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Assessment of reinforced concrete beams cracking depending on the concrete class

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ABSTRACT:
Cracks in reinforced concrete are a common concern that can arise from various causes such as concrete shrinkage, temperature differences, and structural loads. The aim of the study was an analysis of cracks in concrete on which the reinforcement concrete beam was made. The beam was loaded with an evenly distributed load and subjected to bending. Depending on the concrete class (C20/25, C25/30 and C30/37), the cracks in the concrete, the deflection at a load of 5.35 kN/m^2 and the beam's load-bearing capacity, i.e. the value of the load that the beam can withstand without any cracks were assessed.

KEYWORDS:
reinforcement concrete; beam; FEM; crack

1. Introduction

Reinforced concrete structures offer several advantages, making them a popular choice in construction. One major benefit is their high strength-to-weight ratio, particularly when reinforced with materials like fiber-reinforced polymers (FRP). FRP bars, for instance, are lightweight, non-corrosive, and offer high tensile strength, which improves the structural durability of the concrete, especially in corrosive environments [1, 2]. Additionally, reinforced concrete allows for the creation of mixed structures, optimizing both interior and exterior stresses in large public buildings, thus providing flexibility in architectural design while maintaining structural integrity. Prefabricated reinforced concrete frames further enhance construction efficiency, allowing for more stable, cost-effective, and scalable solutions in both high-rise and small buildings. These structures are also advantageous in repair applications, offering high strength and reducing the likelihood of secondary cracking, thus enhancing the longevity of existing buildings [3, 4].

The design of reinforced concrete beams ensures they can adequately withstand ultimate bending moments and shear forces, while serviceability criteria maintain satisfactory performance under normal loads [3, 5]. Additionally, repair techniques for reinforced concrete beams, such as the use of micro-concrete or OPC mortar, restore a significant portion of the beam's capacity after corrosion damage, with micro-concrete offering better long-term performance against chloride ingress [6].

Recent studies on reinforced concrete beams have explored various innovative materials and design approaches to enhance performance. A reliability-based design approach was developed for fiber-reinforced polymer (FRP) reinforced concrete beams, incorporating compression yielding (CY) to improve ductility and reduce costs compared to conventional FRP-reinforced beams.

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This approach demonstrated higher reliability and resistance under different loads [7]. Research also examined sustainable alternatives like bamboo and palm leaves as replacements for steel reinforcement, revealing that these materials enhance the structural behaviour of concrete beams, showing distinct patterns of failure and improved sustainability [8]. Additionally, studies on hybrid Basalt-FRP and steel-reinforced beams without shear reinforcement showed an 11 % improvement in shear capacity compared to steel-reinforced beams, highlighting the benefits of hybrid reinforcement for durability and strength [9]. A performance-based analysis of hidden beams indicated a significant reduction in deflection and stress distribution, making them effective for large-span structures [10].

Cracks in reinforced concrete are a common concern that can arise from various causes such as concrete shrinkage, temperature differences, and structural loads. In reinforced concrete bridge structures, cracks can occur due to inadequate control of shrinkage and temperature during construction, especially in large structures, with widths potentially exceeding permissible limits as outlined by design standards [11]. Experimental studies highlight that crack formation is influenced by factors such as insufficient reinforcement, high temperature exposure, and concrete shrinkage. Methods like dispersed reinforcement using steel or polypropylene fibres have been shown to reduce crack formation and improve structural durability in reinforced concrete slabs [12]. Additionally, finite element analysis reveals that cracks in reinforced concrete beams often propagate dynamically, with bending cracks and significant tensile damage occurring, particularly in areas like beam-column joints [13]. Innovations like bacteria-based self-healing concrete are being explored to mitigate crack formation and enhance long-term durability [14].

2. Materials and methods

The aim of the study was an analysis of cracks in concrete on which the reinforcement concrete beam was made. The beam cross-section shape and static diagram were presented in Figure 1. The beam was loaded with an evenly distributed load and subjected for bending. The reinforcement was designed from steel bars with a diameter of $\phi = 16$ mm, with a yield point of $f_y = 500$ MPa. The beam made with three concrete classes was analysed. There was C20/25, C25/30 and C30/37. The material properties of the concretes were assumed as in the EN 1992-1-1 standard [15].

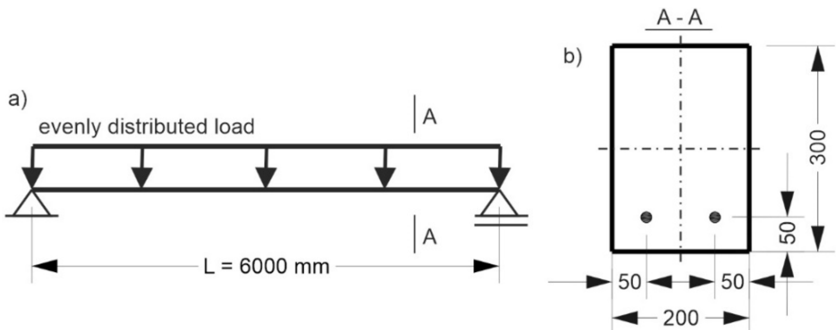

Fig. 1. Analysed beam: a) static diagram, b) cross-section shape

The analysis was carried out based on the results of calculations carried out in the Adina program. Due to the bisymmetry of the beam, a numerical model representing 1/4 of the beam was made. For this purpose, the boundary conditions were given that reflected the preservation of symmetry, as shown in Figure 2. The boundary conditions named by B, C and E were assumed on the surface, however the B conditions was assumed on the line. The beam was loaded with a pressure corresponding to a load of 5.35 kN/m^2. The concrete component was simulated using 3D-solid finite elements. Rebar type elements were used to simulate the reinforcing bars. The special material model of concrete available in ADINA program was used (Fig. 3).

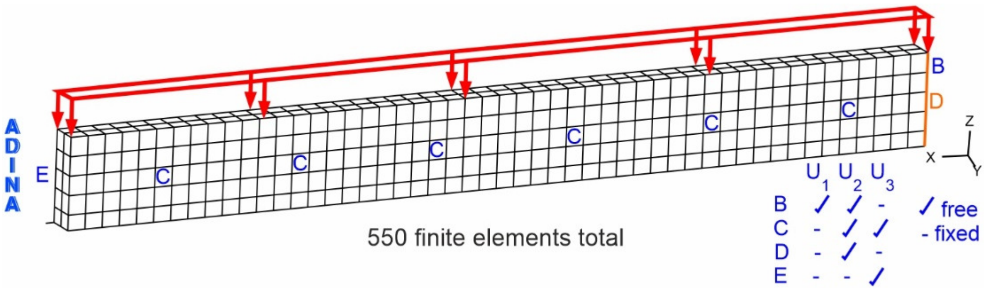

Fig. 2. Beam analysed in ADINA program

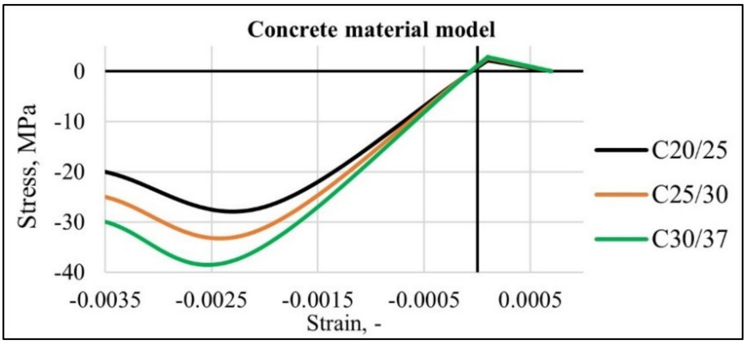

Fig. 3. Concrete material models

Depending on the concrete class, the cracks in the concrete, the deflection at a load of 5.35 kN/m^2 and the beam's load-bearing capacity, i.e. the value of the load that the beam can withstand without any cracks were assessed.

3. Results

A smeared crack approach to fracture of concrete was implemented in the finite element program ADINA, in which when the element at an integration point cracks, the stiffness perpendicular to the crack is reduced to zero and the tensile stress across it is set as a function of the crack opening.

The ADINA concrete model is based on the following criteria:

– a nonlinear experimentally-based stress-strain law for the behaviour in compression and tension,
– an experimentally-based stress failure surface that dictates when either cracking or crushing occurs in concrete, and
– a post-failure response for cracking based on a smeared crack approach that allows cracks to close and reopen.

Finally, four states of cracks are presented in post-processing: 1 – open cracks; 2 – closed cracks; 3 – crushed; 4 – cracks.

The results obtained in numerical simulations were presented in Table 1. In the beam made of concrete C20/25 the maximum crack type of 3 was observed. But in the beams made of concrete C25/30 and C30/37 the 2-type and 1-type of crack was observed as the maximum, respectively.

The deflection of beam made of concrete class of C20/25, C25/30 and C30/37 were 19.3 mm, 16.8 mm and 15.3 mm, respectively. The load carried by beams without any cracks were of 1.87 kN/m^2, 2.33 kN/m^2, 2.79 kN/m^2 for concrete classes of C20/25, C25/30 and C30/37.

Table 1
Results from numerical simulations

Parameter	Concrete C20/25	Concrete C25/30	Concrete C30/37
Kind of cracks under the load of 5.35 kN/m^2	3	2	1
Deflection under the load of 5.35 kN/m^2 [mm]	19.3	16.8	15.3
Load until cracks of concrete [kN/m^2]	1.87	2.33	2.79

In all beams presented in Figures 4-6, the cracks occurred in the lower zone, near the mid-span of the beam. However, the class of the concrete affected on the value of clack, so on the type of crack. In the beam made of C20/25 concrete class the open cracks, closed cracks and crushed were observed. In the beam made of C25/30 concrete class the open cracks and closed cracks occurred. And in the beam made of C30/37 concrete class only the open cracks were observed.

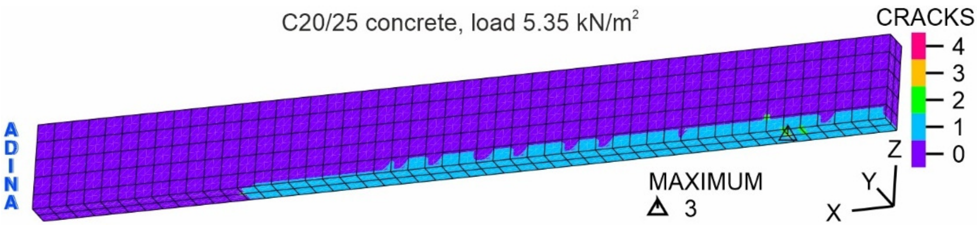

Fig. 4. Cracks in the beam made of C20/25 concrete class

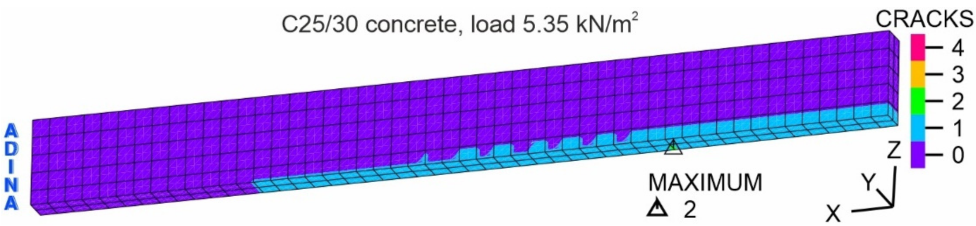

Fig. 5. Cracks in the beam made of C25/30 concrete class

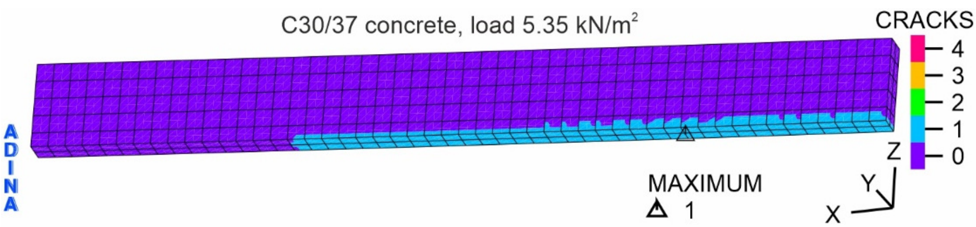

Fig. 6. Cracks in the beam made of C30/37 concrete class

4. Discussion

Cracks appear in concrete when tensile stresses exceed the tensile strength of concrete. At the same time, the size of cracks depends on the applied load. For example, the stress distribution regarding to the XX axis of the beam made of C20/25 concrete was presented in Figure 7. It is easy to notice that the tensile stresses (plus sign) occurred in the lower part of the 3-point bending beam. The maximum tensile stress was of 2.44 MPa, which is bigger than the tensile strength of the concrete regarding the EN 1992-1-1 standards which is equal to 2.2 MPa.

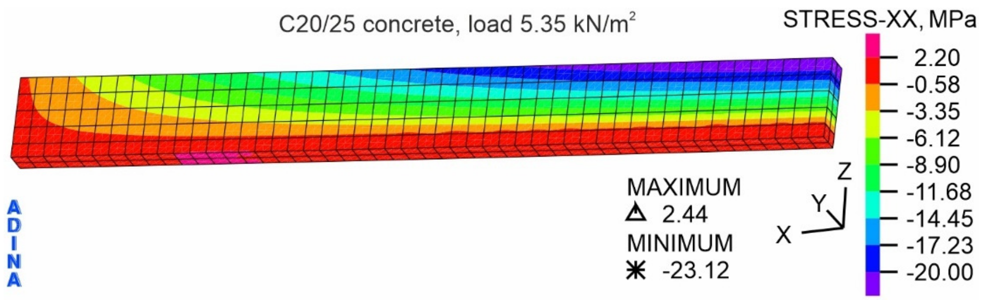

Fig. 7. Stress-XX distribution in the beam made of C20/25 concrete class

The simulations performed proved that the increase in the concrete class affects the reduction of cracks in the beam. The obtained results were consistent with expectations. On this basis, it was assessed that the developed numerical model can be used to analyse complex reinforced concrete structures, taking into account the model parameterization and various optimization criteria.

The Adina program implements a nonlinear concrete material model. This is evident by the observed relationships between the tensile strength of concrete and the crack-free load transferred by the beam. The tensile strength of analysed concrete of C20/25, C25/30 and C30/37 was of 2.2 MPa, 2.6 MPa and 2.9 MPa, respectively. An increase in concrete tensile strength from 2.2 to 2.6 MPa, i.e. by 18 %, affects the crack-free load by 24 %. However, the increase in concrete tensile strength from 2.2 to 2.9 MPa, i.e. by 32 %, affects the crack-free load by 50 %.

5. Conclusions

- The developed numerical model can be used to analyse complex reinforced concrete structures, considering the model parameterization and various optimization criteria.
- In the beam made of concrete C20/25 the maximum crack type of 3 (crushed) was observed. But in the beams made of concrete C25/30 and C30/37 the 2-type (closed cracks) and 1-type (open cracks) of crack was observed as the maximum, respectively.
- An increase in concrete tensile strength from 2.2 to 2.6 MPa, i.e. by 18 %, affects the crack-free load by 24 %. However, the increase in concrete tensile strength from 2.2 to 2.9 MPa, i.e. by 32 %, affects the crack-free load by 50 %.

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Ocena pękania belki żelbetowej w zależności od klasy betonu

STRESZCZENIE:
Pęknięcia w żelbecie są powszechnym problemem, który może wynikać z różnych przyczyn, takich jak skurcz betonu, różnice temperatur i obciążenia konstrukcyjne. Celem pracy była analiza pęknięć w betonie, z którego wykonano belkę żelbetową. Belka została obciążona równomiernie rozłożonym obciążeniem i poddana zginaniu. Analizowano trzy klasy betonu C20/25, C25/30 i C30/37. W zależności od klasy betonu oceniano pęknięcia w betonie, ugięcie przy obciążeniu 5.35 kN/m^2 i nośność belki, tj. wartość obciążenia, jakie belka może wytrzymać bez pęknięć.

SŁOWA KLUCZOWE:
żelbet; belka; MES; pękanie