

Article

Flexural Behavior of Concrete Slabs Reinforced with Embedded 3D Steel Trusses

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Abstract

This paper presents a proposal for slabs reinforced with 3D steel reinforcements. Two configurations of 3D steel reinforcement, manually fabricated using 4 mm diameter rods, were investigated: cubic and square pyramid truss lattices. Two control groups were produced: a non-reinforced slab and a linear steel rod-reinforced slab. Three-point bending tests were conducted to assess the flexural behavior of the slabs. The results were analyzed in terms of flexural strength, peak load, mid-span displacement, energy absorption, crack formation, and ductility. The digital image correlation (DIC) technique was employed to capture the full-field principal strain and determine the mid-span displacement at the point of crack initiation. Furthermore, the compression capacity of each slab was evaluated. The results were compared with those of the non-reinforced and linear reinforced slabs, revealing that the slab with the cubic truss lattice configuration exhibited the highest bending moment capacity. While the square pyramid truss slab demonstrated relatively low bending strength, it exhibited exceptional energy absorption characteristics. In terms of ductility, the cubic truss-reinforced slab showed superior performance. When compared to the slabs with linear rod reinforcement, the 3D-reinforced slabs with cubic and square pyramid configurations enhanced the bending strength by approximately 51.19% and 47.32%, respectively. Overall, this study shows that the oblique connectors in the pyramidal reinforcement, compared to the vertical connectors in the cubic reinforcement, provide greater ductility and promote a more uniform distribution of smaller cracks, thereby enhancing energy absorption.

Keywords: reinforced concrete; 3D steel reinforcement; bending test; ductility



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1. Introduction

Reinforcement in concrete structures enhances mechanical performance through methods like geometry and spatial adjustments. In slabs—typically with a single reinforcement layer—recent innovations have introduced quasi-three-dimensional configurations using

materials like carbon fiber and alkali-resistant glass (AR Glass) called tridimensional textile-reinforced concrete (3D TRC). These multilayer systems, with short fibers linking layers, show improved mechanical properties: up to 65% higher compressive strength, 265% flexural strength gains, and peak flexural loads of 4.5 kN using four layers [1]. Other three-dimensional reinforcements include dual-layer textile systems of carbon fiber and AR Glass, achieving flexural load peaks near 3 kN and strength gains up to 25% over 2D systems. Recorded values include energy absorption of 10.65 J and fracture stresses of 8.20 MPa, with no notable changes in tensile strength from pull-out tests [2]. Sasi and Peled [3] evaluated a 3D AR Glass–aramid fabric system treated with epoxy, finding flexural strength doubled, with modulus of rupture (MOR) values reaching up to 26 MPa. Additionally, a significant reduction in delamination and the propagation of large cracks was observed—factors that contribute to mitigating sudden structural failure. Their subsequent study [4] compared perpendicular and oblique connectors, reporting 87% higher flexural strength and 68% more toughness with angled connectors. Mishra et al. [5] studied polypropylene 3D mesh, showing better compressive strength with oblique fibers (3856 MPa vs. 3562 MPa), greater ductility (52.12% vs. 40.79%), and a higher elastic modulus (1735.2 MPa vs. 1389 MPa). These results highlight the influence of connector orientation on strength, ductility, and toughness. Despite performance benefits over 2D systems [6], 3D TRC faces drawbacks like the exclusion of coarse aggregates—requiring more cement—and high costs for AR Glass, aramid, epoxy, and specialized equipment, limiting practical use.

Others non-TRC systems, like 3D-printed polymer reinforcements (e.g., ABS plastic), have been studied. Katzer et al. [7] developed a hexagonal three-layer structure achieving >6000 N at 1.5 mm deflection (184% increase) and energy dissipation up to 0.373 J. These systems use cement–sand matrices without coarse aggregate. Xu et al. [8,9] evaluated 3D-printed polymer shells, reporting energy dissipation up to 75 J and high ductility. However, their high cost and incompatibility with current standards restrict application. Ultra-fine mortars are also required. To overcome these limitations, Tang et al. [10] proposed spiral polymer reinforcements in concrete columns, demonstrating high ductility and energy absorption and proving that this 3D non-TRC system can be used in potential practical applications.

On the other hand, 3D-printed metallic systems like steel metamaterials offer high energy absorption, ductility, and seismic resistance [11,12] but face barriers like cost and slow production [13]. Ferrocement—mortar reinforced with multilayer steel mesh—has seen real use in architecture and boatbuilding due to its ductility and material efficiency. However, it requires frequent maintenance and is limited to dome forms due to low rigidity. Naaman [14] notes that ferrocement enhances MOR with low reinforcement volume, achieving high strength and ductility. Performance is best when meshes are near the surface, and fibers are added to improve shear and interlaminar strength. These systems, considered quasi-3D, have evolved to include polymeric, textile, or metallic fibers, and even Watson mesh, indicating potential in ferrocement with interlaminar connectors.

So, while there is a substantial body of literature on 3D-shaped reinforcement for slabs, much of it focuses on textile and polymeric structures, as well as 3D-printed concrete. In contrast, the development of metallic reinforcements with 3D shapes has been relatively underexplored, likely due to the challenges associated with modeling, simulating, manufacturing, and testing such materials [15]. Thus, manually manufactured 3D-shaped steel reinforcement for concrete has been rarely reported. For example, in [16], the effect of different continuous reinforcements on the shear behavior of precast beams was studied, considering six reinforcement configurations with supplemental reinforcement on the tension side. The results showed that incorporating reinforcement meshes on the compression side as well significantly improves structural performance compared to configurations that

reinforce only the tension side. Additionally, reinforcements arranged at oblique angles—approximately 60° —provided greater strength than those with connectors placed at 90° . This oblique arrangement also helped significantly reduce delamination, attributed to the increased bond length compared to vertical connectors. Moreover, it was concluded that reducing the spacing between reinforcement layers helps limit crack propagation, thereby enhancing the structural integrity of the element. In [17], slabs with a three-dimensional steel reinforcement configuration were studied. This system consisted of two steel meshes connected by W-shaped stirrups made from bars of varying diameters. When subjected to impact loads, an increase in slab stiffness was observed. However, a reduction in ductility and shear strength was also recorded, attributed to over-reinforcement. This issue was mitigated by using smaller-diameter reinforcements, which allowed for a better balance between stiffness and ductility.

Abdulla and Katab [18] investigated the behavior of a sandwich slab under both impact and static loads. The slab featured an arrangement of concrete shells, an intermediate rubber layer, and connector rods (shear connectors) placed perpendicular to the mesh layers. They found that this configuration significantly affected the dissipation of impact and applied energy needed to initiate the first fractures in the structure, effectively reducing crack propagation. They also observed that the transverse connectors increased both yielding load and toughness. Shaheen et al. [19] and Yerramala et al. [20] investigated 5 cm thick thin slabs with a quasi-three-dimensional configuration, incorporating multilayer steel mesh systems connected by 6 mm diameter spacers. Their findings indicated that while increasing the number of mesh layers enhanced ductility, it also led to a reduction in the ultimate load-bearing capacity. Yang et al. [21] studied railway ties reinforced with a three-dimensional system consisting of two steel fiber meshes combined with basalt fiber-reinforced polymer. This arrangement was arranged in a lattice configuration, forming a pyramidal pattern. The results demonstrated that this configuration is effective in reducing crack propagation, thereby mitigating the risk of sudden failure.

In most of these studies, the reinforcements used are not strictly 3D reinforcements since they consist of multilayer reinforcements without connectors between them. Therefore, non-multilayer 3D steel reinforcements should be further studied to understand their mechanical behavior and explore their potential advantages in applications that demand both high ductility and strength.

The properties and characteristics of 3D metallic and non-metallic reinforcements in concrete structures have been studied using different techniques and approaches. Usually, mechanical properties such as compression or flexural behavior are determined using universal testing machines for destructive tests under a quasi-static load. However, crack-ing detection and crack measurement in concrete and masonry mortars are convenient to perform using optical techniques, such as image monitoring with high-speed cameras for dynamic tests [22] and digital image correlation (DIC) for destructive, nondestructive, or combined tests under dynamic and quasi-static loads, as suggested by [23], especially for the detection of crack initiation and the kinematics of crack propagation in concrete structures [24], as these methods are capable of the detection and measurement of cracks from 0.02 to 0.008 mm in size [25]. As is reported by some authors, DIC can be used as a tool for non-destructive testing in reinforced civil structures such as bridge slabs [26], the mechanical characterization of 3D-printed polymer lattice-reinforced concrete structures [27,28], and the detection of internal damages and structural integrity evaluation.

Given the limited research on the flexural behavior of slabs reinforced with three-dimensional metallic arrangements, this study presents an analysis of two slab prototypes incorporating lattice-truss-based 3D steel reinforcement, especially focusing on the effect of their transverse connectors on their general behavior. The objective is to advance the

understanding and application of 3D steel reinforcements by evaluating key performance indicators, including flexural capacity, crack development, energy absorption, and mid-span displacement, through three-point bending tests. The performance of these slabs is compared to that of non-reinforced samples and those reinforced with linear steel rods. Crack initiation and propagation were monitored using a digital image correlation (DIC) system.

2. Materials and Methods

2.1. Reinforcement Design

According to previous studies [16], the use of shear connectors in reinforcement systems facilitates a more uniform distribution of stresses within structural elements by transferring loads between reinforcement layers. This improves overall structural performance and helps prevent stress concentration. Various connector geometries have been developed, including W-type connectors [17] commonly used in slabs, as well as ring-type [16] and spiral-type [10] connectors, which are more frequently applied in beams and columns, respectively. The resulting three-dimensional configuration of these systems primarily depends on the orientation of the connectors—either perpendicular between layers or arranged obliquely. In slab reinforcement, when the connectors are positioned perpendicularly between layers, a cubic lattice reinforcement can be obtained. In contrast, using oblique connectors orientated at a given angle may result in a reinforcement with a geometry featuring pyramidal lattices. These two 3D geometries are relatively easy to design and to manufacture. In this study, cubic lattice reinforcements (Figure 1a) were manufactured by welding 4 mm diameter longitudinal and transversal rods to form the upper and lower layers. Vertical connectors, each 6 cm in length, were welded to join the vertices of the squares in both layers. For the square pyramidal reinforcement, and to simplify the manufacturing process, zigzag stirrups obtained from 4 mm rods were used (Figure 1b). For this reinforcement configuration, zigzag stirrups were tied to the longitudinal bars using 1.8 mm diameter steel wire. The 3D steel reinforcements are similar to those presented in [21] but are fully constructed from steel and fabricated using a wire-bending tool and welder.

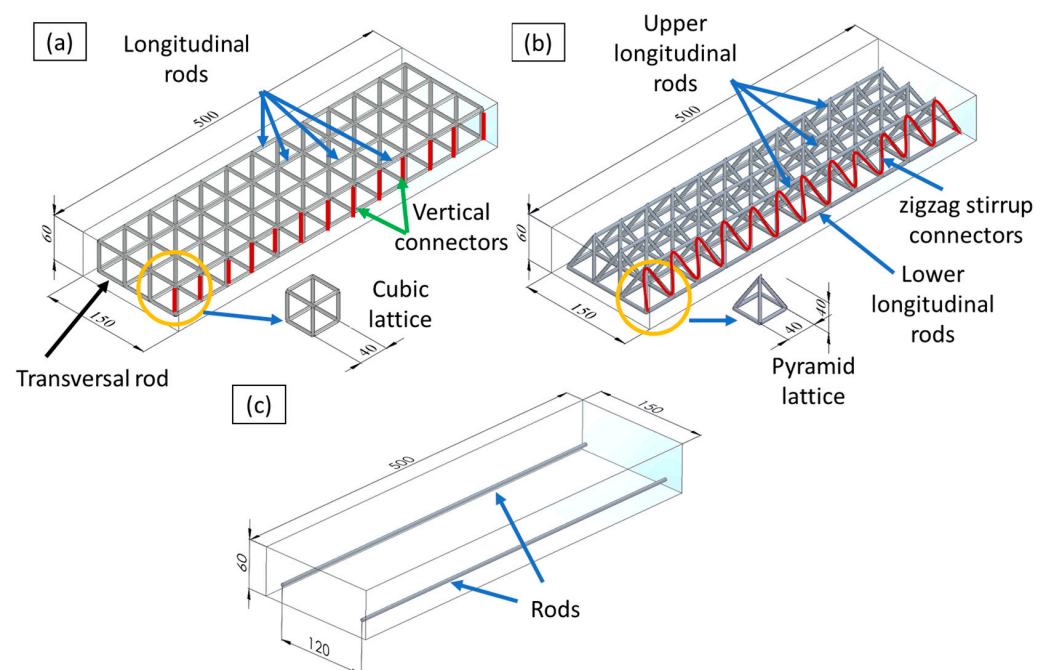


Figure 1. Configuration of the steel reinforcements evaluated: (a) cubic truss lattice, (b) square pyramidal truss lattice and (c) linear rod reinforcements. Dimensions are given in mm.

2.2. Concrete Mixtures and Sample Preparation

The concrete mixtures were formulated according to the ACI-211 [29] regulation for a compression strength of 200 kg/cm², in accordance with the minimum strength requirements for slabs as specified by the ACI 318-19 [30] code for structural concrete. The ingredients and their proportions are reported in Table 1.

Table 1. Ingredients and proportions for concrete mixtures.

Ingredient	Characteristics	Amount
Portland cement	CPC 30 R type (high-rate hydration ratio cement).	16 kg
Water	NA	10 L
Coarse aggregate	Crushed gravel: particle size distribution of 12.7 mm, 2.6–2.8 kg/cm ³ density, 2.0–3.5% water absorption.	34 kg
Fine aggregate	Crushed sand: 100% passing a 4.75 sieve, 2.3–2.6 g/cm ³ density, 1.0–2.5% water absorption, fineness modulus of 2.3–3.1, and particle size distribution < 1 mm.	34 kg
Fiber	Eucomex Fiberstand [®] : 100% monpropylene, specific gravity of 0.91, fiber length of 19 mm, and dosage of 0.4–0.6 kg/m ³ . Useful for preventing delamination, segregation, and cracking formation.	28 g

The compressive strength of the concrete mixture was validated through compression testing on prismatic specimens (cylinders with a diameter of 15 cm and a length of 30 cm), yielding a value of 202.2 kg/cm². The tests were conducted using an ELE International 36-3095/02 compression testing machine (ELE International, Milton Keynes, UK).

The specimens were manufactured using prismatic molds of 500 mm in length, 150 mm in width, and 150 mm in height. The thickness proposed for all the samples was 60 mm. Samples of the same dimension and without reinforcements were manufactured for comparative purposes. The linear steel-reinforced slabs served as the main control group. For easy identification, the following nomenclature was used for the specimens: NRS for non-reinforced slabs, CS for control slabs, QS for cubic truss lattice-reinforced slabs, and SPS for square pyramid truss lattice slabs. For repeat tests, 4 specimens of each configuration were prepared, totaling 16.

The dimensions of the samples and reinforcement rods for the 3D reinforcement slabs were selected based on the methodology outlined in [31], and those for the control slab were in accordance with the American Concrete Institute (ACI) ACI-318-19 [30] guidelines for designing ceiling slab specimens with minimum thickness. It is important to note that the proposed dimensions of the samples, although smaller than those of typical slabs (with a depth of 10 cm and 3/8" rebar), do not represent a downscaling of the structural element but rather reflect a lightweight design approach based on a reduction in slab depth and steel reinforcement ratio. Hence, the reinforcement for the control specimens (those with linear reinforcement) was designed based on the required amount of steel rods. The steel used had a yield strength of 598 MPa, as determined through tensile testing using a Shimadzu AGS-X universal testing machine (Shimadzu, Kyoto, Japan) used for the calculations. For the proposed slab thickness of 60 mm, the minimum required amount of steel rods was determined to be two, spaced 120 mm apart (using also 4 mm diameter rods). Figure 2 shows a photograph of a manufactured specimen.

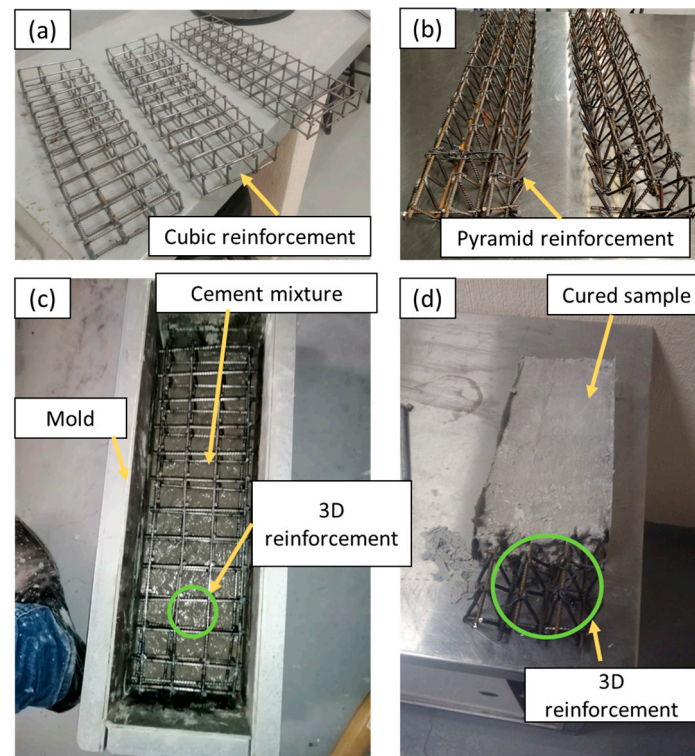


Figure 2. (a) Cubic reinforcement, (b) pyramid reinforcement, (c) manufacturing of the 3D-reinforced samples, (d) a profile showing the embedded 3D reinforcement in a cured sample.

For the linear reinforcement, the two rods were positioned as parallel as possible within the mold during sample fabrication. In contrast, for the 3D-reinforced samples, a 10 mm thick layer was first applied at the bottom of the mold. The reinforcement was then placed in the mold, maintaining a distance of 15 mm from the mold surfaces to allow for easier distribution of the aggregates. The cement mixture was then poured to embed the steel structure. To ensure better bonding between the mixture and the reinforcement, the mold was placed on a concrete vibrating table for 10 s. Given the low weight of the reinforcement and the high density of the mixture, minimal penetration of the reinforcement into the mix was observed. Moreover, aggregates of approximately 10 mm were placed at the bottom of the mold to ensure this cover. After 24 h, the samples were removed from the mold and placed in a curing room with 20% relative humidity and a temperature of 20 °C for 28 days. The key characteristics of each slab are summarized in Table 2.

Table 2. Main characteristic of the slabs tested.

Slab	Slab Weight (kg)	Steel Weight (kg)	Length (mm)	Width (mm)	Thickness (mm)
NRS	8.83	-	500	150	60
CS	9.26	0.10	500	150	60
QS	9.76	1.00	500	150	60
SPS	9.70	1.27	500	150	60

2.3. Three-Point Bending Test

The three-point bending tests were conducted using a Shimadzu universal testing machine with a 10-ton capacity. The testing setup was adapted by securing two supports at the bottom of the machine, consisting of bars with a diameter of 1.5 inches, spaced 350 mm apart (span length). A bar of the same diameter was also used at the point load.

Figure 3 shows the experimental setup. The bending tests were performed at a constant displacement rate of 1 mm/min, following the procedure used by Zahra et al. [28].

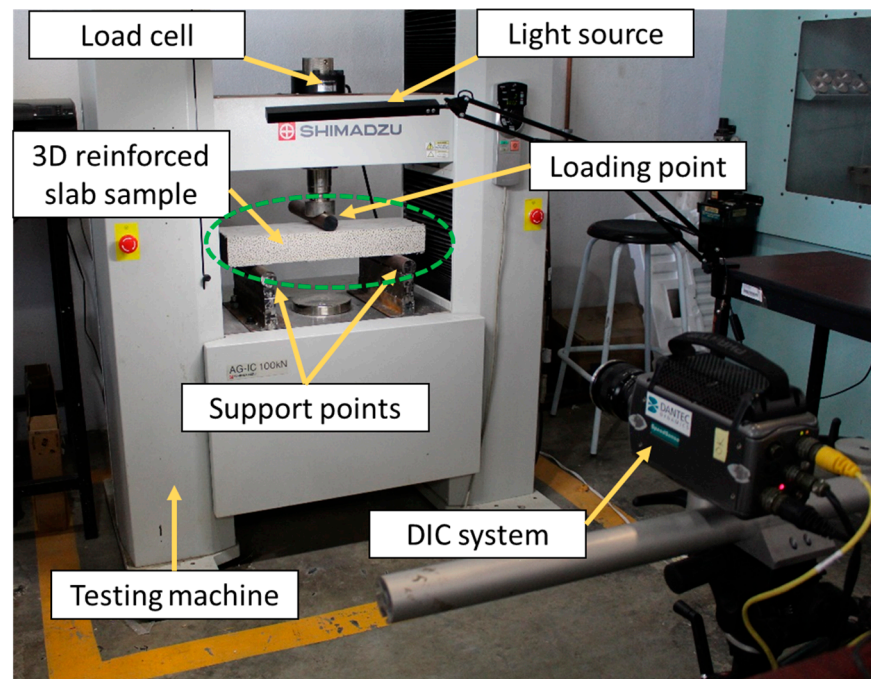


Figure 3. Experimental setup for the bending tests implementing a DIC system.

To evaluate crack initiation and propagation during the bending tests, the DIC technique was employed using the Q-450 system from Dantec Dynamics (Dantec Dynamics, Skovlunde, Denmark), a well-established commercial tool for deformation and strain analysis. The system includes a CCD camera (SpeedSense 9070: Phantom, NJ, USA) with an image resolution of 1280×800 pixels, coupled with a 50 mm f/2 ZF.2 lens. Image acquisition and processing were performed using the ISTR4 4D software (version 4.3.0.45), which was integrated with the DIC system. For the tests, the camera was mounted on a precision tripod and positioned perpendicularly to the sample's surface at a distance of 1.13 m. Since the loading rate was slow, the duration of the tests was relatively long—up to six minutes in some cases. As a result, high-speed image acquisition was not required for this study. The camera was therefore configured to capture images at 10 frames per second (fps), which was sufficient to capture the progression of crack growth. Before the tests, the specimens were coated with random black speckles applied using a pencil to create the speckle patterns necessary for the DIC technique. The speckle pattern had a density distribution of approximately 60%, with an average speckle size of 2 mm. Since the camera lens allows for a wide aperture range, a single light source (LED light bar) was sufficient to obtain good image quality.

In addition to the bending tests, compression tests were conducted to evaluate the compressive capacity of the four types of slabs using a hydraulic compression machine. For these tests, samples measuring 170 mm in length, 150 mm in width, and 60 mm in thickness were used. The average load rate applied was $137 \frac{\text{kg}}{\text{cm}^2} / \text{s}$.

3. Results

3.1. Bending Characteristics

The average load–displacement and bending moment–displacement diagrams of the tested slabs obtained from the bending tests are shown in Figure 4. It can be observed that the highest peak load corresponds to the cubic reinforced slab (QS), whereas the smallest

value corresponds to the non-reinforced slab (NRS). An evident increase in the peak load can be observed in the 3D reinforced slabs compared with the non-reinforced and control slabs (CS). On the other hand, the square pyramid-reinforced slabs exhibited the highest maximum displacement, which represents high ductility, as discussed further.

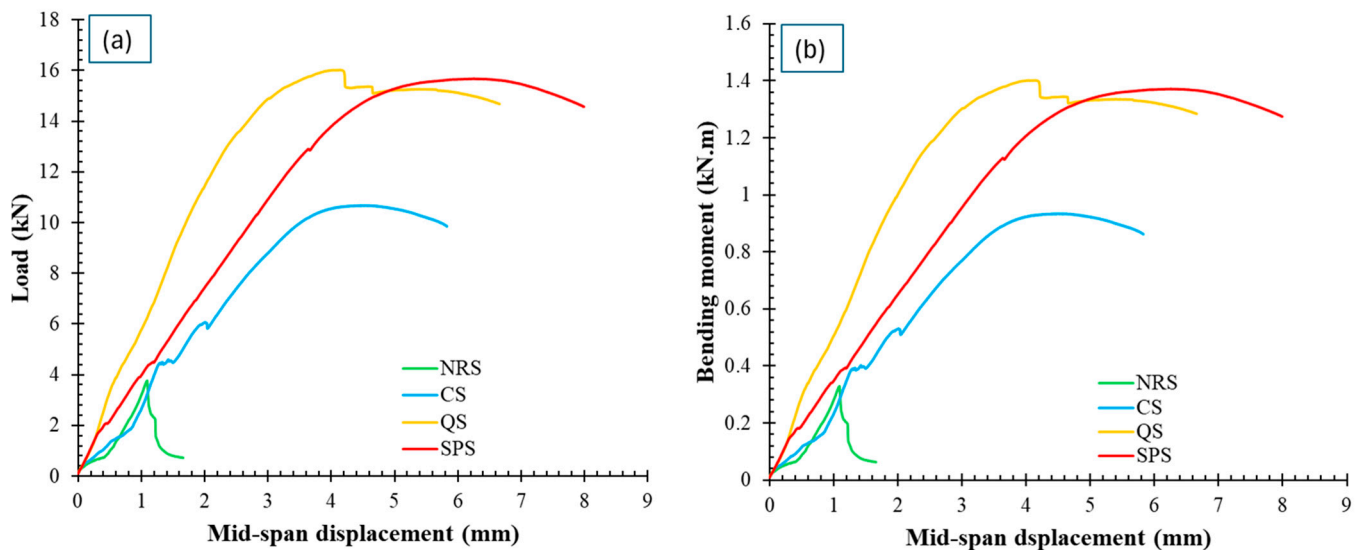


Figure 4. (a) Load–displacement curves and (b) bending moment curves.

The bending properties of the tested samples can be analyzed in terms of moment capacity, displacement of the mid-span, energy absorption, and bending strength. These properties are summarized in Table 3. The values in parentheses represent the coefficients of variance (COVs), calculated from the average and the standard deviation of the repeat tests. For the calculation of the bending moment capacity and bending strength, the classical formulas $PL/4$ and $3PL/2bd^2$ for the three-point bending test were implemented, respectively, where P is the peak load, L is the span length, b is the width, and d is the thickness of the sample.

Table 3. Summary of the results from the bending test.

Slab	Peak Load (kN, COV %)	Ultimate Moment (kN·m)	Maximum Displace- ment (mm)	Energy Absorption (J, COV %)	Bending Strength (MOR) (MPa)
NRS	4.31 (0.87)	0.37	1.34	1.63 (2.67)	3.57
CS	10.69 (13.24)	0.93	6.78	47.93 (8.33)	8.86
QS	16.17 (11.58)	1.41	8.58	96.09 (6.21)	13.39
SPS	15.75 (6.43)	1.37	9.31	101.73 (7.96)	13.05

Overall, the specimens with three-dimensional reinforcement exhibited better performance in several aspects. The first aspect is the maximum (peak) load they can support. As anticipated, the non-reinforced slab exhibited the lowest peak load and bending strength. In comparison, the control slab, which was reinforced with linear steel bars, supported a maximum load of 10.69 kN. This value serves as a reference point for assessing the increase in peak load for slabs reinforced with 3D lattices. The cubic reinforced slab supported a load of 16.17 kN, representing an increase of 51.9% compared to the control slab. In the case of the square pyramid slab, which exhibited a peak load of 15.75 kN, there was an increase of 47.32%. Since the mid-span length was the same for all samples, the increase in bending capacity for the 3D reinforced slabs directly correlates with the rise in peak load. The maximum displacement was defined as the displacement of the mid-span when the

rupture occurred. Notably, the SPS slab displayed the highest maximum displacement, followed by the QS slab.

The energy absorption was calculated by determining the area under the load–displacement curve up to the ultimate point, defined as the load and displacement values when the load decreased by 20% from its peak. This 20% load drop criterion was applied to the load–displacement curves of all tested slabs. Figure 5 presents a graphical comparison of the energy absorption performance of the slabs. The control slab exhibited an energy absorption of 47.93 J, while the cubic reinforced slab absorbed 96.09 J, representing a 100.47% increase. In comparison, the square pyramid-reinforced slab absorbed 101.73 J, showing a 112.24% increase. Thus, if energy absorption is considered a measure of a material's toughness, the SPS slab is the toughest.

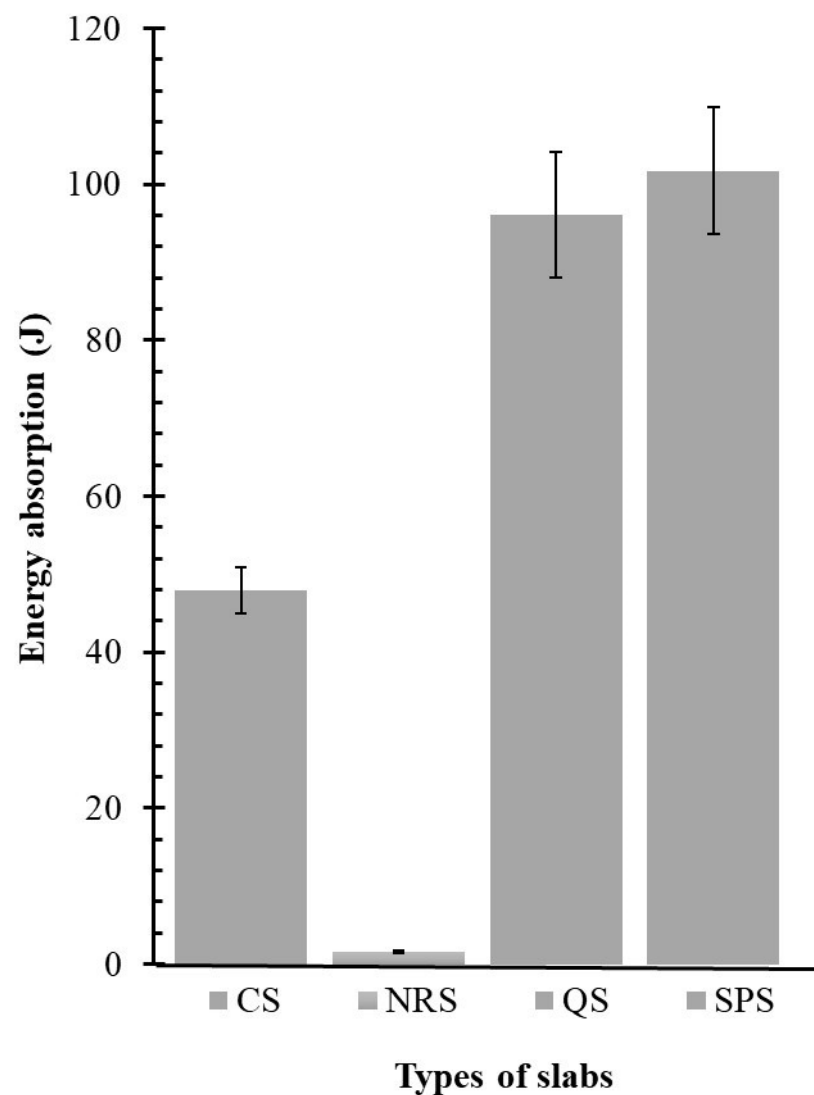


Figure 5. Energy absorption capacity of the tested slabs.

Regarding the bending strength characteristics, as summarized in Table 3, it is evident that the bending strength of the 3D reinforced slabs was significantly higher and quite similar across both configurations, outperforming both the control and non-reinforced slabs. The bending strength of the QS and SPS slabs increased by 58.3% and 59.5%, respectively, compared to the control slab.

The ACI-318 regulation [30] provides a method for calculating the minimum slab thickness and linear metallic reinforcement required for a given load based on the intended

use. However, for experimental slabs, a reduction in thickness may be considered, provided that the proposed metallic reinforcements lead to an improvement in bending strength. In this study, as shown in Table 3, a significant enhancement in the bending behavior of the 3D reinforced slabs was achieved, with only a minimal increase in weight compared to the control slab, as indicated in Table 2.

3.2. Crack Formation Characteristics

The formation and propagation of cracks were evaluated using the principal strain maps generated during the bending tests, which were detected by the DIC system. Since the DIC technique provides full-field in-plane strain or displacement, it allows for the calculation and analysis of principal strain distribution across the region of interest (ROI). For the ROI, a rectangular mask was created over the image of surface of the sample, covering as much of the length span as possible. The definition of the ROI is facilitated by the processing tools available in the ISTR 4D software. Given that cracks cause strain concentrations, the principal strain maps were computed for all images captured during the tests to identify the locations of initial cracks and the corresponding mid-span displacement when they occurred.

Figures 6 and 7 illustrate the locations of crack initiation and propagation in the tested slabs. In Figure 6a,b, a single crack is observed at the mid-span, reflecting the brittle behavior of the non-reinforced concrete. A similar pattern is seen in the control slab (CS) in Figure 6c,d, though two initial cracks are present, indicating a slight improvement in the ductility of the material. In both the NRS and CS samples, crack initiation occurred at nearly the same maximum principal strain values (approximately 45 mm/m). Figure 7 shows that crack propagation in the QS and SPS samples is similar, characterized by multiple cracks, with the initial crack forming at higher magnitudes of maximum principal strains.

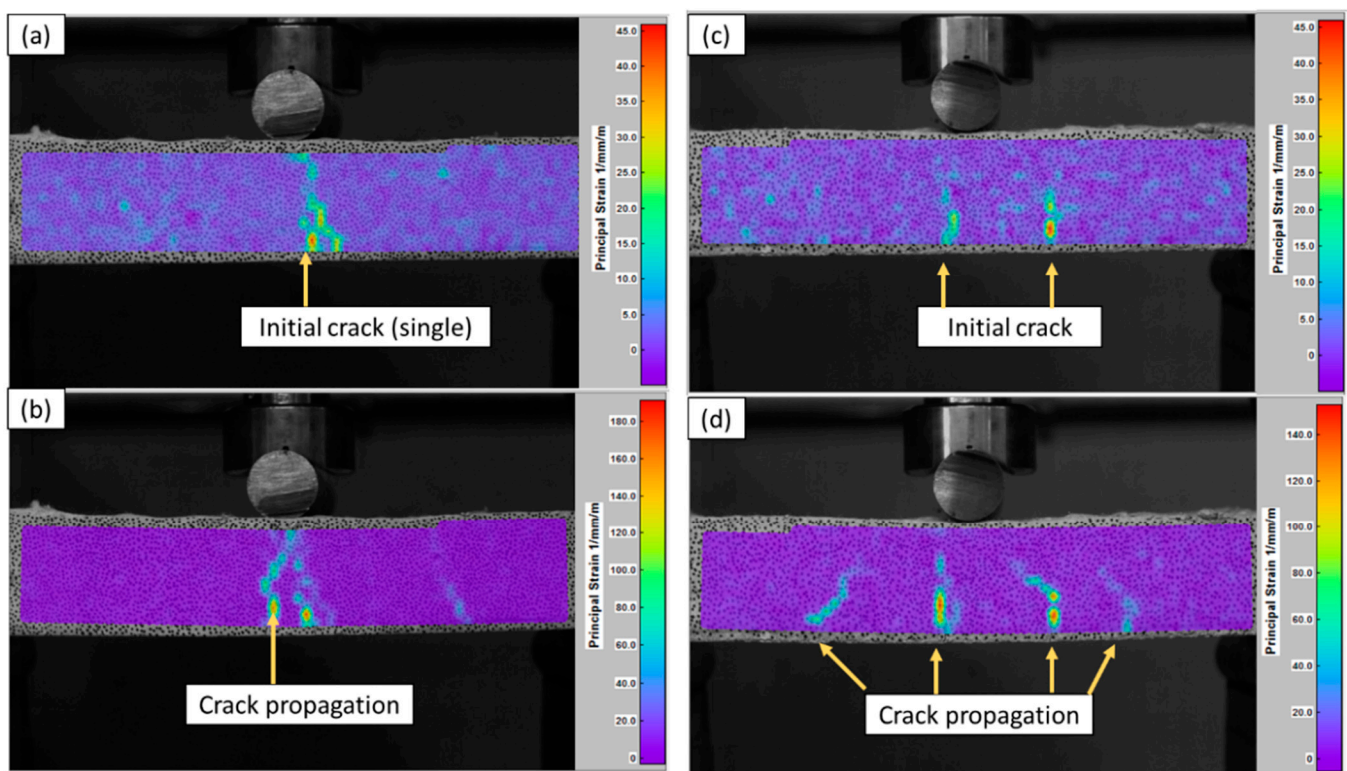


Figure 6. Crack formation and propagation in non-reinforced concrete (a,b) and CS samples (c,d).

As proposed by Zahra et al. [28], the ductility of the slabs can be quantified using the ratio between the maximum displacement and the cracking displacement (the displacement

at the mid-span when the first cracks initiate). Therefore, using the data provided by the DIC system, the displacement corresponding to crack initiation was determined. Table 4 presents the cracking displacement and the ratio of maximum displacement to cracking displacement. It can be observed that the QS sample has the highest maximum/cracking displacement ratio, indicating that, in terms of ductility, the QS outperforms the SPS sample. As reported by Mishra [5] and Alshannag et al. [32], ductility can also be determined using the ratio of maximum displacement to the displacement at which the yielding point occurs. The yielding displacement is derived from the load–displacement diagram using the 0.2% offset method. The maximum/yielding displacement ratios for the slabs are provided in Table 4.

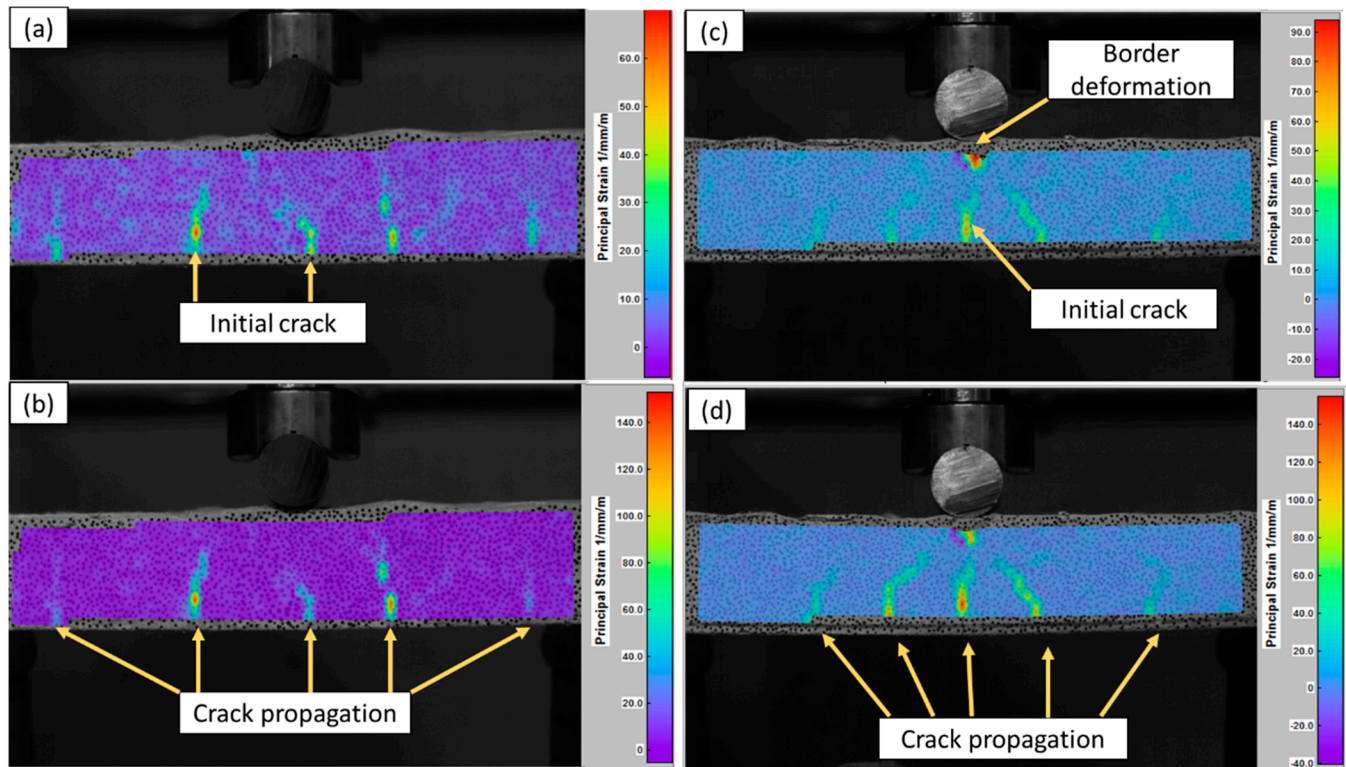


Figure 7. Crack formation and propagation in QS samples (a,b) and SPS samples (c,d).

Table 4. Cracking displacement characteristics of the tested samples.

Slab	Maximum Displacement (mm)	Cracking Displacement (mm)	Yielding Point Displacement (mm)	Maximum/Cracking Displacement Ratio	Maximum/Yielding Displacement Ratio
NRS	1.34	1.0	0.95	1.34	1.41
CS	6.78	1.30	2.8	5.21	2.42
QS	8.58	1.36	1.6	6.27	5.36
SPS	9.31	1.55	2.8	6.0	3.32

After testing the samples, the crack pattern and crack size were examined, along with the condition of the reinforcements following failure. Figure 8a,b presents an example of the crack distribution observed on the samples. As shown in Figure 8c, the reinforcement in the QS slabs also failed. This failure primarily occurred at the welded joints between the vertical connectors and the longitudinal reinforcement. It can also be observed that the SPS sample exhibited a greater number of smaller cracks, while the QS sample developed fewer but larger cracks.

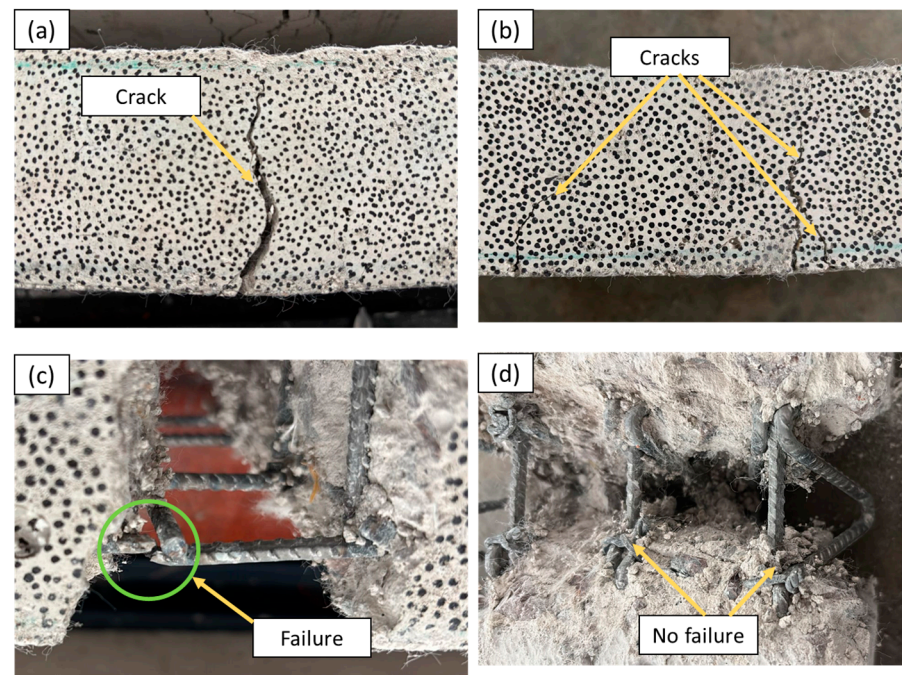


Figure 8. Crack characteristics of the slabs. (a) QS sample, (b) SPS sample, (c) reinforcement in the QS sample after testing, and (d) reinforcement in the SPS sample after testing.

3.3. Compression Characteristics

In addition to the bending tests, the compressive strength of the slabs was evaluated using a compression testing machine, with rectangular samples of 170×150 mm extracted from the bending test specimens. The results, shown in Table 5, include the ratio of the slab weight to the amount of reinforcement steel. It can be observed that the square pyramid-reinforced slab exhibits the lowest compressive strength, which may be attributed to its relatively low cement-to-steel ratio. Overall, the compressive strength of the slabs decreases consistently with the amount of steel reinforcement. The lower-than-expected compressive strength values (especially NRS sample) compared to those predicted from the mixture formulation could be due to the use of nonstandard compression testing samples, particularly given the low thickness of the slabs.

Table 5. Compression strength of the slabs studied.

Slab	Slab Weight/Steel Weight Ratio	Average Compression Strength (kg/cm^2)
NRS	-	178 ± 10
CS	89.42	172 ± 16
QS	9.70	158 ± 6
SPS	7.63	134 ± 4

4. Discussion

The load–displacement diagram in Figure 4 shows that the QS slabs exhibit an abrupt drop in force at 4 mm, indicating a quasi-brittle failure mode. This behavior is likely due to reinforcement failures at the welded joints of nodes near the failure zone, as observed in Figure 8c. In contrast, the SPS samples demonstrate a smoother load–displacement response, with gradual transitions between the elastic, plastic, and failure phases. Furthermore, the yielding plateau in the SPS slabs display a more typical behavior, suggesting their ability to undergo greater deformation while dissipating energy without experiencing

sudden reinforcement failure, unlike the QS specimens. This characteristic is advantageous for applications requiring high ductility, including those subjected to cyclic loading.

From Figures 4 and 5, it can be observed that while the QS slab exhibited the highest average peak load, the SPS slab outperformed in terms of energy absorption. This is likely attributed to the higher density of connectors between the longitudinal planes of the slab in the SPS configuration (transverse connectors). This finding agrees with the state of the art concerning 3D reinforcements either made of textiles, polymers, or metals, especially as reported by Al-Dalaïen et al. [17] and Shaheen [19]. Also, as pointed out by Pinto et al. [16], transverse connectors in the reinforcements—having a greater contact surface with the concrete—absorb more energy than vertical connectors.

In summary, the higher peak load capacity of the QS is primarily due to the greater number of longitudinal connectors, while the superior energy absorption in the SPS is a result of the increased density of transverse connectors (reinforcement ratio). In general, the flexural strength and energy absorption capacity of these reinforcements significantly surpass those of slabs reinforced with textiles and plastics, which reach peak flexural loads of only 4.5 kN and energy absorption values of 10.65 J [1–5]. Furthermore, these reinforcements enable the use of coarse aggregates, contributing to more efficient cement utilization. These characteristics render the reinforcements well-suited for practical applications.

For a more detailed comparison of the 3D steel-reinforced slab specimens, the longitudinal and transverse reinforcement ratios were determined following the methodology described by [16]. These values are presented in Table 6. It can be observed that the longitudinal reinforcement ratios for both 3D reinforcement systems are relatively similar, with the QS system exhibiting a slightly higher ratio. This difference likely contributes to the higher load-bearing capacity observed in the QS slab. In contrast, the SPS slab exhibits the highest transverse reinforcement ratio, which plays a significant role in enhancing energy absorption and ductility. Although this ratio corresponds to 3% reinforcement, it remains within the maximum limits specified by EN 1992-1-1:2004 (Eurocode 2) [33]. Furthermore, although the longitudinal reinforcement index in the QS slab is 15.6% higher than that in the SPS slab, the corresponding increase in the ultimate moment is only 3%. This suggests that the oblique transverse reinforcements in the SPS slabs—due to their longitudinal components—may contribute significantly to flexural strength. This observation may lead to future research on slabs reinforced solely with oblique 3D components, potentially replacing the traditional longitudinal reinforcements. This concept is similar to quasi-3D reinforcements formed by randomly distributed fibers within a concrete matrix, as proposed in [14]. It is important to note that the reinforcement ratio of the control slab was not included in this comparison, since it does not have transverse connectors. However, to conduct a more comprehensive analysis of the differences in mechanical properties between 3D reinforced and linear reinforced slabs, it is essential that their reinforcement ratio be comparable.

Table 6. Reinforcement ratios of the 3D reinforced samples.

Slab	Longitudinal Reinforcement Ratio	Transverse Reinforcement Ratio
QS	0.0222	0.0108
SPS	0.0192	0.0333

From the ductility evaluation, it can be seen that both methods for determining ductility yield consistent results. The enhancement in ductility for the QS, according to the first method, is approximately 20%, while the second method indicates an improvement of about 121%. For the SPS, ductility increases of 15% and 37% were observed for the first and

second methods, respectively. Despite the discrepancies between the two approaches in terms of percentage increase in ductility, the cracking analysis using DIC proves to be a reliable alternative for assessing the ductility of materials in bending tests.

Additionally, the connectors in the 3D reinforcements facilitate the distribution of shear stresses throughout the specimen, leading to the formation of multiple smaller cracks, which supports the findings presented in [18,21]. In contrast, the control slab experiences localized cracking around the load point. As a result, failure in the control slab occurs suddenly and in a brittle manner, while in the three-dimensional slabs, failure occurs gradually. This behavior is particularly advantageous in applications where ductility is crucial, such as bridges, containers, beams, and slabs.

Moreover, the crack propagation patterns in Figure 7a,b and Figure 7c,d, for the cubic and pyramidal reinforcements, respectively, suggest that the orientation of the connectors promotes the distribution of cracks along their length, as pointed out by [4]. This characteristic may influence the design of reinforced concrete elements, depending on the specific application.

Post-test visual inspection of the specimens revealed that the cracks were predominantly aligned with the locations of the 3D reinforcement connectors, corroborating the crack patterns identified by the DIC system. In the QS slabs, failure occurred in both the concrete and the reinforcement, with notable damage observed at the welded joints within the tension zone. In contrast, failure in the SPS specimens was characterized by concrete crushing, with the steel reinforcement remaining intact and showing no signs of yielding (Figure 8d). Thus, it is evident that the welding process used during the manufacturing of 3D reinforcements may be less advantageous compared to wire-tying connections.

The results on the compressive behavior of the 3D reinforced slabs indicate that these reinforcements are not suitable for structural elements subjected to high levels of quasi-static or dynamic compression loads. This finding is consistent with the results reported by Mishra et al. [5], Al-Dala'ien et al. [17], and Shaheen et al. [19].

Based on the findings of this study—particularly regarding flexural strength and energy absorption—it is feasible to propose the construction of structural elements for practical applications, such as beams, columns, foundations, walls, or slabs, provided that their design complies with the strength requirements established by the current local codes, depending on the intended use. To this end, a scaling approach, such as those proposed by Javed et al. [34] and Balık and Bahadır [35], should be considered.

5. Conclusions

This study investigated the bending behavior of slabs reinforced with a 3D steel arrangement, specifically cubic and square pyramid truss lattices. Their flexural performance was compared to that of a control group consisting of slabs reinforced with linear rods. The QS slabs exhibited slightly higher flexural strength than the SPS slabs; however, the difference was marginal. In contrast, the SPS slabs demonstrated greater energy absorption capacity, indicating higher ductility and toughness.

Oblique connectors play a significant role in enhancing both flexural strength and energy absorption. However, their fabrication is more complex compared to that of the cubic connectors with vertical alignment. Moreover, they require a substantially higher transverse reinforcement ratio—almost twice that of the QS slabs.

Due to their welded joints, the QS slabs tend to exhibit brittle failure at the connection points. Therefore, their application should be assessed in terms of manufacturing efficiency and specific design objectives, such as flexural load capacity.

Given that three-dimensional reinforcements lead to an increased reinforcement ratio—which consequently reduces compressive load strength—their use is not fully recommended

for high-compression or impact-prone applications, such as foundations or concrete shielding structures.

On the other hand, this study demonstrates that the DIC technique is a reliable method for assessing slab ductility by analyzing crack propagation during flexural tests.

Future research will focus on determining the optimal reinforcement ratio—depending on the 3D reinforcement configuration—as well as the positioning and orientation of transverse connectors in lattice trusses, with the aim of enhancing flexural capacity and evaluating the impact of these reinforcements on shear stress distribution in structural elements. Additionally, due to the complexity of constructing 3D reinforcements, new and more efficient manufacturing methods should be explored and evaluated.

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References

1. Zhang, Q.; Yang, Q.-C.; Li, W.-J.; Gu, X.-L.; Dai, H.-H. Study on Model of Flexure Response of Carbon Fiber Textile Reinforced Concrete (CTRC) Sheets with Short AR-Glass Fibers. *Case Stud. Constr. Mater.* **2023**, *18*, e01791. [\[CrossRef\]](#)
2. El Kadi, M.; Tysmans, T.; Verbruggen, S.; Vervloet, J.; De Munck, M.; Wastiels, J.; Van Hemelrijck, D. Experimental Study and Benchmarking of 3D Textile Reinforced Cement Composites. *Cem. Concr. Compos.* **2019**, *104*, 103352. [\[CrossRef\]](#)
3. Sasi, E.A.; Peled, A. Three Dimensional (3D) Fabrics as Reinforcements for Cement-Based Composites. *Compos. Part. Appl. Sci. Manuf.* **2015**, *74*, 153–165. [\[CrossRef\]](#)
4. Haik, R.; Adiel Sasi, E.; Peled, A. Influence of Three-Dimensional (3D) Fabric Orientation on Flexural Properties of Cement-Based Composites. *Cem. Concr. Compos.* **2017**, *80*, 1–9. [\[CrossRef\]](#)
5. Mishra, R. FEM Based Prediction of 3D Woven Fabric Reinforced Concrete under Mechanical Load. *J. Build. Eng.* **2018**, *18*, 95–106. [\[CrossRef\]](#)
6. Naaman, A.E. Textile Reinforced Cement Composites: Competitive Status and Research Directions. In *Proceedings of the International RILEM Conference on Material Science*; Brameshuber, W., Ed.; RILEM Publications SARL: Aachen, Germany, 2010; pp. 3–22.
7. Katzer, J.; Szatkiewicz, T. Effect of 3D Printed Spatial Reinforcement on Flexural Characteristics of Conventional Mortar. *Materials* **2020**, *13*, 3133. [\[CrossRef\]](#)
8. Xu, Y.; Šavija, B. 3D Auxetic Cementitious-Polymeric Composite Structure with Compressive Strain-Hardening Behavior. *Eng. Struct.* **2023**, *294*, 116734. [\[CrossRef\]](#)
9. Xu, Y.; Zhang, H.; Schlangen, E.; Luković, M.; Šavija, B. Cementitious Cellular Composites with Auxetic Behavior. *Cem. Concr. Compos.* **2020**, *111*, 103624. [\[CrossRef\]](#)
10. Tang, C.; Liu, J.; Qiao, J.; Wei, Y.; Shi, C.; Hao, W. The Preparation and Axial Compressive Properties of 3D-Printed Polymer Lattice-Reinforced Cementitious Composite Columns. *J. Build. Eng.* **2024**, *97*, 110770. [\[CrossRef\]](#)
11. Contreras, N.; Zhang, X.; Hao, H.; Hernández, F. Application of Elastic Metamaterials/Meta-Structures in Civil Engineering: A Review. *Compos. Struct.* **2024**, *327*, 117663. [\[CrossRef\]](#)

12. Xiao, J.; Liu, H.; Ding, T.; Ma, G. 3D Printed Concrete Components and Structures: An Overview. *Sustain. Struct.* **2021**, *1*, 1–15. [[CrossRef](#)]
13. Raphael, B.; Senthilnathan, S.; Patel, A.; Bhat, S. A Review of Concrete 3D Printed Structural Members. *Front. Built Environ.* **2023**, *8*. [[CrossRef](#)]
14. Naaman, A.E. Evolution in Ferrocement and Thin Reinforced Cementitious Composites. *Arab. J. Sci. Eng.* **2012**, *37*, 421–441. [[CrossRef](#)]
15. *Textile Fibre Composites in Civil Engineering*; Elsevier: Amsterdam, The Netherlands, 2016, ISBN 9781782424468.
16. Pinto, R.S.; Sousa, V.C.; Tapajós, L.S.; Ferreira, M.D.P.; Lima Neto, A.F. Influence of the Supplementary Reinforcement on the Shear Strength of Beams with Prefabricated Truss Stirrups. *Rev. IBRACON De. Estrut. Mater.* **2022**, *15*. [[CrossRef](#)]
17. Al-Dala'ien, R.N.; Syamsir, A.; Usman, F.; Abdullah, M.J. The Effect of the W-Shape Stirrups Shear Reinforcement on the Dynamic Behavior of RC Flat Solid Slab Subjected to the Low-Velocity Impact Loading. *Results Environ.* **2023**, *19*, 101353. [[CrossRef](#)]
18. Abdulla, A.I.; Khatab, H.R. Behavior of Multilayer Composite Ferrocement Slabs with Intermediate Rubberized Cement Mortar Layer. *Arab. J. Sci. Eng.* **2014**, *39*, 5929–5941. [[CrossRef](#)]
19. Shaheen, Y.B.I.; Etman, Z.A.; Gomaa, O. Structural Behavior of Thin Ferrocement Plates with and without Stiffeners Subjected to Compression Loading. *Asian J. Civ. Eng.* **2019**, *20*, 237–260. [[CrossRef](#)]
20. Yerramala, A.; Ramachandurdu, C.; Bhaskar Desai, V. Flexural Strength of Metakaolin Ferrocement. *Compos. Eng.* **2013**, *55*, 176–183. [[CrossRef](#)]
21. Yang, Y.; Xu, C.; Xia, L.; Yang, J.; Dong, Z.; Wu, G. Experimental Study on Static Performance of Ballastless Track Slabs Reinforced by New FRP Trusses. *Eng. Struct.* **2024**, *316*, 118566. [[CrossRef](#)]
22. Yao, Y.; Silva, F.A.; Butler, M.; Mechtcherine, V.; Mobasher, B. Tension Stiffening in Textile-Reinforced Concrete under High Speed Tensile Loads. *Cem. Concr. Compos.* **2015**, *64*, 49–61. [[CrossRef](#)]
23. Ospitia, N.; Tsangouri, E.; Pourkazemi, A.; Stiens, J.H.; Aggelis, D.G. NDT Inspection on TRC and Precast Concrete Sandwich Panels: A Review. *Constr. Build. Mater.* **2021**, *296*, 123622. [[CrossRef](#)]
24. Vincens, B.; Corres, E.; Muttoni, A. Image-Based Techniques for Initial and Long-Term Characterization of Crack Kinematics in Reinforced Concrete Structures. *Eng. Struct.* **2024**, *317*, 118492. [[CrossRef](#)]
25. Gehri, N.; Mata-Falcón, J.; Kaufmann, W. Automated Crack Detection and Measurement Based on Digital Image Correlation. *Constr. Build. Mater.* **2020**, *256*, 119383. [[CrossRef](#)]
26. Christensen, C.O.; Schmidt, J.W.; Halding, P.S.; Kapoor, M.; Goltermann, P. Digital Image Correlation for Evaluation of Cracks in Reinforced Concrete Bridge Slabs. *Infrastructure* **2021**, *6*, 99. [[CrossRef](#)]
27. Liu, J.; Kanwal, H.; Tang, C.; Hao, W. Study on Flexural Properties of 3D Printed Lattice-Reinforced Concrete Structures Using Acoustic Emission and Digital Image Correlation. *Constr. Build. Mater.* **2022**, *333*, 127418. [[CrossRef](#)]
28. Zahra, T.; Asad, M.; Thamboo, J. Flexural Behaviour of Cementitious Composites Embedded with 3D Printed Re-Entrant Chiral Auxetic Meshes. *Smart Mater. Struct.* **2024**, *33*, 025011. [[CrossRef](#)]
29. *ACI PRC-211.1-22*; Selecting Proportions for Normal-Density and High-Density Concrete-Guide. American Concrete Institute: Farmington Hills, MI, USA, 2022.
30. *ACI 318S-19*; Building Code Requirements for Structural Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2022.
31. Hernández-Pérez, J.; Jiménez-Montoya, A.; Pascual-Francisco, J.B.; Contreras-Ramírez, J.C.; López-Segundo, N.; Miramar-Mena, T. Deflection Analysis of Proposals for Lightened Slabs with Embedded Three-Dimensional Metal Arrangement. *Pädi Boletín Científico Cienc. Básicas Ing. ICBI* **2024**, *12*, 68–74. [[CrossRef](#)]
32. Alshannag, M.J.; Charif, A.; Alqarni, A.S.; Nasser, S. Flexural Performance and Ductility of RC Beams Made Using Natural LWA. *Case Stud. Constr. Mater.* **2022**, *16*, e00942. [[CrossRef](#)]
33. *EN 1992-1-1:2004+A1:2014*; Eurocode 2: Design of Concrete Structures-Part 1-1: General Rules and Rules for Buildings. CEN: Brussels, Belgium, 2014.
34. Javed, A.; Krishna, C.; Ali, K.; Afzal, M.F.U.D.; Mehrabi, A.; Meguro, K. Micro-Scale Experimental Approach for the Seismic Performance Evaluation of RC Frames with Improper Lap Splices. *Infrastructure* **2023**, *8*, 56. [[CrossRef](#)]
35. Balik, F.S.; Bahadir, F. Experimental Studies On 1/5 Scaled Reinforced Concrete Frames By Using Different Strengthened Methods. *Konya J. Eng. Sci.* **2019**, *7*, 663–680. [[CrossRef](#)]

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