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Experimental and Numerical Investigations on the Flexural Behavior of Reinforced Rubberized Concrete Beams with Different Longitudinal Reinforcement Ratios

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Abstract

The flexural behavior of reinforced rubberized concrete beams was assessed, and it was demonstrated that they exhibited a constant performance decline with an increase in rubber content. Numerical simulations are critically important in the study and engineering of concrete elements due to several key reasons, as follows: to allow engineers to anticipate the behavior of concrete components under diverse loads; to help elucidate intricate mechanisms such as crack initiation, propagation, and fracture processes; and to explore new materials, geometries, and reinforcement layouts without the need for extensive prototyping. This paper presents both experimental and numerical investigations on the flexural behavior of conventional and rubberized concrete reinforced beams. The parameters of the research included the percentage replacement of natural aggregates by rubber particles and the change in the longitudinal reinforcement ratio. The results showed an increase in the load-carrying capacity and a decrease in the midspan deflection with an increase in reinforcement ratio. Substituting natural aggregates with rubber particles resulted in a slight decrease in the load-carrying capacity but an increase in the midspan deflections. Numerical simulations using ATENA v5 software predicted the load-carrying capacity, failure mode, and cracking patterns of the reinforced concrete beams.

Keywords: rubberized concrete; longitudinal reinforcement ratio; flexural behavior; cracking pattern; numerical simulations



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1. Introduction

Rubber concrete, also known as rubberized concrete or crumb rubber concrete, is a composite material in which a fraction of the natural aggregates, such as sand or gravel, is substituted with ground or shredded rubber, usually derived from recycled discarded tires. Besides the environmental advantages of utilizing rubber as a substitute for natural aggregates in concrete, the inclusion of rubber particles can also provide additional benefits for structural performance [1].

Although the presence of rubber particles leads to a reduction in the values of both mechanical [2] and elastic properties of concrete [3,4], it can provide significant ductility [5]

and energy dissipation reserves in concrete elements [1,6,7]. The reduced values of mechanical properties, compared to conventional concrete, have been attributed to a weaker interfacial transition zone due to reduced bonding between the rubber particles and the cement matrix [8].

While research on the behavior of structural components utilizing rubberized concrete materials is limited relative to material-level studies, the potential advantages have been demonstrated. Axial compression tests on reinforced rubberized concrete columns with [9,10] or without confinement suggested that, apart from a reduction in the load-carrying capacity, the columns were able to undergo up to two times the lateral displacements compared to conventional concrete columns [11].

The flexural behavior of reinforced rubberized concrete beams was assessed, and it was demonstrated that they exhibited a constant performance decline with an increase in rubber content [12]. The incorporation of supplementary cementitious materials, such as rice husk ash, resulted in an improvement in the flexural performance [13], with similar reports on the shear-carrying capacity of beams [14]. Moreover, incasing rubberized concrete in double-skin steel tubes contributed to improved flexural behavior of the beams [12,15]. Previous research works showed that under-reinforced beams made with crumb rubber concrete (CRC) mixtures of comparable compressive strength exhibited nearly identical ultimate flexural capacity, cracking moment, crack spacing, deflection at peak load, and ductility, despite significant variations in rubber content. Their performance could be well predicted by existing equations [16]. Rubberized concrete beams reinforced with welded wire mesh exhibited diminished compressive and tensile strengths as the crumb rubber content increased. However, the incorporation of welded wire mesh layers changed the failure mode from shear to flexure. Moreover, the presence of wire meshes enhanced both the shear and flexural capacities by approximately 4–11% and significantly improved deflection capacity and ductility, particularly at 20% rubber content [17]. High-strength GFRP-reinforced beams with crumb rubber aggregates and steel fibers exhibited reduced shear capacity as rubber content increased, but the use of steel fibers—particularly at higher rubber volumes—resulted in recovered or improved shear capacity, toughness, and post-diagonal-cracking strength, often transforming brittle shear failure into more ductile flexural failure [18]. Lightweight rubberized concrete beams subjected to drop-weight impact displayed lower peak impact forces, longer force duration, slightly smaller midspan displacements, and 10–18% higher imparted energy per unit mass compared to normal concrete [19].

Numerical simulations are critically important in the study and engineering of concrete elements due to several key reasons. These include allowing engineers to anticipate the behavior of concrete components—beams, slabs, and columns—under diverse loads, encompassing extreme events (e.g., seismic, impact, and fire) [5,9,20]. This prediction ability is essential for a secure and optimized structural design. It also helps elucidate intricate mechanisms such as crack initiation, propagation, fracture processes, and interfacial behaviors that are challenging or costly to examine experimentally [4,21]. Simulations allow the exploration of new materials (e.g., rubberized concrete), geometries, and reinforcement layouts without the need for extensive prototyping [10,16,22]. They can guide optimal mix design and reinforcement layout and predict long-term durability. However, numerical simulations necessitate meticulous calibration, experimental validation, and consideration of computational expenses. Erroneous modeling assumptions or inadequate experimental data may result in incorrect predictions. Hence, the optimal approach is the repeated use of both methodologies to ensure that accurate numerical models are used to produce trustworthy results.

Although prior tests indicated the feasibility and advantages of rubberized concrete materials in structural components, existing experimental data has been restricted to configurations where only small aggregate replacement proportions, generally under 20%, have been utilized [23].

This paper presents both experimental and numerical investigations on the flexural behavior of conventional and rubberized concrete reinforced beams. The parameters of the research included the percentage replacement, 40%, of small coarse aggregates (4–8 mm) by rubber aggregates obtained from discarded tires and the change in the longitudinal reinforcement ratio (0.5%, 1%, and 1.5%). The numerical models were developed using the ATENA v5 Finite Element Analysis (FEA) software [24]. The results indicated that even though the longitudinal reinforcement yielded, the ultimate failure mechanism of RC beams corresponded to the crushing of concrete in the compression zone for both conventional and rubberized concrete types of elements. The beams made of rubberized concrete were more ductile than their reference counterparts, and the ductility decreased with an increase in the longitudinal reinforcement ratio, irrespective of the type of concrete. The numerical and experimental results were in good agreement with one another in terms of peak loads and ductility.

2. Materials and Methods

2.1. Materials

A commercially available CEM I 42.5R-type cement was utilized. The selection of the cement type was based on the requirement for high early-age compressive strength. Rounded-edge river aggregates were utilized as natural aggregates. The rounded edges mitigate stress concentrations and inhibit the onset of early-stage cracking.

The rubber aggregates came from a local supplier and were obtained from shredding of commercial vehicle tires [25]. The resulting rubber aggregates had a rougher surface, as shown in Figure 1. They were sorted based on their maximum grain size and cleaned of impurities, steel bits, and textile fibers resulting from the shredding process, before they were delivered in bulk. The rubber aggregates would replace the small coarse aggregates (4–8 mm) at a rate of 40% by volume [23,26].



Figure 1. Rubber aggregates.

As with previous studies [2], the target compressive strength of concrete was C30/37 [27]. Based on the laboratory tests, a C30/37 concrete would be the most economical solution that would lead to a desired compressive strength of at least 20 MPa at the standard age of 28 days for rubberized concrete. The concrete mix proportions, shown in Table 1, were ordered from a local batching plant. For each type of concrete, conventional and rubberized concrete (RuC), a set of 15 cylindrical specimens (100 mm × 200 mm;

diameter $\times$ height) were cast to assess the mechanical properties at the standard age of 28 days.

Table 1. Mix proportions of conventional (Ref) and rubberized concrete (RuC40).

Concrete	Cement [kg/m ³]	Water [l/m ³]	Superplasticizer [l/m ³]	Sand [kg/m ³]	Coarse Aggregates		
					4–8 mm [kg/m ³]	4–8 mm Rubber [kg/m ³]	8–16 mm [kg/m ³]
Ref	489	198.3	2.4	582	388	-	646.7
RuC40					233	43.4	

The reinforcement used in the concrete beams was of the BST500 type.

2.2. Specimens

The geometrical dimensions of the considered beams are presented in Figure 2. The reinforcement layout is presented in Figure 3, taking into account all considered longitudinal reinforcement ratios (0.5%, 1.0%, and 1.5%). The middle third of the clear span was not provided with stirrups so that only the flexural effect could be considered. Similar reinforcement layouts have been previously reported in the scientific literature [28]. Stirrups were provided in the two shear spans, spaced apart at 10 cm. They were made of low-carbon steel, OB37.

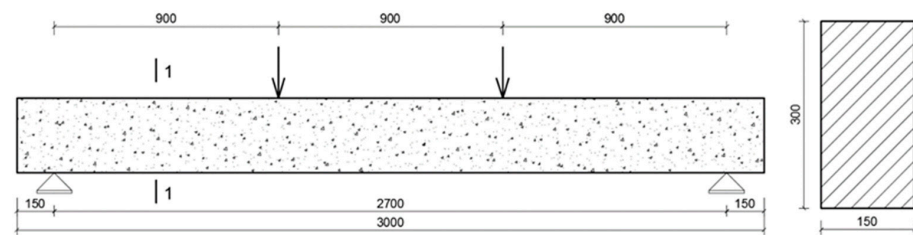


Figure 2. Geometrical dimensions of the reinforced concrete/rubberized concrete beams (dimensions in mm).

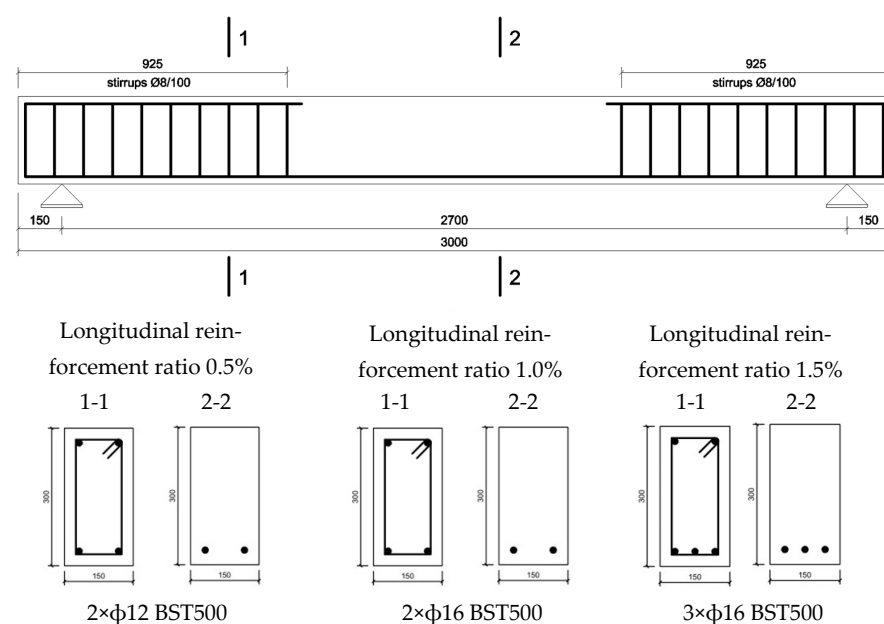


Figure 3. Reinforcement layout of the reinforced concrete/rubberized concrete beams (dimensions in mm).

A 4-point loading test layout was selected to ensure that the midspan of the beams was subjected to pure bending. Similar layouts were also adopted in previous studies [13,15,29,30].

The beams were equipped with linear-variable displacement transducers located on both sides at the top and bottom parts of the midspan section. Additional displacement transducers (resistive type, TR) were located on both sides of the RC beams, at the midspan section, and at the sections where the two loads were applied, as shown in Figure 4. The load was slowly applied at a rate of 2kN/minute so that the development of cracks could be tracked and highlighted in real time with marks corresponding to the load intensity. In order to assess the load-carrying capacity reserve of the beams, the load was applied until they failed by crushing of the concrete, even though the longitudinal reinforcement already yielded [31].

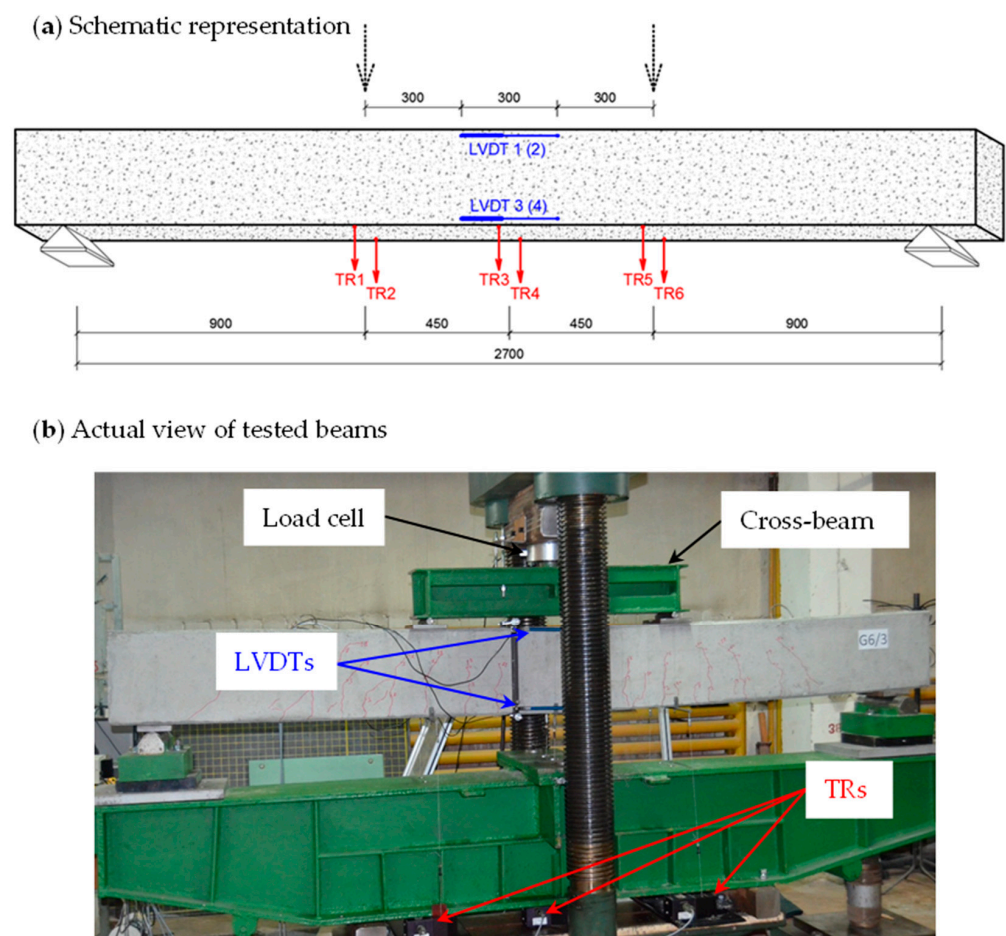


Figure 4. Experimental setup: (a) schematic representation; (b) actual view of tested beams.

Three beams were considered for each concrete mix shown in Table 1 and for each value of the longitudinal reinforcement ratio, for a total of 18 specimens.

2.3. Numerical Model

The numerical model of the beams was generated using the ATENA FEA program [24]. The material parameters were adopted from the laboratory tests prior to the flexural testing of the RC beams.

Concrete was modeled using 3D CCIsoTetra element, a type of three-dimensional solid isoparametric tetrahedral finite element used for advanced numerical analysis of concrete and reinforced concrete structures. The element had 10 nodes, making it a second-

order element offering higher accuracy, integrated using Gauss integration points. [24]. These elements are frequently used in research and engineering to model the behavior of concrete components, especially when analyzing complex phenomena like cracking and/or crushing [32–34]. The biaxial failure criterion was adopted for concrete, as shown in Figure 5. The parameters required to generate the failure surface were obtained from the laboratory investigations on the stress–strain curves for the two types of concrete [35–37].

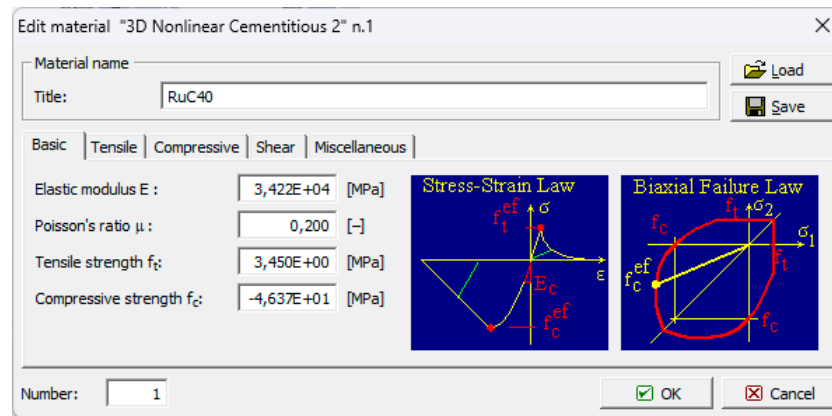


Figure 5. Biaxial failure criterion used for concrete.

The reinforcement was modeled using a CCBBarWithBond [38] type of element, and the behavior considered was the bilinear model with strain hardening. The data required to generate the limits of the two subintervals was obtained from the laboratory investigations [24]. The behavior of longitudinal steel reinforcement was modeled using a bilinear model with strain hardening [24,39]. A bond–slip behavior was adopted for the reinforcement [40], as shown in Figure 6.

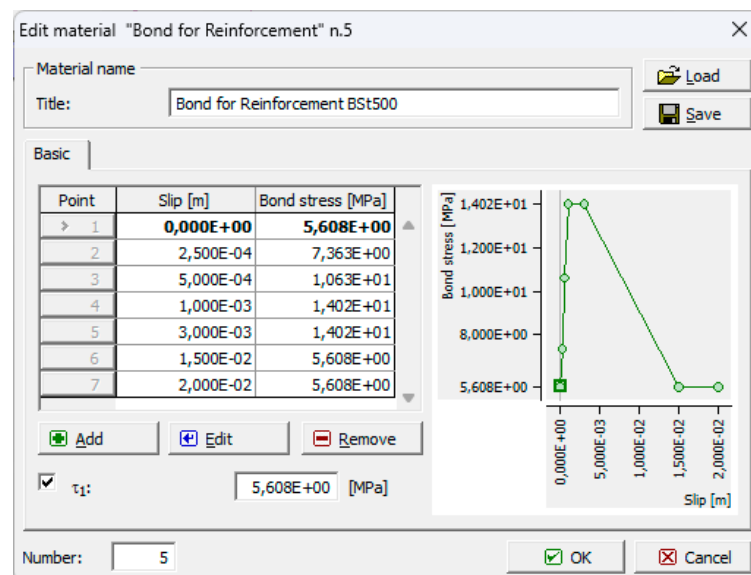


Figure 6. Bond–slip curve.

The mesh size was 4 cm, as shown in Figure 7. A static non-linear analysis was conducted with 2 kN load increments until convergence could no longer be obtained. This was considered the stage when the element failed and coincided with the crushing of concrete.

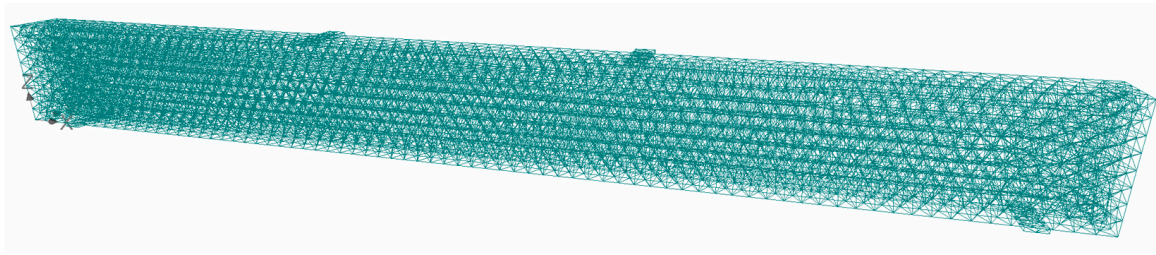


Figure 7. Generated numerical model of RC beams.

3. Results and Discussion

The results are presented below in terms of the material properties and flexural performance of reinforced regular and rubberized concrete beams.

3.1. Material Properties from Laboratory Tests

The stress–strain curve of BST500 steel is presented in Figure 8, whereas Figure 9 shows the stress–strain curves of Ref and RuC40 concrete. The material properties derived from the laboratory tests are summarized in Table 2. The full stress–strain curves for both conventional and rubberized concrete were determined using a patented device to convert a piece of load-controlled testing equipment to a displacement-controlled one [41]. This enables capturing the post-peak behavior of concrete. The test followed the guidelines of SR EN 12390-3 [42] in terms of applied load. The compressive strength of concrete was determined in accordance with SR EN 12390-3 [42], whereas the modulus of elasticity in compression was determined following the specifications of SR EN 12390-13 [43].

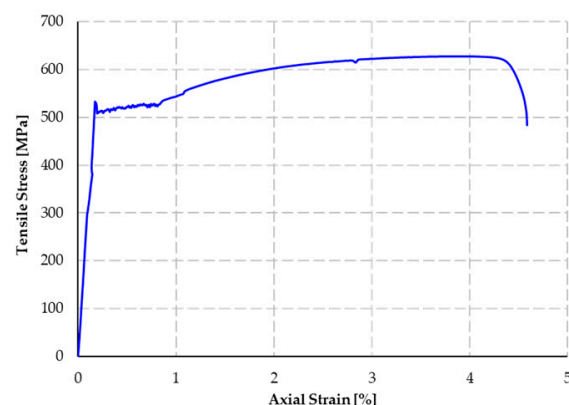


Figure 8. Stress–strain curve of BST500 steel.

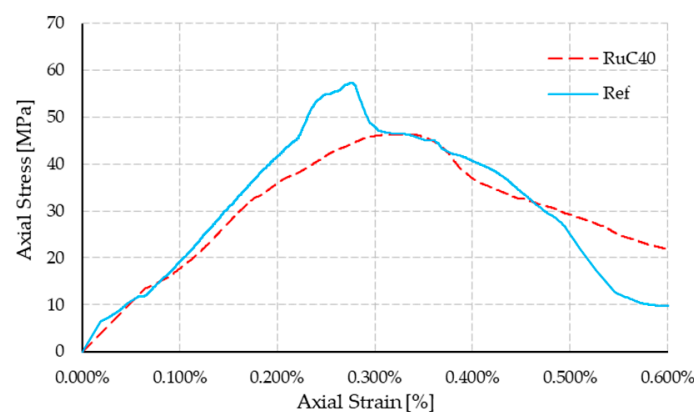


Figure 9. Stress–strain curve of concrete.

Table 2. Material characteristics.

Material	f_y [MPa]	f_u [MPa]	E [GPa]	f_c' [MPa]	E_c [GPa]	$\varepsilon_{cu,exp}$ [‰]	ε_{cu} [44] [‰]
BST500 *	516	620	202	-	-	-	-
Ref **	-	-	-	57.37	37.81	2.8	3.0
RuC40 **	-	-	-	46.37	34.22	3.4	3.5

* Average of 3 determinations. ** Average of 15 determinations.

Where f_y is the yield strength of steel, f_u is the ultimate strength of steel, f_c' is the compressive strength of concrete, $\varepsilon_{cu,exp}$ is the ultimate strain of concrete determined through laboratory tests, ε_{cu} is the ultimate strain of concrete computed according to SR EN 1992-1-1, Table 3.1 [44], and E and E_c are the Young's moduli of steel and concrete, respectively.

It can be observed that even though the concrete strength class was C30/37, the batching plant delivered a much stronger concrete. The material characteristics determined by laboratory tests were used as input data in the numerical model. The values of the ultimate strain, experimentally determined, are lower than the ones mentioned in [44] by 6% and 2.86% for the Ref and RuC40, respectively. A similar trend was also recorded for the moduli of elasticity.

A 40% volumetric replacement of small coarse aggregates by rubber aggregates resulted in a 19.17% (average) decrease in the value of the compressive strength and 9.49% (average) decrease in the value of the modulus of elasticity. Similar decreasing trends were previously reported in the scientific literature [2,3].

3.2. Flexural Performance—Experiments

3.2.1. Force–Midspan Deflection Curves

The force–midspan deflection curves of all specimens are presented in Figure 10. For both types of elements, made of conventional concrete and rubberized concrete, an increase in the longitudinal reinforcement ratio resulted in a higher load-carrying capacity, as well as lower values of the midspan deflection [45–47].

Post-peak softening behavior was observed for the beams made of rubberized concrete with 1% and 1.5% longitudinal reinforcement ratios. This could be explained by the fact that once the longitudinal reinforcement started to yield, the bond between the reinforcement and the surrounding concrete was lost due to significant deformation of the reinforcement. Similar trends were reported in previous research work [48–50].

The obtained values are summarized in Table 3. It can be observed, corroborating with the curves shown in Figure 10, that the flexural behavior is governed by the longitudinal reinforcement ratio and less influenced by the type of concrete, conventional or rubberized concrete.

Substituting small coarse aggregates with rubber particles resulted in decreases of 1.56%, 3.01%, and 5.87% in the values of the peak load (average) for longitudinal reinforcement ratios of 0.5%, 1.0%, and 1.5%, respectively. At the same time, the peak vertical displacement showed a decreasing trend, for both types of concrete mixes, with an increase in the amount of tensile steel. This was due to the increased stiffness of the reinforcement cage.

Substituting natural aggregates with rubber aggregates resulted in slightly higher peak deflections for longitudinal reinforcement ratios of 1.0% and 1.5% compared to the beams made of conventional concrete.

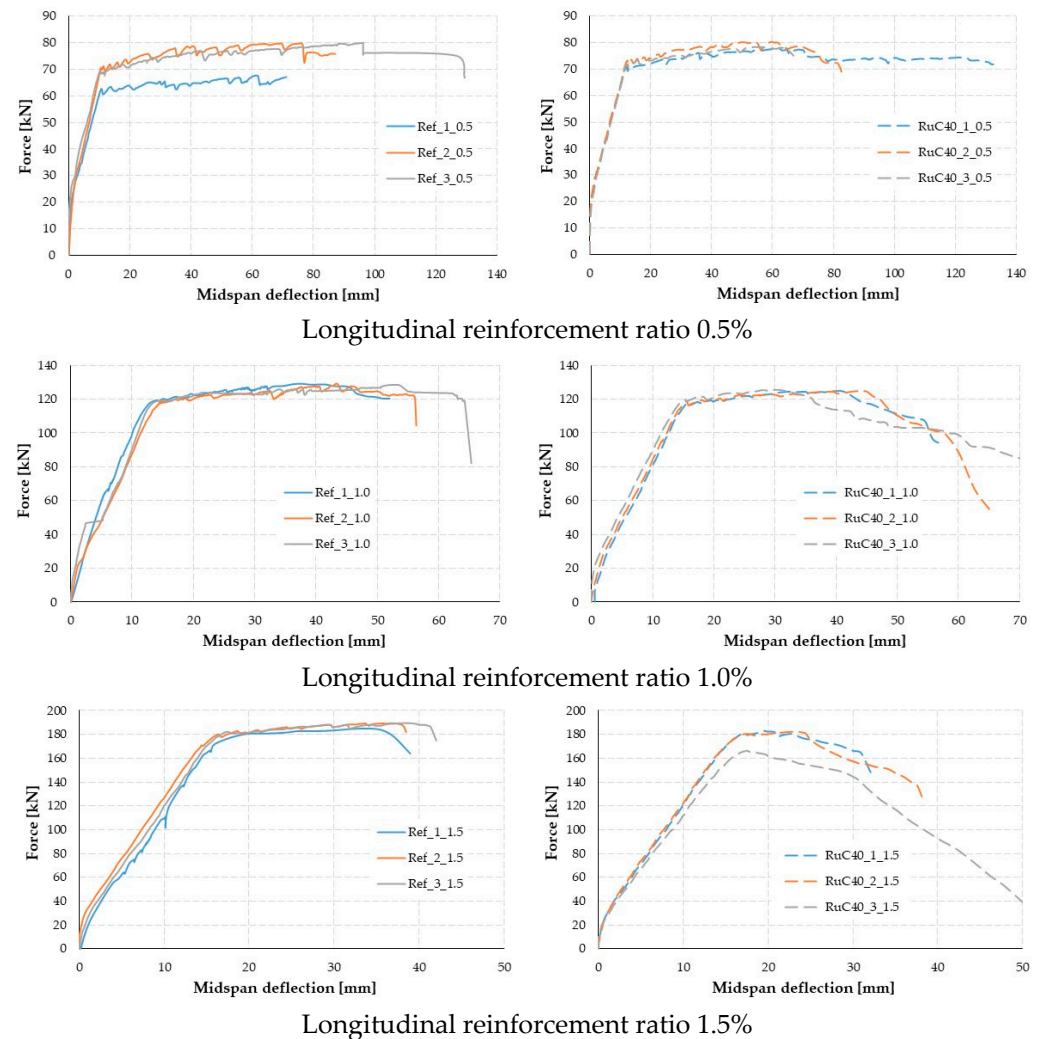


Figure 10. Force–midspan deflection curves for different longitudinal reinforcement ratios: beams made with conventional concrete (continuous line); beams made with rubberized concrete (dashed line).

Table 3. Performance parameters of RC beams.

Longitudinal Reinforcement Ratio	Parameters	Ref	RuC40
0.5%	Fmax [kN]	80.01	78.76
	Deflection [mm]	95.87	94.02
	Bending moment [kNm]	35.69	35.44
	Rotation [radians]	0.019	0.016
1.0%	Fmax [kN]	128.94	125.06
	Deflection [mm]	57.9	66.32
	Bending moment [kNm]	58.02	56.28
	Rotation [radians]	0.0083	0.0062
1.5%	Fmax [kN]	187.99	176.96
	Deflection [mm]	39.82	41.51
	Bending moment [kNm]	84.6	79.63
	Rotation [radians]	0.0039	0.0017

3.2.2. Cracking Patterns

In terms of failure mode, all elements ultimately failed due to the crushing of concrete in the compressed zone. The cracking patterns of the RC beams at failure are presented in

Figure 11 for the beams made of conventional concrete, Ref mix (Table 1), and in Figure 12 for the beams made of rubberized concrete, RuC mix (Table 1). It can be observed that due to the replacement of natural aggregates by rubber particles, the number of cracks increased. Similarly, increasing the longitudinal reinforcement ratio led to more flexural cracks before failure [46], irrespective of whether the beams were made of regular or rubberized concrete [51].

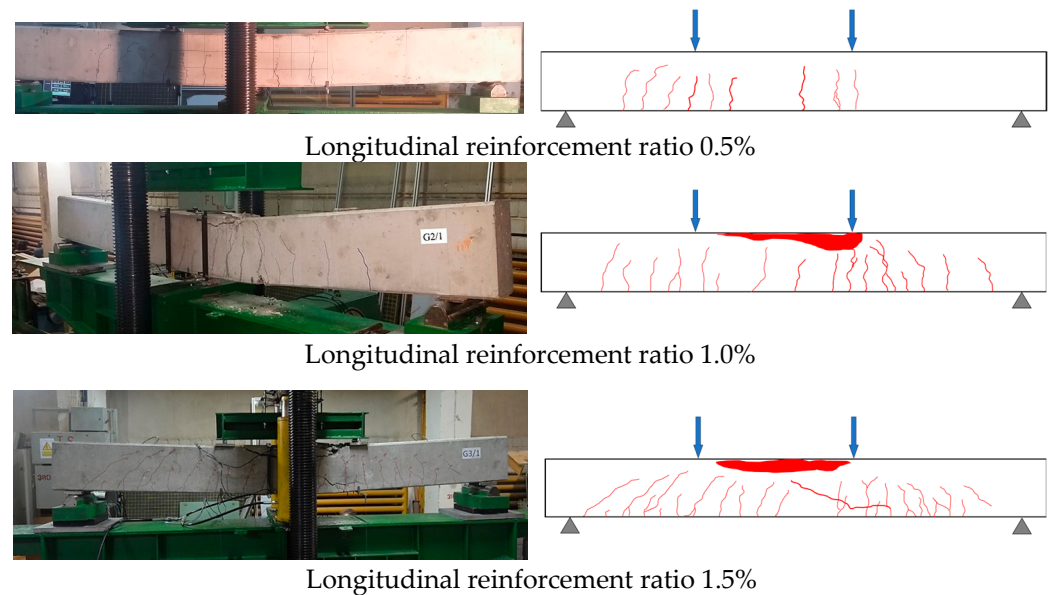


Figure 11. Cracking pattern at failure for different longitudinal reinforcement ratios: beams made of conventional concrete.

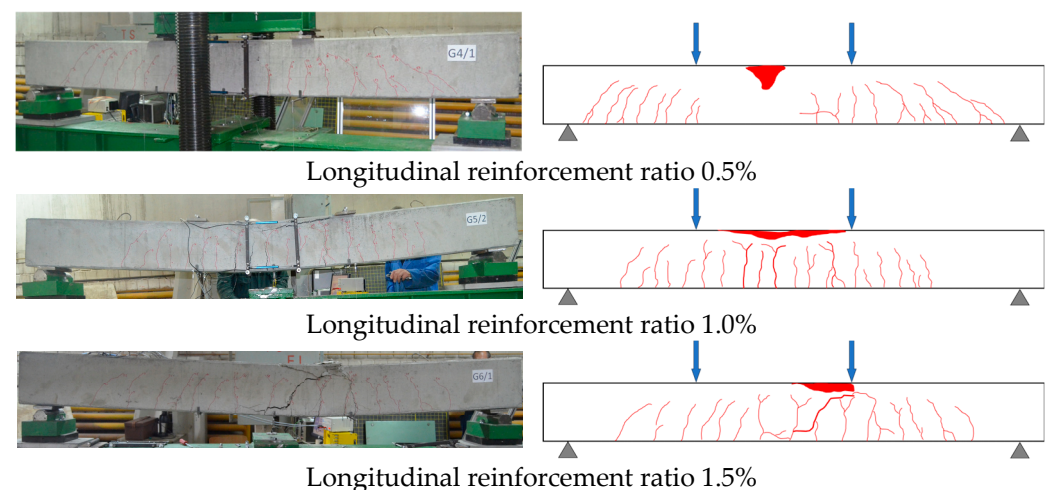


Figure 12. Cracking pattern at failure for different longitudinal reinforcement ratios: beams made of rubberized concrete.

Compared to previously reported results [52,53], the cracking pattern extended well outside the pure bending region of the element and, in some cases, such as the beams made of rubberized concrete with 0.5% and 1.5% longitudinal reinforcement ratios, significant cracks started to develop parallel to the longitudinal reinforcement, suggesting a possible debonding phenomenon. Moreover, in the case of rubberized concrete beams, the cracks were wider compared to conventional concrete beams [54].

3.3. Flexural Performance—Numerical Simulations

The results obtained by means of FE analysis are presented in terms of load–midspan deflection curves, cracking patterns, and ductility coefficients for all three longitudinal reinforcement ratios and the types of concrete.

3.3.1. Force–Midspan Deflection Curves

The force–midspan deflection curves obtained from the numerical simulations using ATEANA v5 FEA software are presented in Figure 13, along with corresponding experimental results. The yielding of the longitudinal reinforcement, prior to the crushing of the concrete and the ultimate failure of the beams, can be observed from both the shape of the force–midspan deflection graphs and the stress level presented in Figure 14.

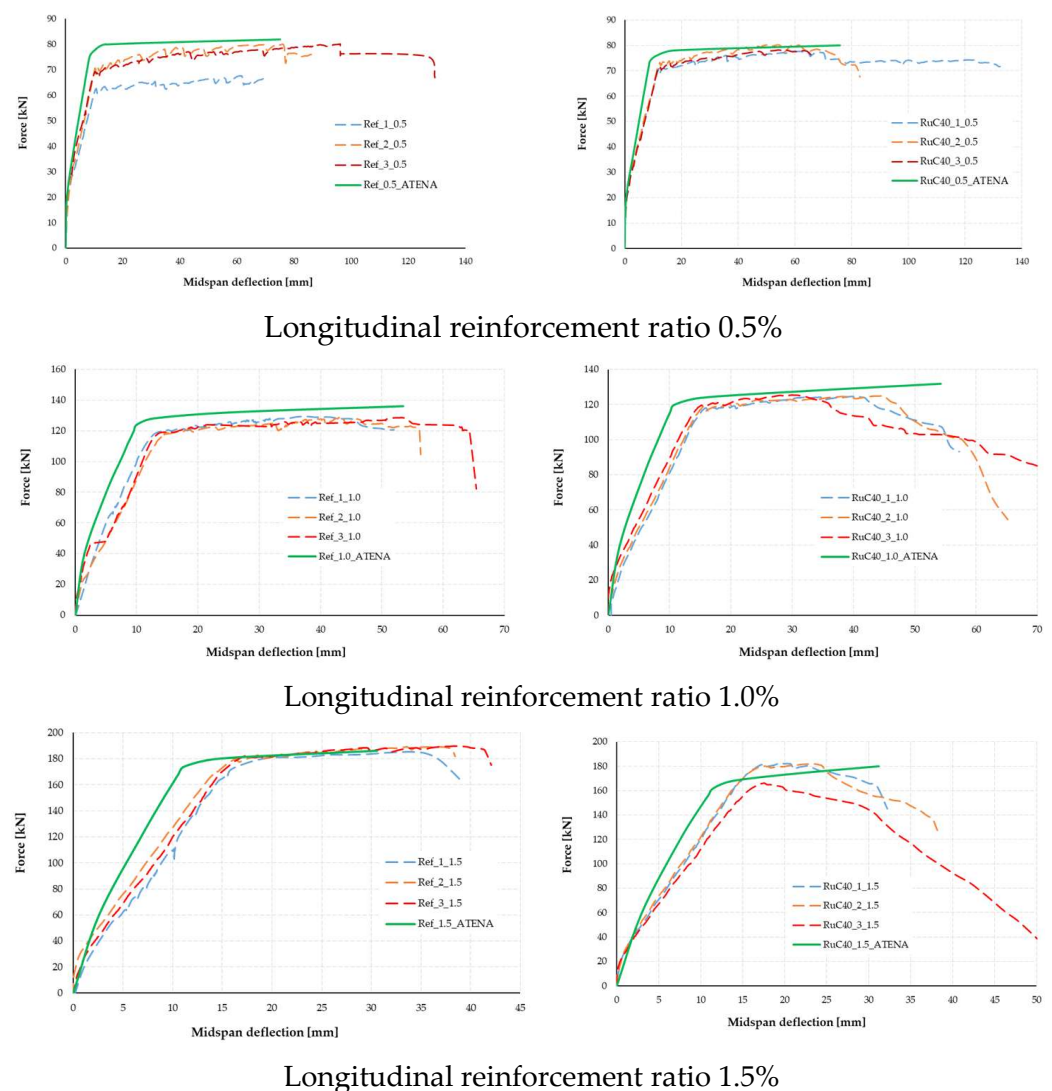


Figure 13. Force–midspan displacement curves using ATEANA v5 FEA software—comparison with experimental data on Ref concrete (left) and rubberized concrete (right).

The results obtained in terms of the peak values of the applied load and the corresponding midspan deflection are presented in Table 4. Table 4 presents the experimental data in terms of the average values of three specimens. However, for the Ref case with a 0.5% longitudinal reinforcement ratio (Figure 10) and the RUC40 case with a 1.5% longitudinal reinforcement ratio (Figure 10), the average of only two specimens was considered, since the third was a clear outlier.

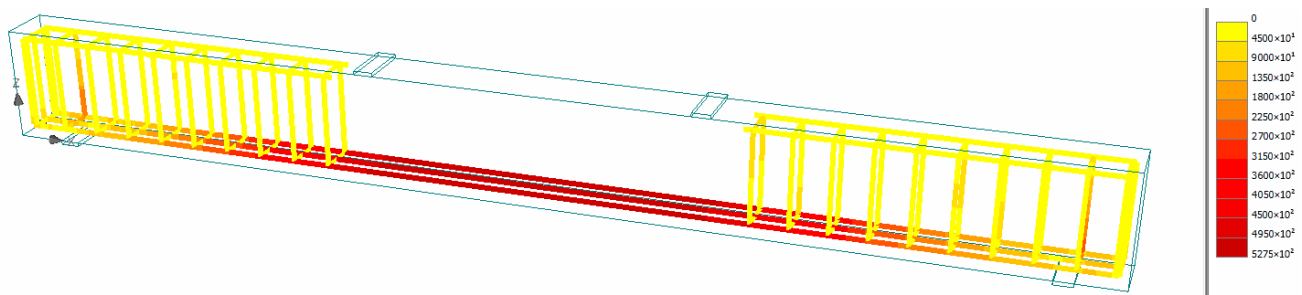


Figure 14. Yielding of the longitudinal reinforcement (ATENA FEA software—1.5% longitudinal reinforcement ratio).

Table 4. Numerical vs. experimental results.

Longitudinal Reinforcement Ratio	Parameters	Ref	StDev	Experiment				ATENA	
				COV	RuC40	StDev	COV	Ref	RuC40
0.5%	Fmax [kN]	80.01	0.08	0.1%	78.76	1.43	1.82%	82.00	80.00
	Deflection [mm]	95.87	1.15	1.19%	94.02	3.69	3.93%	75.20	75.90
1.0%	Fmax [kN]	128.94	0.29	0.22%	125.06	0.36	0.29%	136.00	132.00
	Deflection [mm]	57.90	0.68	1.18%	66.32	0.97	1.46%	53.48	54.20
1.5%	Fmax [kN]	187.99	0.24	0.13%	176.96	0.95	0.54%	186.00	180.00
	Deflection [mm]	39.82	0.19	0.49%	41.51	1.13	2.73%	30.60	31.20

Based on the standard deviation (StDev) and coefficient of variation (COV) values, it can be concluded that there is a good repeatability between the results obtained for both conventional and rubberized concrete elements for all considered longitudinal reinforcement ratios. Concrete is inherently a heterogeneous material and, therefore, it is sometimes difficult to observe trends in terms of statistical results. However, in the case of Ref concrete beams, an increase in the longitudinal reinforcement ratio resulted in a corresponding decrease in the values for StDev and COV when applied to deflection.

It can be observed that in terms of the maximum values of the applied load, both the numerical and experimental (average) results were in good agreement, with an accuracy interval between -5.55 and 1.06% , but the values were generally overestimated by the numerical model.

On the other hand, the corresponding peak deflections were underestimated by the FE analysis, resulting in much stiffer behavior of the beams compared to the experiments. This larger difference may be attributed to the bond behavior model considered in the numerical model compared to the real behavior. From Figure 13, it can be observed that load–deflection curves are generally steeper in the linear-elastic range of material behavior than the tested beams [55]. This could be caused by small geometrical imperfections of the tested beams, small misalignments, and other internal defects that were not accounted for in the numerical model. Such differences between numerically predicted and experimentally observed initial stiffness of reinforced concrete beams have also been documented in earlier studies [55,56].

Moreover, even though bond–slip behavior was considered for the longitudinal reinforcement in the numerical model, the real behavior could not be fully replicated, especially for rubberized concrete beams [49,57,58].

However, the trends observed during the experimental program were also confirmed by the numerical simulations. The peak values of the applied load increased with an increase in the longitudinal reinforcement ratio, whereas the peak deflections showed a decreasing trend.

3.3.2. Cracking Patterns

The cracking patterns obtained from the numerical simulations are shown in Figure 15 for crack openings larger than 0.05 mm. It can be observed that the number of cracks, or the cracked area of concrete, increases with an increase in the longitudinal reinforcement ratio, as well as with the replacement of natural aggregates with rubber particles. However, the distribution of cracks is difficult to grasp, since the computer program highlights every single crack it detects during the loading process, no matter whether micro- or macroscopic, internal or on the surface of the element. During the experiments, microscopic cracks could not be detected. Moreover, any internal cracks that would occur during the loading process would not be visible to the external observer.

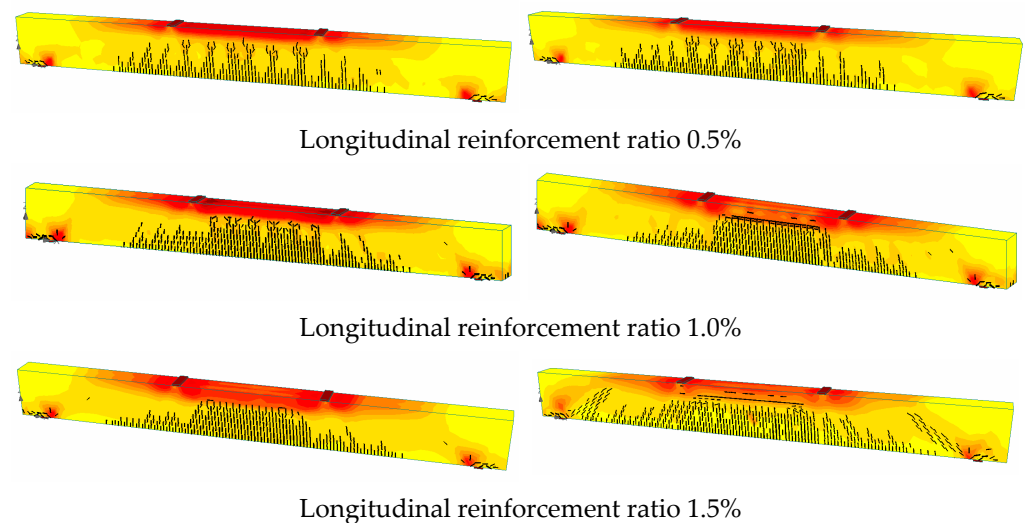


Figure 15. Cracking pattern obtained by means of ATENA FEA software (Ref concrete—**left**, rubberized concrete—**right**)—crack opening > 0.05 mm.

The distribution of cracks matches the orientation of the vertical or inclined cracks observed during the experimental program and shown in Figures 11 and 12. The horizontal cracks, symbolizing the debonding between the longitudinal reinforcement and concrete observed for values of the longitudinal reinforcement ratio of 1.5%, in the case of reference concrete, and 0.5%, in the case of rubberized concrete, could not be obtained from numerical simulations. Since concrete is a highly heterogeneous material, the exact distribution of cracks is difficult to obtain by numerical simulations [56,59]

At the same time, the compressive stress concentrations at the upper part of the beams, between the loading points, confirm the experimental observations and the ultimate failure mode of the RC beams by means of concrete crushing.

3.3.3. Ductility

Ductility denotes the ability of a member to sustain inelastic deformation with no marked reduction in load-carrying capacity up to failure. This parameter plays a fundamental role in quantifying the energy absorption capacity of beams and in assessing the available structural safety margin [60]. A frequently used approach to assess the ductility of beams is the displacement ductility, defined as the ratio of midspan deflection corresponding to the ultimate load to the midspan deflection corresponding to the onset of yielding [53]. The values of the displacement ductility coefficient are summarized in Table 5.

Table 5. Ductility of RC beams.

Longitudinal Reinforcement Ratio	Experiment		ATENA	
	Ref	RuC40	Ref	RuC40
0.5%	7.26	8.32	7.17	8.87
1.0%	4.00	4.31	4.21	5.03
1.5%	2.43	2.16	2.73	2.71

It can be observed that, despite significantly underestimating the midspan deflection at ultimate state, the numerical model manages to capture the ductility of beams quite well compared to the experimental values. In both scenarios, the ductility coefficient for RuC40 beams is larger than that for Ref beams for longitudinal reinforcement ratio values of 0.5 and 1.0. On the other hand, a reversal can be observed when the longitudinal reinforcement ratio increases to 1.5

4. Conclusions

This paper presents the results of research work on the flexural behavior of reinforced concrete beams made of rubberized concrete with different longitudinal reinforcement ratio values. Both numerical and laboratory tests were conducted. The findings have practical implications in terms of using rubber aggregates from discarded tires as a potential replacement for small coarse natural aggregates. However, the current study has its limitations in terms of natural aggregate replacement percentages, as well as the type of natural aggregates to be replaced by rubber crumbs.

Based on the results obtained, the following conclusions are drawn:

1. Substituting small coarse aggregates (4–8 mm) with rubber aggregates obtained from discarded tires, at a 40% volume replacement, results in a decrease in the value of the compressive strength, 19.17% (average), and an increase in the value of the peak compressive strain, 21.43% (average).
2. An increase in the value of the longitudinal reinforcement ratio results in an increase in the load-carrying capacity of both regular and rubberized concrete beams. On the other hand, the midspan deflection decreases with an increase in the longitudinal reinforcement ratio. A similar decreasing trend is observed for the ductility coefficient.
3. Substituting natural aggregates with rubber particles results in a slight decrease in the load-carrying capacity but an increase in midspan deflection. It can, therefore, be concluded that rubberized concrete beams are more flexible than conventional concrete beams. The increased flexibility is also confirmed by the larger number of cracks exhibited by the rubberized concrete beams before failure, as well as higher values for the ductility coefficient for longitudinal reinforcement ratios less than 1.0.
4. Numerical simulations using ATENA software are able to capture the load-carrying capacity of both conventional and rubberized RC beams, with a slight overestimation of the experimental results by as much as 5.55%. On the other hand, the maximum deflection is highly underestimated by the numerical model. This requires further investigations on the bond characteristics between the reinforcement and both regular and rubberized concrete.
5. All beams ultimately fail by the crushing of concrete at the top of the RC beams in the pure bending section of the beams. The experimentally observed failure patterns are also confirmed by numerical simulations, as highlighted by both cracking patterns and stress distributions.

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