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Structural Behavior of Reinforced Concrete Beams Containing Nanomaterials Subjected to Monotonic and Cyclic Loadings

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Abstract: The use of nanomaterials improves the performance of reinforced concrete (RC) beams in terms of cracking load, failure load, and deflection. To further evaluate this improvement, the behavior of RC beams subjected to cyclic loading has to be experimentally investigated. In the present study, the effect of adding nanomaterials to RC beams was studied experimentally under monotonic and cyclic loadings. Eight RC beams with the dimensions of 2200 mm × 350 mm × 120 mm were prepared and divided into two groups. Both groups were tested under three-point bending, but one group was tested monotonously whereas the other group was tested cyclically. Each group consisted of four beams. The first beam in each group was tested without adding any nanomaterials. Nanotitanium, nanoaluminum, and nanosilica were added to the concrete mixes of the remaining three to replace 1% of the cement content. The performances of the tested beams were compared in terms of load-deflection curves, failure mode, cracking load, failure load, bending stiffness, toughness, and residual strength ratio (RSR). The results from both monotonic and cyclic loadings indicated better performances when nanotitanium was used.

Keywords: reinforced concrete; nanoconcrete; nanosilica; nanoaluminum; nanotitanium; monotonic loading; cycling loading

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1. Introduction

Nanotechnologies are related to several areas, including design, characterization, manufacture, and use in structures, devices, and systems. This is realized through the firm control of nanoscale dimensions. Nanotechnology involves new approaches for researching and enhancing material behavior, as well as for designing and creating nanoparticles, which are liquids, powders, or solids with particle sizes ranging from 1 to 100 nm [1].

It is typically known that the comprehension, control, and rearrangement of matter on the nanoscale scale (i.e., fewer than 100 nanometers) generates materials with essentially novel characteristics and purposes [2]. Nanotechnology has two major methodologies. First is the "top-down" methodology representing the idea that the large structures are decreased in size to the nanoscale while keeping their first properties without atomic-level control. Second is the "bottom-up" methodology, which is also known as "molecular nanotechnology" and has been presented by Drexler et al. [3], representing the idea that materials are designed from atoms through an assembly process. Although most modern technologies depend on a top-down methodology, molecular nanotechnology has great potential in materials and fabrication, electronics, medicine, energy, the computer processing of data, and biotechnology.

Engineers have used nanotechnology to create a new, multipurpose, cementitious composite with excellent mechanical functions and durability and possibly many new characteristics including low electrical resistance, high ductility, self-healing, and cracking self-control.

Nanotechnology in cement is a progressing field. The components of nanomaterials facilitate the improvement of novel cement admixtures, for instance, innovative plasticizers, superplasticizers, nanoparticles, and nanoreinforcing agents. Hybridization and grafting techniques enable direct alteration to the underlying cementitious materials and structures. Such strategies can be employed efficiently as a bottom-up method to regulate the quality, process, and performance of superior concrete and to supply new materials with high functionalities and intelligent characteristics that are not available at present. To realize the full potential of nanoscale cementitious materials, a number of challenges must be overcome, including the correct dispersion of nanoscale admixtures, scaling up the laboratory indications, their application on a wide scale, and effectively reducing the cost . Hereafter, there is a summary displaying the impacts of adding nanomaterials and the most current advancements in the mixing of hydrated cement. Meanwhile, chemical admixtures, plasticizers, and superplasticizers, which have been largely employed for many years with efficiency and for compact concrete, are beyond the scope of this study and will not be examined further. Recent innovations in their applications are described in [4].

The use of nanomaterials in RC structures has been widely implemented in the last few years to mitigate the problem of low concrete tensile strength. Chalangaran et al. [5] studied the effect of using recycled rubber crumbs in a number of concrete samples. Their results showed that the concrete with recycled rubber crumbs could significantly enhance environmental noise absorption.

Adding materials to the concrete mix to enhance its strength and durability is a non-stop research race. In that race, Mansouri et al. [6] experimentally studied the effect of implementing steel fibers in concrete to enhance its abrasive resistance while others used nanomaterials for enhancing other mechanical properties of concrete. Amin et al. [7] studied the effect of adding different ratios of steel fibers to RC beams with different cross-sectional shapes. Their results revealed an enhancement in the performance of the RC beams. Their results also showed that there was an improvement in the mechanical properties of concrete. The shear behavior was also improved.

Many researchers studied the effect of using different nanomaterials on the mechanical properties of concrete [8–16]. Lotfy and Abdelshakor [17] studied the effect of the addition of nanometakaolin on the flexural behavior of RC beams. Their study showed that when partially replacing cement with nanometakaolin, a notable effect was observed on the cracking load, ultimate load, maximum deflection, and toughness of the tested beams. Mageed [18] found that when adding nanometakaolin at 1% and 2% to RC beams, the ultimate load increased by 40% compared to the control beam. Chalangaran et al. [19] indicated that the optimum use of nanosilica and nanometakaolin additives could decrease the negative effects of using rubber material in the concrete mixture and also enhance the overall workability of the concrete mixture.

Research efforts were performed on the structural flexural behavior of RC beams with different nanosilica proportions as cement partial replacements. Rashmi et al. [20] found that the concrete compressive strength increased by 20% when utilizing 2% nanosilica as the cement replacement ratio. Their study also revealed that RC beams containing nanosilica showed an improvement in the first cracking and ultimate loads and increases in the flexure stiffness at both the cracking and ultimate stages. Jaishankar et al. [21] experimentally studied the effect of changing the percentages of nanosilica on the flexural behavior of RC beams. Their results confirmed the benefits of adding such an additive, showing high flexural performance, higher failure load capacity, and improved ductility. Their results also showed a reduction in the concrete cracking characteristics such as crack width and intensity.

Silva et al. [22] studied the shear and flexural behaviors of sixteen RC beams when using nanosilica and nanoaluminum as cement partial replacements. Their results showed that adding nanoparticles to the concrete mixes can lead to increases in both bending and shear strengths. They also found that the effect of nanoparticles is altered by the amount of cement adopted in the mixture. The effect of using nanosilica, nanotitanium dioxide, and nanoaluminum with or without steel fibers on the mechanical properties of concrete was studied by Sahar [23]. The results showed that the concrete compressive strength was noticeably improved by increasing the percentage of nanosilica. The maximum strength was found with 3% of nanosilica and 1% of nanotitanium dioxide and nanoaluminum.

Most of the literature on the effects of implementing nanomaterials in RC beams is related only to monotonic loading and there is a lack of studies on its effect under cyclic loading. Moreover, a comprehensive comparison of using different types of nanomaterials with respect to the toughness, bending stiffness, and residual strength ratio is still missing. In this paper, four RC beams were tested monotonously; one of them was taken as a control beam, whereas nanotitanium, nanosilica, and nanoaluminum were added to the concrete mixes of the remaining three to replace 1% of the cement content. The cyclic performance of four similar beams was then examined. A comprehensive comparative experimental analysis was performed by considering a number of parameters including load-deflection curves, failure mode, cracking load, failure load, bending stiffness, toughness, and residual strength ratio (RSR). Details about the conducted experimental investigations are given in the following sections.

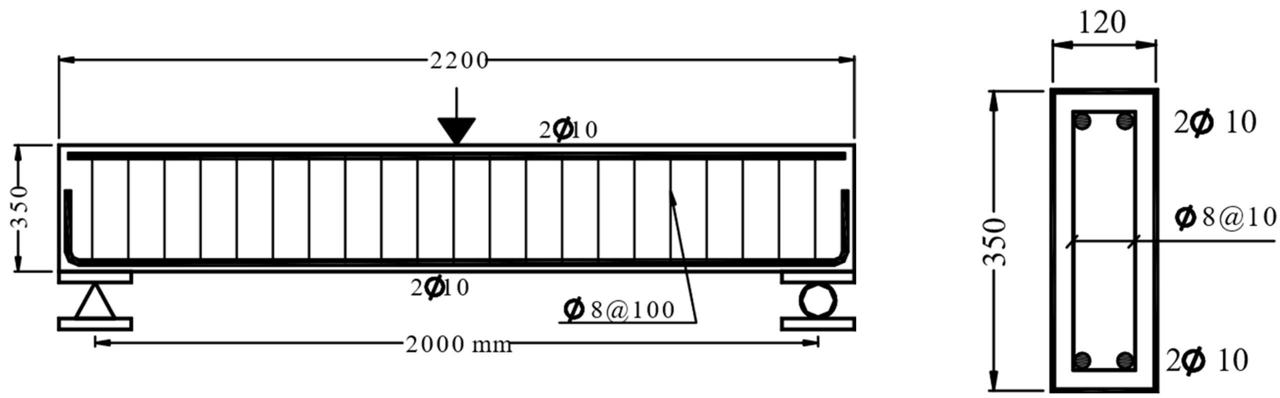
2. Experimental Program

Eight 2000 mm long concrete beams with a cross-section of 120 mm by 350 mm were prepared. The first beam (B1) was the control beam without the addition of any nanomaterials. Nanotitanium, nanoaluminum, and nanosilica were added to the concrete mix of beams, named as B2, B3, and B4, respectively, to replace 1% of the cement content. Beams B1—B4 were tested monotonously. Four similar beams, B5–B8, were then tested under cyclic loading. The elevation and cross-section of the tested beams are illustrated in Figure 1. The concrete mix contained coarse aggregates consisting of crushed dolomite with a nominal maximum size of 9.5 mm to comply with ASTM grading. The fine aggregates consisted of clean and harsh desert sand, silt, loam, clay, and organic compounds, in addition to locally manufactured Portland cement and tap water.

Titanium Dioxide Nanoparticles (NT-TiO_2-NP), Aluminum Oxide Nanoparticles (NT-Al_2O_3-NP), and Silicon Dioxide Nanoparticles (NT-SiO_2-NP) were obtained from Nanotech Egypt for Photo Electronics. The properties of the nanomaterials are listed in Table 1.

The cement and nanomaterials were mechanically mixed with other components, i.e., coarse and fine aggregates, to guarantee the homogeneity of the concrete mixtures. The mixing process was carried out in accordance with the specifications from the product datasheet available on the supplier’s website [24].

The material quantities were determined in accordance with the ACI standard 318-18 [25]. Four concrete mixtures (M1–M4) were prepared, which were compatible with beams B1—B4. The water-cement ratio (water/cement) was controlled at 0.50. The cementitious content (cement + Nanomaterials) was maintained at 350 kg/m^3. The concrete mixture proportions are provided in Table 2. Each concrete beam was cast from one batch. The concrete mechanical properties are listed in Table 3. The concrete compressive strength was evaluated using twenty-four 150 mm cubes while the splitting tensile strengths were obtained using twenty-four 150 mm dia. and 300 mm high cylinders. The yield strengths for the longitudinal and transverse reinforcements were 400 MPa and 280 MPa, respectively. According to ECP 203 [26], reinforced concrete beams were designed to fail due to flexure characteristics other than shear.



(**a**) (**b**)

Figure 1. (**a**) Beam elevation; (**b**) Beam cross-section.

Table 1. Nanomaterials properties [24].

Nanomaterial	Properties			
	Color	Solubility	Avg. Size	Form
Nanotitanium	White	Water/Ethanol dispersion	50 ± 5 nm	Quasi-spherical form
Nanoaluminum			6 ± 2.5 nm	Spherical shape
Nanosilica			35 ± 5 nm	Nearly spherical

Table 2. Mix proportions and beams numbers.

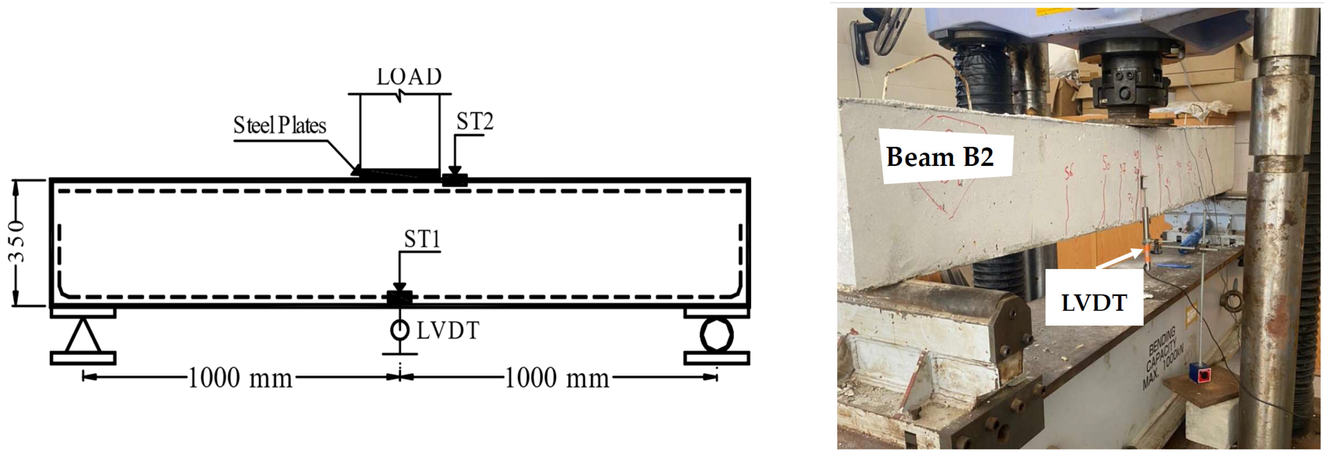
Concrete Mix No.	Beam No.	Mix Proportions (kg/m³)						
		Cement	Coarse Agg	Fine Agg	Water	Nanomaterial		
						TiO_2	SiO_2	Al_2O_3
M1	B1, B5	350	1271	635.7	175	----	----	----
M2	B2, B6	350	1271	635.7	175	3.5	----	----
M3	B3, B7	350	1271	635.7	175	----	3.5	----
M4	B4, B8	350	1271	635.7	175	----	----	3.5

Table 3. Mechanical properties of the concrete specimens with different mixtures.

Mix Code.	Compressive Strength (N/mm^2)	Tensile Strength (N/mm^2)
M1	67.95	4.79
M2	75.92	5.23
M3	74.15	5.15
M4	72.81	5.11

3. Test Procedure

The experimental flexural tests were conducted under three-point bending as shown in Figure 2. One LVDT located at the mid-span of the beams measured the vertical deflection. Two strain gauges, ST1 and ST2, were also attached at the mid-span section of the beams to monitor the steel tensile strains and concrete compressive strains, respectively.



(**a**) (**b**)

Figure 2. Test setup (**a**) Schematic; (**b**) Photo.

3.1. Monotonic Loading Tests

As previously discussed in Section 2, four beams (B1–B4) were tested under monotonic loading. In order to perfectly track the behaviors of all tested beams as well as the failure mechanism, displacement-controlled static loading at a rate of 1 mm per minute was applied for all tested beams. During the tests, the instrumentation data were continually acquired using a data-gathering system. The data logger was used to record the testing data, including loads, deflections, tensile strains, and compressive strains. The response parameters considered in the evaluation of the beams were as follows: load-deflection curves, bending stiffness, cracking load, failure load, failure mode, tensile and compressive strains, and toughness.

3.1.1. Load-Deflection Curves, Bending Stiffness, and Failure Mode

Figure 3 shows the load-deflection curves for all beams, with the deflection values calculated based on the LVDT located at the mid-span of the beams. The load-deflection curves demonstrated typical flexural behaviors. The first change in the load-deflection curve slope was noticed when cracking occurred on the concrete. The second change in the load-deflection curve was when the yielding of steel was reached. Yielding caused additional changes in the slopes of the load-deflection curves. The deflections were 34.35 mm, 28.65 mm, 30.45 mm, and 29.70 mm for beams B1, B2, B3, and B4, respectively. The decreases in the deflections were 18%, 12%, and 14% for beams B2, B3 and B4, respectively, compared to the control concrete beam B1. The results show that deflection noticeably decreased when using nanomaterials. The deflection of beam B2 significantly decreased when compared to the control beam B1. It was also shown that the bending stiffness noticeably improved when using nanomaterials. The bending stiffness of beam B2 significantly increased compared to the control beam, B1. All the tested beams failed in the flexural mode. Figure 4 shows the failure modes for all beams.

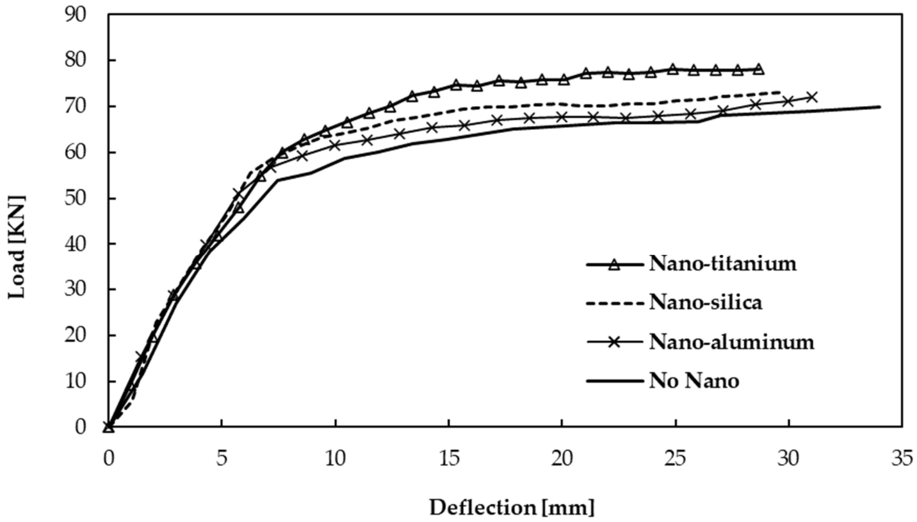


Figure 3. Load deflection curves for all tested beams.

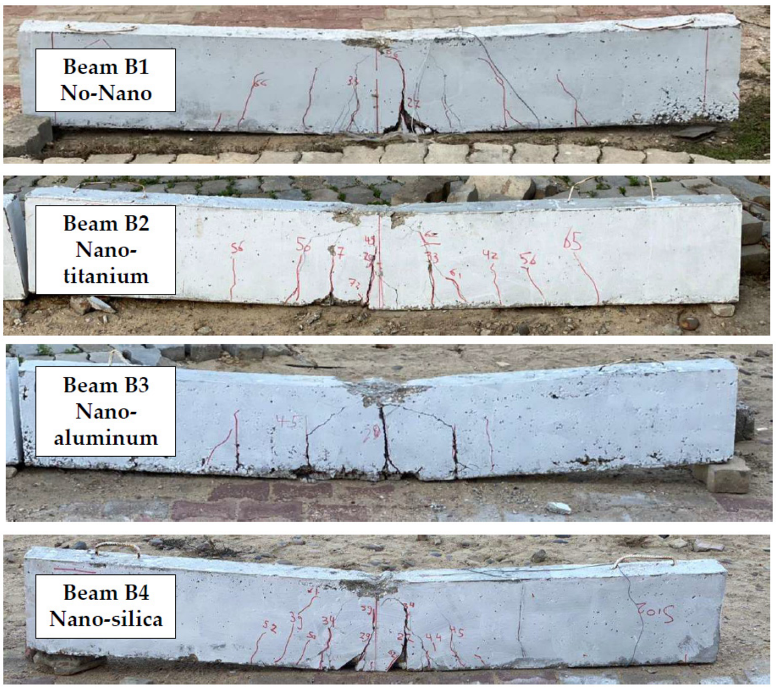


Figure 4. Failure modes of the tested RC beams subjected to monotonic loading.

3.1.2. Cracking and Failure Loads

Table 4 summarizes the cracking and failure loads for all tested beams. The results indicated that using nanomaterials had a noticeable enhancing effect in delaying the time of occurrence of the first cracks. The cracking times were delayed by 13%, 5%, and 9% for beams B2, B3, and B4, respectively, when compared to beam B1.

The results also showed that using nanomaterials increased the load capacity. The increases in the load capacities were 11%, 4%, and 5% for beams B2, B3, and B4, respectively, compared to the control beam B1. This can be attributed to the good bonding characteristics of the nanomaterials. The results also showed that improving the mechanical properties of the concrete mixture played a significant role in increasing the load capacity of RC beams while maintaining the ductile failure mode. It is worth mentioning that nano-titanium had the best performance among all nanomaterial types.

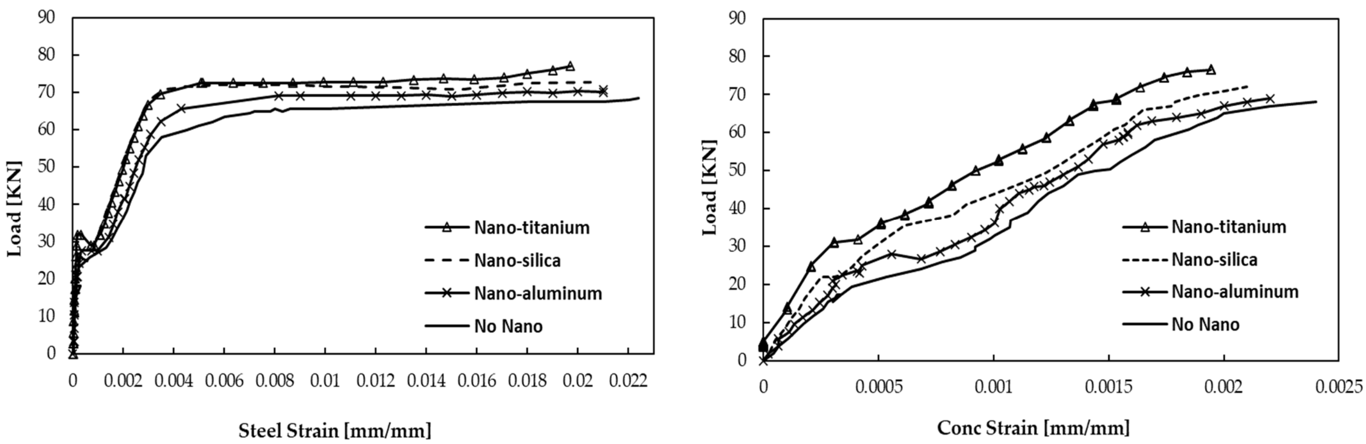
Table 4. Summary of the recorded results under monotonic loading.

Beam No.	Cracking Load (kN)	Failure Load (kN)
B1	23	70.1
B2	26	77.6
B3	24	72.8
B4	25	73.6

3.1.3. Tensile and Compressive Strains

Figure 5 shows the load-strain curves for all beams. Strains were measured at the mid-span section of the beams to monitor the steel tensile strains and concrete compressive strains. The maximum tensile strains reached 0.0224, 0.0197, 0.0210, and 0.0205 for beams B1, B2, B3, and B4, respectively. The maximum tensile strain was decreased by 12%, 6%, and 8% for beams B2, B3, and B4, respectively, when compared to beam B1. On the other hand, the maximum compressive strains reached 0.0024, 0.00185, 0.0022, and 0.0021 for beams B1, B2, B3, and B4, respectively. The maximum compressive strains decreased by 23%, 8%, and 13% for beams B2, B3, and B4, respectively, when compared to beam B1.

Figure 5a shows that all beams had similar behaviors before cracking; however, beam B2 has the highest cracking load. Beams B2 and B4 have approximately the same yield load. Figure 5 also shows that at the same load level, the strain values decreased when using nanomaterials, indicating an increase in the bending stiffness and confirming the results presented in Section 3.1.1. Nanotitanium had the greatest stiffness among all nanomaterial types.



(**a**) (**b**)

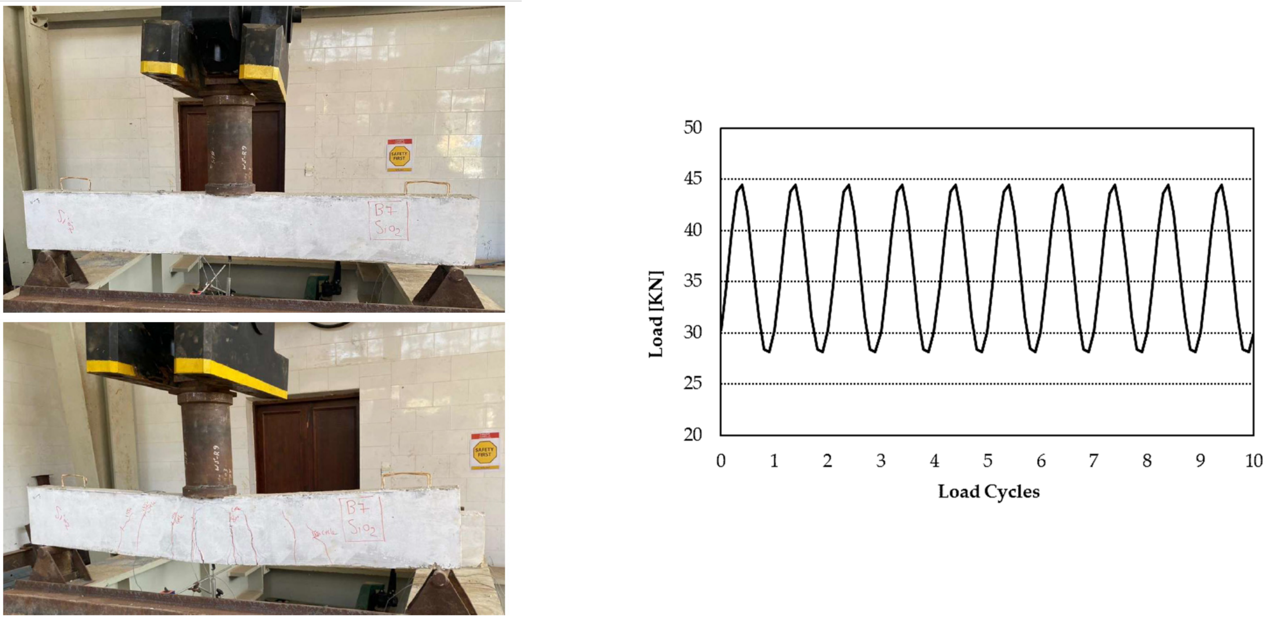
Figure 5. Load strain curves for all tested beams: (**a**) load-tensile steel strain, and (**b**) load-concrete compressive strain.

3.1.4. Flexural Toughness Response

The flexural toughness was determined by calculating the areas under the load-deflection curve. JCI-SF4-84 [27] suggested that the area be calculated to a deflection value of (Span/150). The flexural toughness values in this study were 500.64, 638.68, 559.33, and 596.97 Joules for beams B1, B2, B3, and B4, respectively. The increases in the flexural toughness were 28%, 12%, and 19% for beams B2, B3, and B4, respectively, when compared to the control concrete beam B1. Again, the flexural toughness of beam B2 significantly increased when compared to the control beam B1.

3.2. Cyclic Loading Tests

Four similar beams (B5–B8) were then tested under cyclic loading as previously described in Section 2. A minimum load of 1 kN was applied to each beam prior to the cyclic tests to provide stable contact between the beam and its loading point or supports. The load was applied at a continuous frequency of 2 Hz, as shown in Figure 6a. The selected average cyclic load level was approximately 50% of the failure load previously obtained from the monotonic test shown in Table 4. This average level was chosen to make sure the cracking level was reached in order to better evaluate the use of nanomaterials, especially in the late stages of loading. Cyclic loading, with the lower and upper load levels of 28 kN and 44 kN, was first applied for 300 cycles. Loading over 10 typical cycles is shown in Figure 6b. The beams were then loaded monotonically until failure. The response parameters considered in the evaluation of the beams were load-deflection curves, failure mode, stiffness degradation, tensile and compressive strains, failure load, and residual strength ratio.



(**a**) (**b**)

Figure 6. (**a**) Photo of a beam under the flexural cyclic loading; (**b**) Loading over 10 typical cycles.

3.2.1. Load-Deflection Curves, Bending Stiffness, and Failure Modes

The load-deflection curves for all beams over 10 typical cycles are shown in Figure 7 with the deflection values calculated based on the LVDT located at the mid-span of the beams. The load-deflection curves demonstrated typical flexural behavior. The differences between the maximum and minimum deflections were 0.49, 0.45, 0.47, and 0.46 mm for beams B5, B6, B7, and B8, respectively. The percentage decreases were 8%, 4%, and 6% for beams B6, B7, and B8, respectively, when compared to control beam B5. All the tested beams failed in the flexural mode. Figure 8 represents the failure modes for all beams.

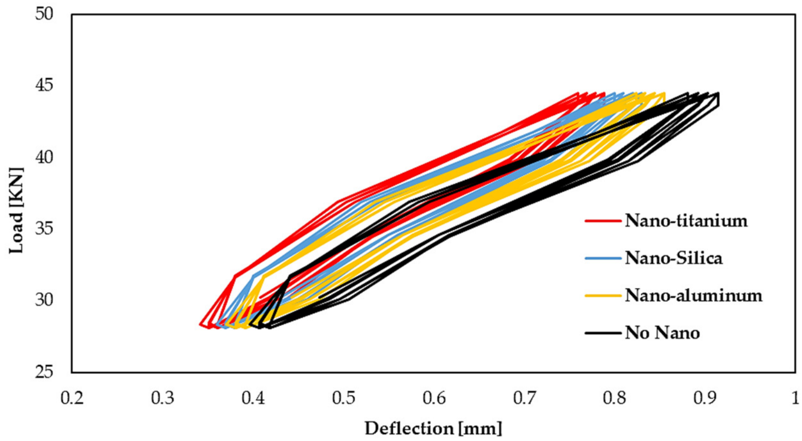


Figure 7. Load-deflection curves for the tested beams.

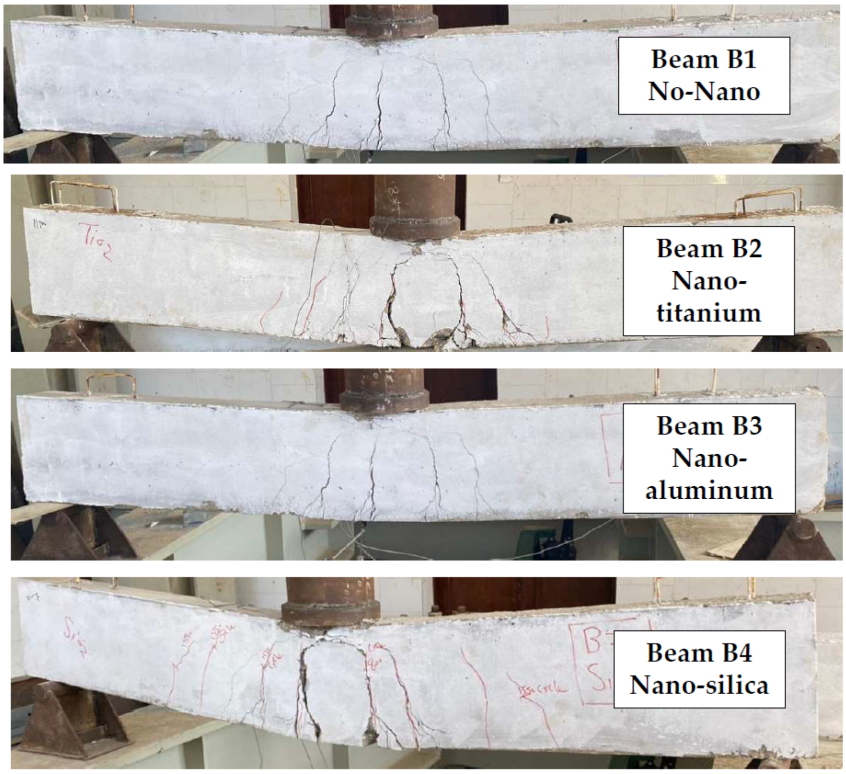
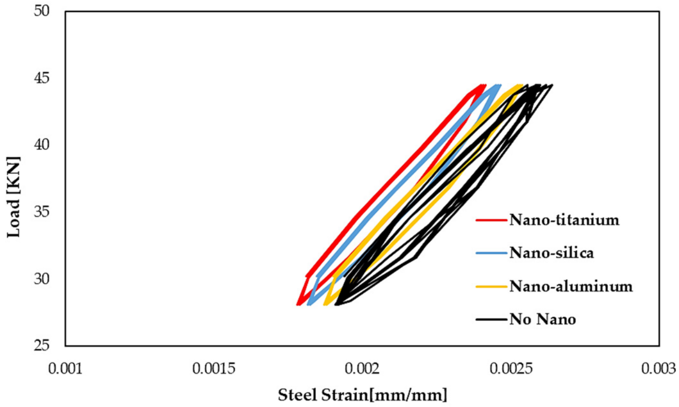


Figure 8. Failure modes for the tested RC beams subjected to cyclic loading.

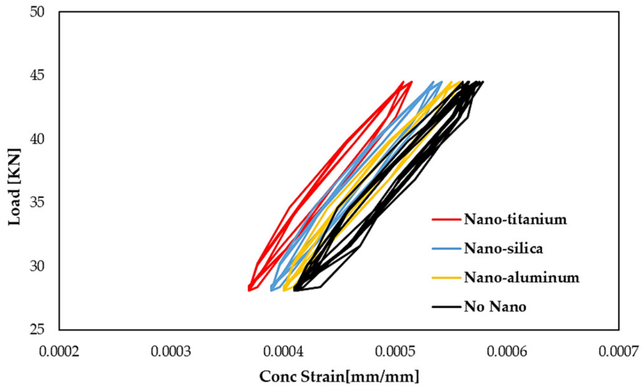
3.2.2. Tensile and Compressive Strains

Figure 9 shows the load-strain curves for all beams over 10 typical cycles. The strains were measured at the mid-span of the beams to monitor the steel tensile strains and concrete compressive strains. The maximum tensile strains reached 0.0058, 0.0052, 0.0055, and 0.0054 for beams B5, B6, B7, and B8, respectively. On the other hand, the maximum compressive strains reached 0.00026, 0.00024, 0.00025, and 0.000245 for beams B5, B6, B7, and B8, respectively.

Figure 9 also illustrates that at the same load level, the strain values decreased when using nanomaterials, indicating an increase in the bending stiffness and confirming the results previously presented in Section 3.2.1. Nanotitanium had the greatest stiffness among all nanomaterial types.



(**a**)



(**b**)

Figure 9. Load-strain curves for all tested beams: (**a**) load-tensile steel strain, and (**b**) load-compressive concrete strain.

3.2.3. Residual Strength Ratio (RSR)

The ratios were 87.30%, 93.50%, 89.80%, and 91.1% for beams B5, B6, B7, and B8, respectively. These results showed that the beams with nanomaterials experienced a higher RSR compared to the control beam, indicating better performance. Table 5 summarizes the failure loads of all beams under both monotonic and cyclic loadings. Moreover, the obtained RSR values are also reported in the table.

Table 5. Failure loads of all tested beams.

Beam No.	Failure Load Under Monotonic Loading (kN)	Failure Load Under Cyclic Loading (kN)	Residual Strength Ratio (RSR)
B5	70.1	61.2	87.30%
B6	77.6	72.5	93.42%
B7	72.8	65.4	89.83%
B8	73.6	67.1	91.16%

4. Conclusions

In this study, an experimental investigation was conducted to explore the monotonic and cyclic behaviors of RC beams before and after adding nanomaterials. A comprehensive analysis was performed by considering many parameters including load-deflection curves, failure mode, cracking load, failure load, bending stiffness, toughness, and the residual strength ratio (RSR). The cyclic test results were found to be compatible with the monotonic test results. Based on the outcome of this study, the following conclusions can be drawn.

The compressive strength was increased by 12%, 7%, and 9% when using nanotitanium, nanoaluminum, and nanosilica to replace 1% of the cement content, respectively, compared to the control beam. On the other hand, the tensile strength was increased by 9%, 6%, and 7%, respectively. This indicates that using nanotitanium produced the optimal mixture, which considerably improved the mechanical properties. Moreover, nanoaluminum and nanosilica had noticeable effects.

Using nanotitanium had a noticeable effect in delaying the occurrence times of the first cracks. It also increased the load capacity while maintaining the ductile failure mode.

The deflections at the mid-span of the beam noticeably decreased when using nanotitanium. It was also shown that the bending stiffness noticeably improved when using nanomaterials.

The maximum tensile and compressive strains decreased when using nanomaterials. At the same load level, the strain values decreased when using nanomaterials, indicating an increase in the bending stiffness. The nanotitanium enhanced concrete beam had the greatest stiffness among all other nanomaterials types.

The flexural toughness of the tested beams also increased when using nanomaterials.

The beams with nanomaterials had a higher residual strength ratio (RSR) compared to the control beam, indicating better performance.

It is worth mentioning that nanotitanium had the best performance among all nanomaterial types. This might be attributed to the fact that titanium dioxide is a semiconductor with excellent photocatalytic properties in addition to photocatalytic sterilizing properties of the surfaces of ultrafine titanium nanoparticles, which make it useful as an additive in construction materials. It also improved the hydration process of cement by improving its internal structure.

The conclusions of this study were limited to the tested beams. Since the use of nanomaterials improved the bending stiffness of the RC beams, it can be used in the rehabilitation of the structural elements. Moreover, the significant effect of using nanomaterials in the RC beams revealed the need to study their behaviors under high strain rate loading in future work. This could include impact and blast loads. Future analytical and experimental studies for investigating the long-term effect of using nanomaterials are also needed. These could include durability tests, corrosion resistance, and chemical resistance.

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