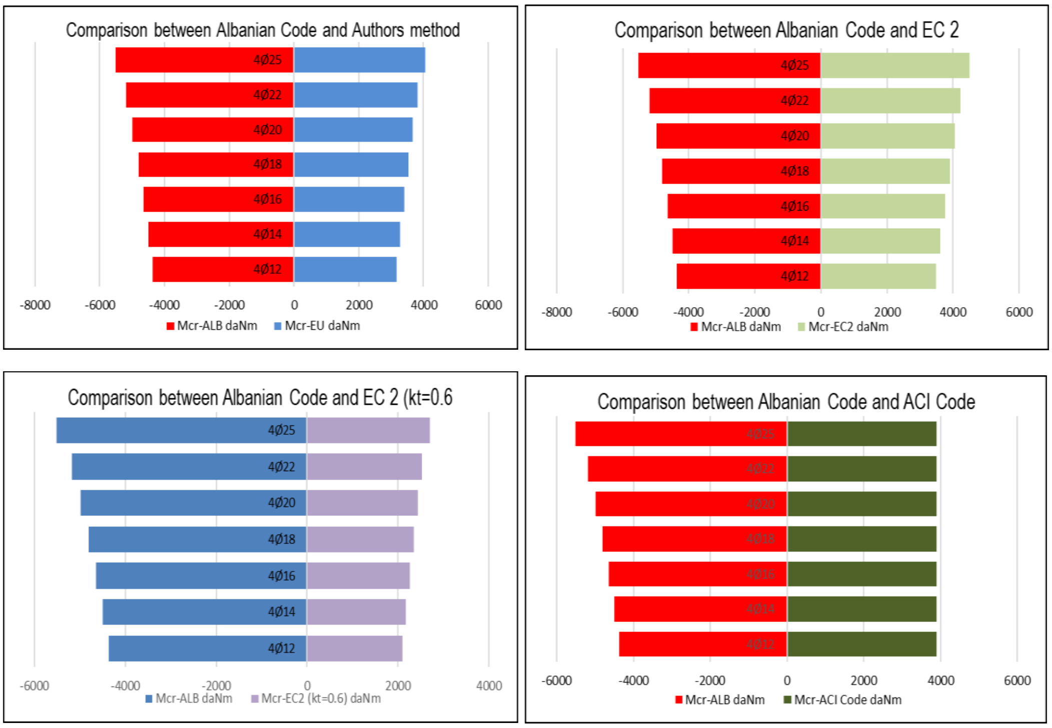


Figure 7. Comparative Diagrams of M_{cr} between Albanian Code an others Code for different reinforcement area (4Ø12 to 4Ø25)

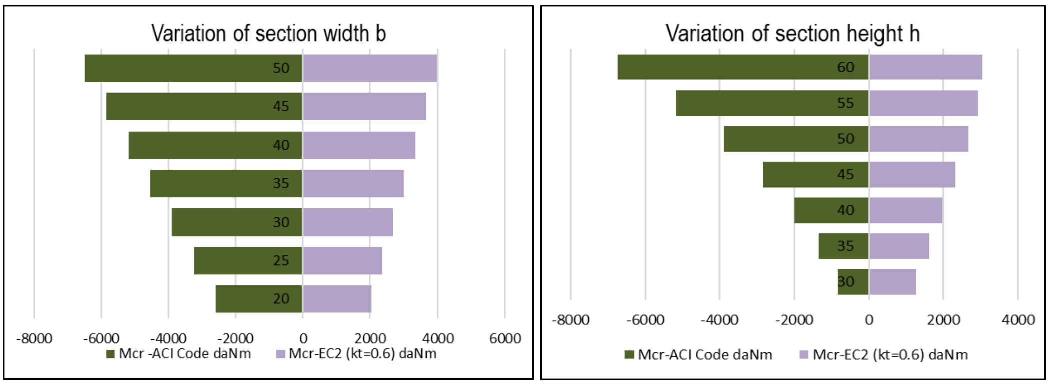
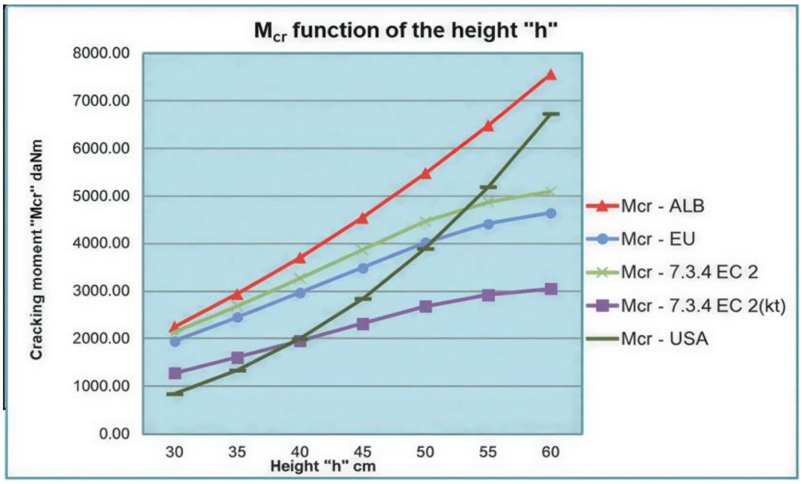
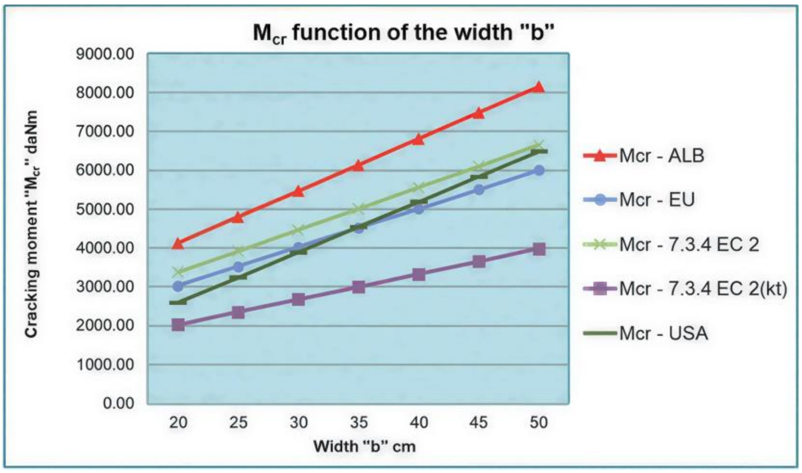


Figure 8. Comparative Diagrams of M_{cr} between ACI Code an EC2 (k_t=0.6)

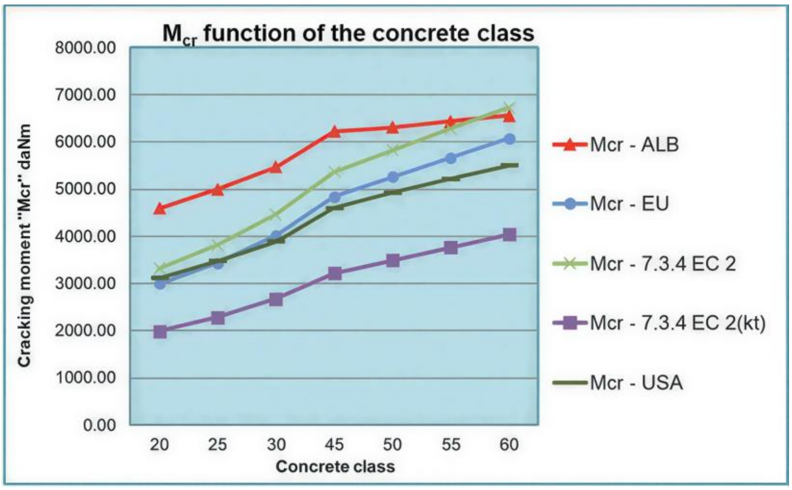
Based on the diagrams of Figure 8, even though the U.S. ACI Code does not take in consideration the reinforcement contribution, it still generates higher values of M_{cr} compared to Eurocode, with sole exception for smaller values of cross section heigh. This is in accordance with Authors pervious experiences that Eurocode is more conservative compared to U.S. ACI Code.



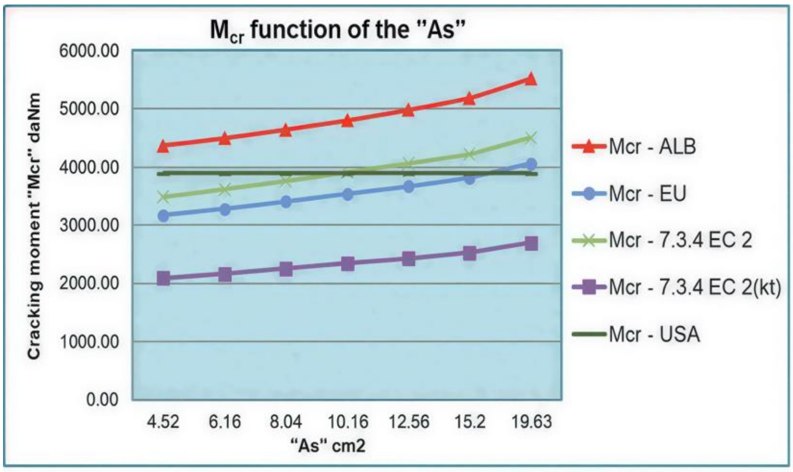
(a)



(b)



(c)



(d)

Figure 9. Comparative diagrams of M_{cr} for the four specified methods (a) until (d)

The results, after studying the diagrams above, are:

In order to make the comparison more accurate, the Authors have performed the calculation based on Eurocode method also for a value of k_t=1, although Eurocode recommends k_t=0.6 or k_t=0.4 depending on load duration. A value of 1 is accepted to exclude the impact of this coefficient on the M_{cr} size, enabling the comparison with other ways of calculating the M_{cr}.

Almost always the value of M_{cr} calculated according to the Albanian codes is higher than the one calculated according to EC 2. Albanian codes accept a tensile deformation of concrete greater than EC 2. In the numerical example presented there is ε_{bt} = 0,0120 % and ε_{ct} = 0,0084 %. In conclusion, since according to the Albanian codes the tensile deformation of concrete, at the moment when the first crack is created, is accepted to be higher than the value according to EC 2, the bending moment that creates the first crack (M_{cr}) is higher. The value of M_{cr} calculated according to the Albanian codes is always higher than the one calculated according to U.S. design codes. This is because the U.S. standards do not take into account the contribution of the tensile reinforcement.

The value of M_{cr} calculated according to the method proposed by the authors of this paper, based on EC 2, is almost equal (~ -10%) to M_{cr} according to EC 2, for kt = 1. This suggests that the approximation approach is in relatively close agreement with the Eurocode-based approach for the cases considered. The value of kt is accepted 1, in order to compare the methods, as this coefficient only takes into account the duration of the load action [9].

The value of M_{cr} calculated according to EC 2 differs significantly from that calculated according to U.S. design codes. For small values of the cross-sectional height (h), the M_{cr} values according to EC 2 are higher than those determined according to U.S. design codes. As the height (h) increases, the situation reverses.

It is observed that when the cross-sectional width (b) increases, M_{cr} also increases. When (b) increases 250%, M_{cr} increases 197% (ALB), 197% (EC 2) and 250% (U.S.A). The increase of (b) affects more the M_{cr} calculated according to the U.S. design codes.

It is observed that when the cross-sectional height (h) increases, M_{cr} also increases. When (h) increases 200%, M_{cr} increases 335% (ALB), 238% times (EC 2) and 800% (U.S.A). The increase of (h) affects more the M_{cr} calculated according to the U.S. design codes.

It is observed that as the concrete class increases, M_{cr} also increases. When the concrete class increases by a factor of 3, M_{cr} increases by 143% (ALB), 202% (EC 2), and 177% (U.S.A). The increase in concrete class has a greater influence on the M_{cr} calculated according to EC 2.

It is observed that when the reinforcement area A_s increases, M_{cr} also increases — with the exception of the U.S. code. The M_{cr} calculated according to this standard does not depend on A_s at all. When A_s increases 4.34 times, M_{cr} increases by 128%. This applies to both the Albanian codes and EC 2 and the effect is almost the same.

Upon the results obtained from this paper, we may give some valid recommendations:

This means that based on the Albanian codes a reinforced concrete element in bending does not crack, while according to EC 2 the opposite happens. Therefore, must be taken maximum care in accurately determining M_{cr}.

The values of M_{cr} calculated according to the U.S. design codes differ significantly from the corresponding values calculated according to the Albanian codes and Eurocodes. As a result, in this case unlike other calculations the U.S. design codes cannot be used as alternative standards for verifying the accuracy of calculations performed based on the Albanian codes and Eurocodes.

And finally, we can conclude that this paper highlights the importance of accurately determining the bending moment corresponding to the formation of the first crack (M_{cr}), as it is essential for assessing whether a reinforced concrete element subjected to bending will crack or not. The Eurocode 2 predictions for the cracking moment seem to be more conservative and internally consistent. These are thought to be a safer recommendation for serviceability design.

Case Study: Application to a Representative RC Beam

A case study was performed to demonstrate the distinctions between the two design codes within a more representative engineering context. The example that was used employed a simply supported, rectangular cross-section, reinforced concrete beam.

Geometry and material properties is as follows:

- Width: b=300 mm
- Height: h = 500 mm
- Effective depth: d=460 mm
- Reinforcement area: As= 1256mm 2 (4Ø20)
- Concrete strength: fck= 30MPa
- Steel modulus: Es= 200GPa

The cracking moment M_{cr} was calculated according to (see Table 4):

- Eurocode 2
- ACI 318-19
- Albanian design code
- Approximation approach

Table 4. Cracking moment for different methods

Method	Mcr (kNm)
Eurocode 2	42
ACI 318-19	48
Albanian Code	46
Approximation approach	43

The results prove the overall trend of the parametric study, with Eurocode 2 calculation being the safest out of all. ACI 318-19 formulation is also obtaining higher values than the other calculations (as in the previous parametric study). The Albanian code also overestimates Mcr mostly because of the higher assumptions of the admissible tensile strain. Approximation approach has good agreement with Eurocode 2 (+/5%) suggesting its applicability as practical intermediate method in mixed-code situations.

In order to give a more direct comparison between the methods, the results have been presented as relative to Eurocode 2:

$$R_{Mcr} = M_{cr} / M_{cr,i,EC2} \tag{43}$$

This normalization allows direct comparison of the relative conservativeness of each method.

Values > 1 → overestimation

Values < 1 → underestimation

The results show that:

Albanian code: typically, 1.05 – 1.15

ACI 318-19: 0.95 – 1.25 (high variability)

Approximation approach: 0.95 – 1.05

This confirms that Eurocode 2 provides the most stable and consistent baseline for comparison.

DISCUSSION

The discrepancies observed in between the design procedures studied can be mostly explained through a simplified analytical interpretation of the cracking moment expression. In general terms, the cracking moment may be expressed as:

$$M_{cr} = \frac{f_{ct} I}{y} \tag{44}$$

where f_{ct} is the tensile strength of concrete, I is the moment of inertia of the section, and y is the distance from the neutral axis to the extreme tension fiber. For a rectangular cross-section, the moment of inertia can be approximated as:

$$I \propto b \cdot h^3 \tag{45}$$

and $y \approx h/2$ which leads to the following proportional relationship:

$$M_{cr} \propto f_{ct} \cdot b \cdot h^2 \tag{46}$$

This simplified form of the equation also helps shed some light on the parametric trends that are evident in the results. In particular, it shows how much more significant in the sectional height h is in setting the cracking moment, as M_{cr} Scales quadratically with h while the width b has a linear effect. Moreover, this one also shows the high sensitivity of the ACI 318-19 formulation to the geometrics properties as it is based on gross-section inertia. On the other hand, Eurocode 2 and Albanian code take into account some addenda, like reinforcement interaction and effective tensile area, that relieve the pure geometrical dependence. As a result, the obvious numerical variation between the two codes are in fact entirely borne out of the differences in the mechanical assumptions concerning the behavior of the material and the manner in which the sections are modeled.

This analytical interpretation supports the sensitivity trends identified in the parametric study and provides a theoretical basis for the observed differences between code formulations.

Mechanistic Interpretation of Code Differences

The differences identified between the various code-based predictions for the cracking moment M_{cr} can be readily linked to the fundamental mechanical assumptions embodied in each of the various discretization schemes.

These discrepancies between the predictions of the cracking moment M_{cr} by the different code may be theoretically analyzed by considering the governing formulation, and the mechanical considerations of the same.

For the ACI 318-19 formulation, the cracking moment is based on the classical elastic beam theory assuming that the cracking takes place when the tensile stress in the outer fiber reaches the modulus of rupture. The formulation is as follows:

$$M_{cr} = \frac{f_r\, I_g}{y_t} \tag{47}$$

Where the moment of cracking directly depends on the gross section properties. This shows the high sensitivity of the ACI method to the geometry of the section, especially to the height as the moment of inertia depends on h3, while reinforcement ratio sensitivity is reduced in the absence of reinforcement contribution.

However, Eurocode 2 adopts another form considering the properties of the material and the effects of reinforcement interaction, in a simplified form the cracking moment can be written as:

$$M_{cr} \propto f_{ct,eff} \cdot b \cdot h^2 \cdot (1+\alpha_e\, \rho_s) \tag{48}$$

This expression captures the effect of effective tensile strength of concrete ($f_{ct,eff}$) and the effect of the interaction of the concrete with the reinforcement as modular ratio (α_e) and reinforcement ratio (ρ_s). As consequence Eurocode 2 consider the effect of the tension stiffening effect and the crack can be first initiated earlier, being more conservative for Mcr.

For Albanian code of design, the higher admissible tensile strain in concrete would practically result in that cracking occurs at higher strains, thus in terms of mechanics would give a longer elastic domain in the tensile zone, resulting in a higher redistribution of stresses before cracks, and hence to systematically higher values of Mcr, when compared to EC 2.

Such distinctions can be related to fracture mechanics and softening in nonlinear materials. More sophisticated solutions involve tension softening, bond-slip interaction and the degradation of stiffness. Standardized representations using codes could provide an approximation of these effects from the most elastic condition. Hence the conservative Eurocode 2 could be understood as an implicit approximation of these nonlinearities and the ACI 318-19 relatively closer to the elastic ideal.

This analysis indicates that the deviations between code predictions are primarily associated with different mechanical assumptions regarding material behavior and reinforcement interaction between code prediction are not coincidental but are originated due to distinct mechanical assumptions of material behavior and reinforcement interaction.

Interpretation of the Approximation Approach

It should be emphasized that the proposed formulation should not be interpreted as a new predictive model, but rather as a transitional engineering approximation but as an interim engineering approximation, which is intended to have as similar as possible results to the prescribed code solutions based on Eurocode.

This form of formulation that is currently being used should not be seen as a validated predictive model. It should be seen, rather, as a hybrid code engineering approximation.

Its provision enables the partial integration of Eurocode based principles in the Albanian solution, especially concerning the effective tensile area and the interaction of the concrete with the reinforcement.

The good correlation observed with the Euro-code based estimates (. i.e. within about +/- 5-10% in the cases considered) indicates that the method could offer a pragmatic intermediate solution in engineering practice where various system coexists.

It's worth noting however, that this does not validate in itself and more evaluation through nonlinear numerical simulations and/or experiments must be undertaken before recommending more general application of this formulation.

Hence, the above formulation should be understood as an engineering approximation and not a confirmed predictive formulation.

Sensitivity Ranking and Critical Regimes

From the parametric results, it is apparent that the effect of these parameters on the cracking moment order as:

$$h > f_{ct} > A_s > b$$

Indicates that the dominant factor for Cracking behavior is the dimensions, specifically height, with reinforcement factors becoming important only in the Eurocode and thethe Albanian formulations. The largest discrepancies between code predictions are observed for: larger section heights, Lower reinforcement ratios, and higher classes of concrete strength, Where the divergence in the underlying assumptions become starker.

Practical Design Implications

The results of this study are highly relevant to structural engineering practice, particularly in mixed-code environments such as Albania. The overestimation of M_{cr} under the Albanian code may lead to unconservative serviceability assessments, potentially underpredicting crack development and associated durability issues.

However, on the other hand the fact that Euro code 2 is a conservative approach it predicts cracks at an earlier stage which leads to more secure designs with better crack control and long-term behaviour.

The ACI 318-19 equation, which is based on gross-section properties, could result in varying values depending on the section shape, especially for deeper sections.

- These differences can significantly affect:
- Reinforcement design and detailing;
- Methods for controlling the width of cracks;
- Strength and long life.

According to this, the following criteria should be followed, it is highly recommended that, engineers should be careful when choosing different design standards and should also stick to a consistent approach, especially when doing serviceability limit state checks.

Sensitivity and Reliability Considerations

The results demonstrate that M_{cr} is highly sensitive to Section height (h) Concrete tensile strength Reinforcement ratio (for EC2 and Albanian code) This indicates that reliable prediction of cracking behaviour would require accurate material characterization and geometric definition.

Relation to State-of-the-Art Approaches

From a wider perspective, the variation between the code formulations agrees with the development of cracking models for reinforced concrete.

Advanced methods, such as fracture mechanics, nonlinear constitutive relationships and finite element models, reveal that crack initiation can occur due to a complex interaction between tensile strength, degradation of stiffness, bond slip and material heterogeneity. In this sense, the code-based equations are just simpler engineering approximations to a nonlinear process.

The conservative nature of Eurocode 2 is more in line with contemporary design approach which prefers durability and serviceability. Meanwhile, simplified equations of ACI 318-19 may be acceptable for preliminary design purposes but may ignore the full sensitivity of cracking to reinforcement and material interaction.

The intention of this study should not be to replace the more sophisticated model; it is only the potential consequences of a simplified code-based approach, which should be given greater emphasis in a mixed regulation.

Limitations of the Study

The present work presents some limitations to be considered. Firstly, the analysis is conducted considering rectangular cross-sections only and linear elastic elastic behaviour up to cracking, while concrete exhibits non-linear behaviours such as tension softening, bond-slipping interaction and stiffness degradation. Secondly, the referencing to forms based on analytical code is purely theoretical and untouched by experimental evidence.

The areas of reference are based on literature and have not been subjected to real structural performance. Third, there is no numerical validation using sophisticated simulation programs (e.g., nonlinear finite element analysis; ABAQUS, OpenSees). Additional work should involve experimental validation, nonlinear simulations, extension to other cross-section shapes, and probabilistic approaches.

SUMMARY AND CONCLUSION

The paper shows a comparison between two approaches for calculating the moment of cracking, M_{cr} for reinforced concrete sections, according to the Albanian design code, Eurocode 2 and ACI 318-19. The comparison shows all the differences that arise from the two approaches. The Albanian code provides a relatively higher estimate of M_{cr} because it is based on a higher admissible tensile strain in concrete thereby postponing the beginning of the cracking process. Meanwhile, Eurocode 2 produces a more conservative estimate because it is based on the idea of effective tensile area and concerns explicitly the interaction between concrete and reinforcement

Eurocode 2 consistently provided the most stable reference for serviceability in the studied parameter range since it showed, among all the studied codes, the lowest dispersion and the most constant bias toward safe predictions (on average between 8 and

10%). The trend toward higher M_{cr} values was consistently observed with the Albanian code, while the greatest level of coefficient of variation was with the ACI 318-19 formulation, specifically with section height. The approximation method proposed herein was observed to remain quite close to the Eurocode predictions (+/- 5–10%) and so demonstrates potential as a transitional consistency tool as an intermediate consistency method when working in mixed codes, with some further validation.

According to the results of this study, practical conclusions are as follows: First, Eurocode based methods should be emphasized in serviceability limit state verification for reinforced concrete in Albania, especially when crack control is involved. Second, the application of different design codes at the same project should be taken very seriously since considerable differences in M_{cr} prediction may arise.

Third, simplified methods like ACI 318-19, while useful should be supplemented by other checks for a more refined evaluation of cracks. Fourth, future updates to the Albanian design code should incorporate crack assessment concepts similar to the Eurocode standards.

Engineers and students in Albania, who design or study the reinforced concrete structures, should know clearly that the bending moment when the first crack is created, defined according to the Albanian codes, is greater than the one calculated according to EC 2.

AUTHOR CONTRIBUTION

Conceptualization, I.K.; methodology, I.K., and E.C.; software, I.K., and E.C.; validation, I.K., and J.K.; formal analysis, J.K.; investigation, F.B.; resources, I.K.; data curation, I.K., and E.C.; writing—original draft preparation, I.K.; writing—review and editing, I.K., and F.B.; visualization, I.K., and E.C.; supervision, I.K.; project administration, I.K.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest associated with this publication, and that no external financial support influenced the research outcomes.

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