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Behavior of Reinforced Reactive Powder Concrete Two-Way Slabs under Static and Repeated Load

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Abstract

This paper studies the behavior of reinforced Reactive Powder Concrete (RPC) two-way slabs under static and repeated load. The experimental program included testing six simply supported RPC two-way slabs of 1000 mm length, 1000 mm width, and 70 mm thickness. All the tested specimens were identical in their material properties, and reinforcement details except their steel fibers content. They were cast in three pairs, each one had a different steel fibers ratio (0.5 %, 1 %, and 1.5 %) respectively. In each pair, one specimen was tested under static load and the other under five cycles of repeated load (loading-unloading). Static test results revealed that increasing steel fibres volume fraction from 0.5 % to 1 % and from 1% to 1.5%, led to an increase in the: first crack load by (32.2 % and 52.3 %), ultimate load by (36.1 % and 17.0 %), ultimate deflection by (33.6 % and 3.4 %), absorbed energy by (128 % and 20.2 %), and the ultimate strain by (1.1 % and 6.73 %). It also increased the stiffness and the ductility of the specimens especially at the final stages of loading. Additionally, it delayed the propagation of the cracks, controlled their growth, kept the integrity of the specimens at post cracking stage, and avoided their ruin at the failure stage through its "bridging" effect. For the repeated load test, applying five cycles of repeated load to the steel fiber reinforced RPC two-way slab specimens led to a decreasing in the ultimate load capacity, ultimate deflection, ultimate strain, and absorbed energy in a comparison with the corresponding static test specimens, and that because of the loading-unloading process which causes a fluctuation of stresses and more damages in concrete. Increasing the steel fibers volume fractions decreased the dissipated energy of the specimens that subjected to a repeated load, where the difference percent of dissipated energy between the first and second cycles of (R0.5 %, R1 %, and R1.5 %) specimens were (68.0 %, 46.2%, and 32.4%) respectively.

Keywords: Two-Way Slab; Reactive Powder Concrete; Repeated Load; Steel Fibers.

1. Introduction

The small tensile strength of the ordinary concrete has some unfavourable outcomes on its performance as an important building and construction material. This involves the necessity for steel reinforcement and sometimes huge section members which are aesthetically unfavourable and consume large amounts of materials. Reactive Powder Concrete (RPC) is an emerging technology has the ability to overcome the aforementioned handicaps, where it can be used to create small section members with high efficiency. RPC is usually formed from extremely fine powder materials (cement, sand, quartz powder and silica fume), steel fibers (optional) and super plasticizer [1]. By optimizing the granular packing of the dry fine powders, a material of very small amounts of defects such as micro-cracks and voids in a comparison with the conventional concrete can be achieved. RPC has a very good durability because of its low and non-connected porosity and due to its perfect impermeability, hence it has been used for isolation and containment of nuclear waves [2].

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The fibrous RPC that produced under a good quality control condition has very good mechanical properties, where it has a high tensile strength, and its compressive and flexural strengths reach 800 and 40 MPa respectively [3], also it has ductility and energy absorption values approaching those of steel material [4]. It was detected that the constitutive relationship of RPC is similar to that of mortar and it is typical elastic brittle material [5]. This research also indicated that the compressive stress- strain relation of the RPC has a linear ascent stage until the ultimate strain, then the strength drops sharply and an explosive failure occurs suddenly. Hence it is so difficult to observe complete descending stage. To solve this problem, steel fibers are usually added, and this also improves the ductility for a large extent. Repeated load is a load that applied to a member then removed for many times. Load-unload process may cause a fluctuation of stress or reversal stresses if reversal of load cycles have been applied.

Mohammed M. Kadhum 2014 [6] studied, experimentally, the behaviour of RPC two-way slabs of different curing conditions. He concluded that increasing micro-steel fibers content causes an increase in the stiffness, ultimate load, ultimate deflection, and ductility of the slab specimens, and delays the cracks propagation and control their growth. Also he found out that using the heat treatment method increases the first crack and the ultimate load of the specimens. He concluded also that the addition of the steel fibers to the RPC improves the tensile strength and ductility properties so that slabs can be constructed without conventional reinforcement or of smaller amounts in the tension zones of the RPC for many structural applications, so that, costs and self-weights can be reduced, and also it will be possible to construct with thinner thicknesses, longer spans, and taller structures.

Hussain A. Jabir 2016 [7] studied, experimentally and theoretically, the behaviour of laced one-way concrete slab under static and repeated loading. He tested half of the experimental specimens under static load and the other half under five cycles repeated load (loading-unloading). Test results showed that the ultimate load, the ultimate deflection, and the ductility factor (the ratio of deflection at ultimate load to the deflection at first yielding of tension steel reinforcement) of the repeatedly loaded specimens were smaller than that of the corresponding statically loaded specimens. It was also observed that when the number of load cycles of repeatedly loaded specimens was increased, the corresponding deflection and number of cracks increased. Because of the repeated load application on the slab, a residual deflection occurred, that means the slab does not return to its original situation after the applied load cycles removed, where the flexural steel reinforcement was unable to return the dissipated energy without permanent deformations for the repeatedly loaded specimens.

Sivagamasundari R., and Kumaran G., 2011[8] investigated the behaviour of concrete one-way slabs reinforced by GFRP rebars under static and repeated loading (fatigue loading) of constant and variable amplitudes, and presented a comparison between them and those reinforced by conventional reinforcement. Regarding the effect of concrete grade, the researchers observed that increasing the compressive strength of the concrete by 50 % for the specimens tested under fatigue load, enhanced the fatigue performance by about 33% for the same slabs; in addition, the magnitude of damage for the GFRP reinforced slabs was smaller than that of the slabs reinforced by conventional steel reinforcement. The researchers observed also that the residual, ultimate deflection and crack width of the slab specimens that subjected to a constant amplitude fatigue loading were greater than those of the corresponding slabs that tested under variable amplitude fatigue loading.

Naser H. Tu'ma, 2016 [9] studied in a part of his thesis the finite element modelling for the RPC beams reinforced by fibre reinforced polymer bars using ANSYS software. In this study, the steel fibers were modelled as a smeared reinforcement in SOLID65 element (the element that was used to represent the concrete material). Six different ways of steel fibers distribution was examined, plain concrete element (without steel fibers), horizontal one-layer, vertical one-layer, inclined one layer, equally two-way distribution (two layers ,vertical and horizontal) ,and three-way distribution (three layers, vertical, horizontal and inclined). A good agreement between the experimental and the finite element results was achieved. The equally two-way distribution of steel fibers gave the closest results to the experimental results.

Hisham M. Al-Hassani, Wasan I. Khalil, and Lubna S. Danha, 2013 [10] investigated experimentally the influence of three parameters on the mechanical properties of RPC, compressive strength, tensile strength (direct, splitting and flexural), flexural toughness, load-deflection capacity and static modulus of elasticity. The adopted parameters were silica fume content SF (0%, 10%, 15%, 20%, 25%, and 30%), hooked macro steel fibres volume fraction Vf (0%, 1%, 2% and 3%) and superplasticizer type (Sikament®-163N and PC200). The authors detected that silica fume content had a significant positive effect on the compressive strength, while its effect on the tensile strength was relatively low. It was also concluded by the authors that steel fibres leads to a considerable increase in the tensile strength and a slight increase in the compressive strength of RPC.

This paper presents an experimental study about the behavior of reinforced Reactive Powder Concrete two-way slabs under static and five cycles repeated load (loading-unloading).

2. Experimental Program

2.1. Materials

Ordinary Portland cement (Type-I), natural sand of maximum particle size smaller than 1.18 mm, silica fume (SF), tap water, and SikaViscocrete-5930 super plasticizer (SP) were used to produce the Reactive Powder Concrete mix for all the specimens. Discontinuous discrete hooked end steel fibres of 1mm diameter and 30 mm length were added. The mix proportions of the used Reactive Powder Concrete mix are shown in Table 1.

Table 1. Mix proportions of the used RPC mix

Material	Proportion
cement	**750 kg/m^3**
sand	**1200 kg/m^3**
SF	**200 kg/m^3**
w/b*	**0.2**
SP	2% binder weight

* Water to binder ratio

2.2. Test Specimens

Six simply supported Reactive Powder Concrete two-way slabs have been cast and tested. All of their geometrical, material properties, and reinforcement details were identical except their steel fibers content. They were cast in three pairs, each one had a different steel fibers ratio (0.5 %, 1 %, and 1.5 %) respectively. In each pair, one specimen was tested under static load while the other was tested under repeated load as detailed in Table 2. The dimensions and some other details of the slab specimens are shown in Figure 1. All the specimens were reinforced by one layer of 6 mm diameter deformed rebar (f_y =420 MPa) at 170 mm c/c spacing in both directions.

Table 2. Designation of the test specimens

Specimen designation	Load type	Steel fiber %
S0.5%	static	0.5
R0.5%	repeated	0.5
S1%	static	1
R1%	repeated	1
S1.5%	static	1.5
R1.5%	repeated	1.5

2.3. Instrumentation

A number of measurement tools and instruments were used to conduct the experimental work of this research such as strain, deflection, load, and crack width measurements. One strain gauge (5 mm) was installed in each reinforcement mesh at the mid of the closest bar to the plate of loading, three strain gauges (20 mm) were installed at the bottom face of each slab specimen. The used strain gauges for steel and concrete are product of TML Japan.Two dial gauges were installed for measuring the vertical deflection in two locations, the first one was in the center of the slab bottom to measure the downward deflection, and the other one was installed above the support to measure the uplift. A tool consists of twenty metal slices of different thicknesses ranging from 0.05 to 1 mm was used to measure the width of cracks. The locations of the concrete strain gauges and the dial gauges are shown in Figure 2, where the strain gauges are marked with blue rectangles.

2.4. Testing Procedure

All the specimens were prepared for the test by painting the surfaces by white color and installing the strain gauges in their adopted locations in the bottom face of the slab specimen. After that, the specimen was placed in its right position on the testing frame so that the support lines of the frame were identical with those of the slab specimen. Thereafter; loading plate and dial gauges were fixed in their specified positions, Figure 3.

In the static load test, the specimen was loaded gradually till failure stage. The load was applied with an increment of approximately (300 kg) using a hydraulic jack and a load cell of 200 Ton capacity. Regarding the repeated load test, the specimen was increasingly loaded up to 60 % of the corresponding static failure load with approximately (300 kg) increment, then the load released to 40 % of the static failure load at the same rate of the loading process. This loading cycle has been repeated for five times. After that, the specimen was loaded gradually up to failure. After each loading step, the magnitude of the applied load, vertical deflection at the center of the slab, uplift of the supports, cracks width, crack patterns, and strain in both steel reinforcement and concrete surface were recorded.

All the tested specimens were examined in approximately the same environmental conditions (Lab room conditions) with a variance of not more than 5%. This mean there is no environmental effect on the test result especially the recorded data of the strain indicator device.

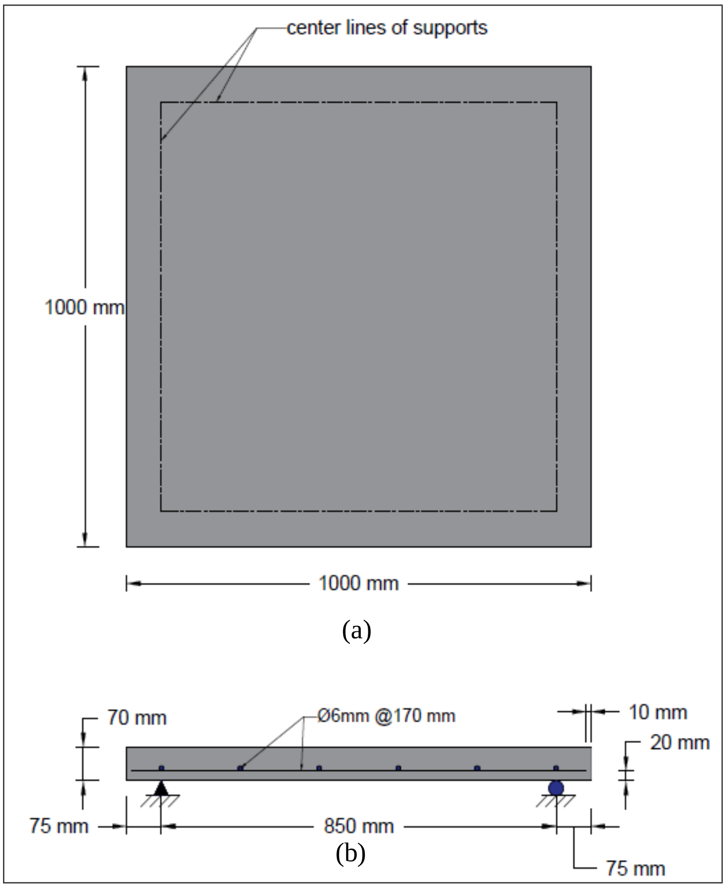


Figure 1. Dimensions and other details of the slab specimens: (a) Top view, (b) Sectional view

3. Test Results and Discussion

3.1. Static Test Results

Static test program included examining three reinforced RPC two-way slab specimens. A flexural failure occurred in all the tested slab specimens, the cracks were initially formed in the bottom face of the slab under the loading plate (where the maximum bending occurred and the tensile stress exceeded the concrete modulus of rupture) then radiated to the edges of the slab. It was observed that for all the tested specimens, when the first crack initiated, it was of a very small width (smaller than 0.05 mm) and its shape was close to a polygon with short crack lines initiated from its corners and extended towards the slab edges, this crack layout is compatible with the state of loading and boundary conditions of the tested slabs. As the loading process continued, the cracks along the diagonals of the tension face widened and extended, then a number of additional cracks were formed in the central region of the tension face. At higher load stages, the central deflection increased and the cracks along the diagonals propagated and extended till they reached to the slab corners and passed through the slab sides toward the upper face of the slab. At the final stages of the loading, the steel reinforcement yielded, excessive deflections happened, the generated cracks widened and spread progressively till the bottom face of the slab was filled with cracks in all directions and the slab was no longer carry any loads and failure occurred, Figure 4. Shows the crack pattern of the tension face for the tested specimens after failure.

Test results revealed that increasing steel fibers volume fraction from 0.5 % to 1 % and from 1 % to 1.5 %, led to an increase in the first crack load and the ultimate load by (32.2 % and 52.3 %) and (36.1 % and 17.0 %) respectively, as it are shown in Table 3. It was noticed that the widths of the cracks of all the tested specimens remained small till the final stages of loading, where they were approximately equal to (0.2 mm) at a loading stage of (80-85 %) from the ultimate load. This caused by the presence of the steel fibers which delayed the propagation of the cracks and controlled their growth.

Test results also revealed that increasing steel fibers volume fraction from 0.5 % to 1 % and from 1 % to 1.5 %, led to an increase in the deflections at first crack by 4.8 % and 36.4 % respectively, and also led to an increase in the ultimate deflection as shown in Table 4. It was noticed that the increase of the ultimate deflection, when steel fibers volume fraction increased from 0.5 % to 1 %, was clear and significant (33.6 %), however; it was small when steel fibers volume fraction increased from 1 % to 1.5 % (3.4 %).

For S1 % and S1.5 % specimens, when they gradually loaded, the deflection was still increased linearly as the load increased even after the first cracks generation by high stages of loading, while for S0.5 % specimen, the load-deflection relation was linear only before the first cracks generation as it clears from Figure 5, and that belongs to the effect of the steel fibers that's increase the stiffness of the concrete. It was also clear from Figure 5. That the slope of the linear parts is directly proportion with the steel fibers volume fraction which also belonged to the influence of steel fibers that is increased the stiffness of the concrete. After the longitudinal reinforcement had yielded and the steel fibers pullout reached its final stage, the deflection increased continuously without an appreciable increment in the load. The rate of deflection increasing was so fast at the ultimate load of all slab specimens and no reliable data could be recorded at this stage, for this reason, all load-deflection curves had been terminated at the last load step before failure.

Test results indicated that increasing steel fibers volume fraction from 0.5 % to 1.5 % decreased the principal strain at the first crack due to the effect of the steel fibers on the increasing of the stiffness for the specimens at the linear stage .This result is compatible with the linear behavior of the load-deflection curve for S1 % and S1.5 % specimens. It was observed that there is no significant strain even that after the initiation of the first crack for all the tested specimens, the strain was recorded after the generation of the first crack load by about (5, 10, 20) KN for a case of (0.5, 1 and 1.5) % of steel fibers volume ratio. The pattern of the principal strain load behavior for all the adopted steel fibers volume ratios was compatible even that there is a difference between them which is greater between the cases of (0.5 and 1) % than in a cases of (1 and 1.5) % percentage. However the ultimate principal strains had increased as the steel fibers volume fraction increased due to the positive effect of the steel fibers on the ductility of the specimens as shown in Table 5 and Figure 6. The load-strain behavior of the steel reinforcement for S1 % and S1.5 % specimens is shown in Figure 7, no strain data could be obtained for S0.5 % specimen, due to the damage of the steel reinforcement strain gauge of this specimen. It was achieved from the experimental data that the yielding strain of the steel reinforcement is approximately equal to 0.00226; it is marked with red dashed lines in Figure 7.

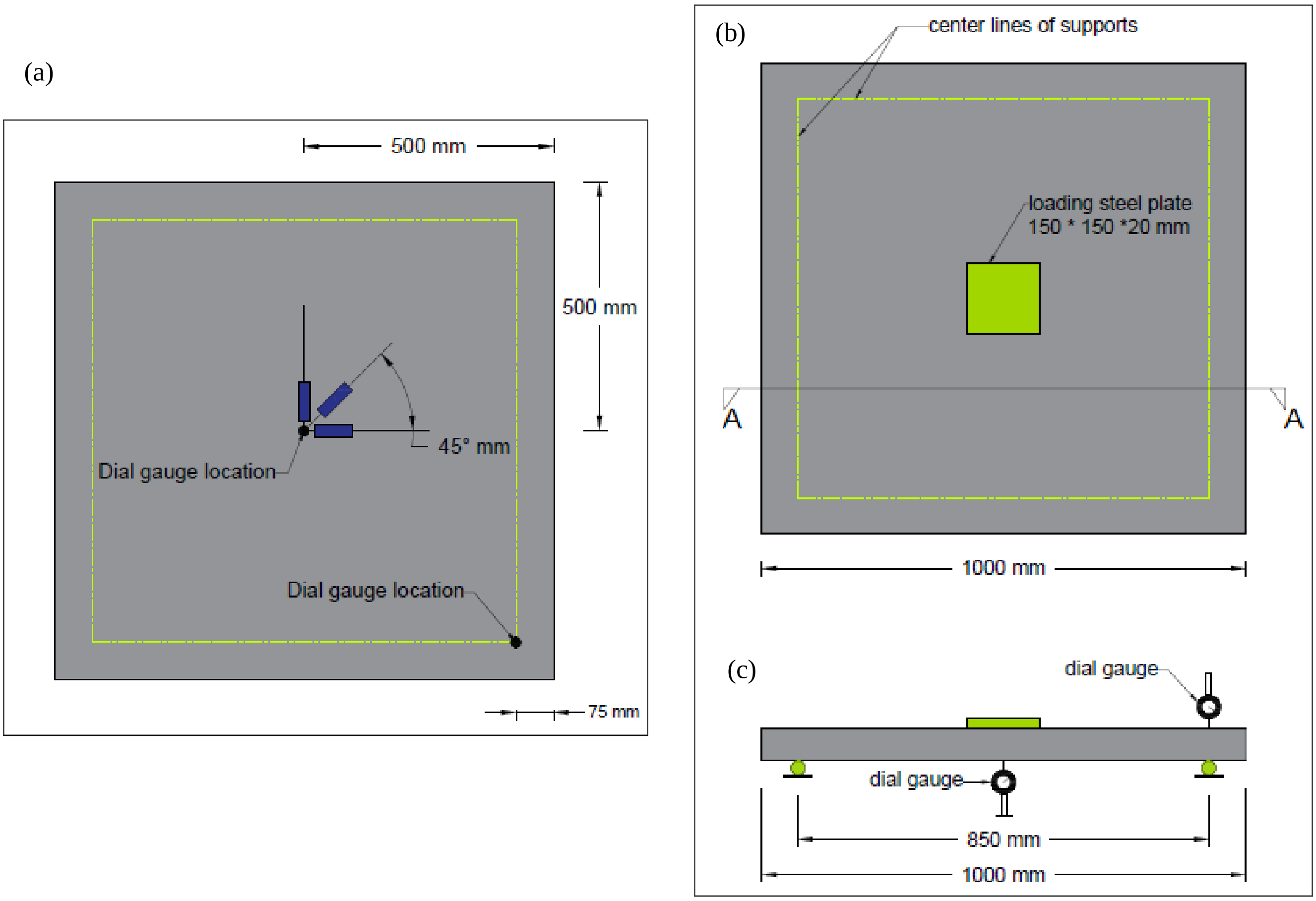


Figure 2. Schemes of the test set-up: (a) The bottom face, (b) The top face, (c) Section A-A

Figure 3. Photo of the test set-up

Strain-load pattern of the steel reinforcement prove the positive effect of the steel fiber additives, where for a case of (1 %) steel fiber volume ratio, the required load that is cause a steel to yield was (50) kN while it was required to increase the load to (70) kN to cause a steel yielding in the specimen of 1.5 % steel fibers volume ratio.

Table 3. Cracking and ultimate load for the static load test specimens

Specimens	P_{cr} (kN)	% Increase in P_{cr}	P_u (kN)	% Increase in P_u	% P_{cr}/P_u
S0.5%	14.9	-	54.0	-	27.6
S1%	19.7	32.2 %	73.5	36.1 %	26.8
S1.5%	30.0	52.3 %	86.0	17.0 %	34.9

Table 4. Central deflection of the static load test specimens

Specimen	Deflection at first crack (mm)	% Increase in deflection at first crack	Ultimate deflection (mm)	% Increase in ultimate deflection
S0.5%	2.1	-	11.0	-
S1%	2.2	4.8 %	14.7	33.6 %
S1.5%	3.0	36.4 %	15.2	3.4 %

Flexural toughness is the total energy that can be absorbed by the specimen before failure, which can be calculated from the area under the load-deflection curve in flexure [11]. Test results showed that the absorbed energy is directly proportion with the percentage of the steel fibers volume fraction, where when the steel fibers volume fraction was increased from 0.5 % to 1 % and from 1 % to 1.5 %, the absorbed energy increased by 128 % and 20.2 % respectively, as it is shown in Table 6. The rate of increase in the total absorbed energy indicated that steel fibers volume ratio did not has the same rate of effect on the absorbed energy and there is a limit after which the effect will be inversed to a negative effect.

3.2. Repeated Test Results

Repeated test program included testing three reinforced RPC two-way slab specimens loaded by a concentrated repeated load of five cycles ranged between 40 % and 60 % from the ultimate load capacity of the corresponding statically loaded specimens. It was noticed that the crack pattern of the slab specimens that subjected to the adopted repeated load process was nearly similar to that of the specimens under static load, however; further cracks had been developed and widened when the number of loading cycles was increased, Figure 4. The ultimate deflection of the repeated test specimens is shown in Table 7. The recorded values of the ultimate deflection proved the fact that there is an optimum limit for the steel fibers volume ratio after which the effect of increasing this ratio will be negative. Where, as it is clear from Table 7, there is no valuable difference in the ultimate deflection between the cases of (1 and 1.5) % ratio.

During the loading-unloading process, the path of the ascending part of the load-deflection curve was not the same as the descending part; the difference between the two paths is usually called the Dissipated Energy. This means that the slab did not return to its original position when the load was released and there was a residual deflection. Tests results showed that the increasing of the steel fibers volume fractions from 0.5 % to 1 % and from 1 % to 1.5 % decreased the dissipated energy of the specimens by 11 % and 20 % respectively as shown in Table 8. This could be caused by the positive effects of increasing the steel fibers volume fraction, which are increasing the ductility of concrete and decreasing the permanent deformations (dissipated energy). It was noticed that the maximum dissipated energy occurred at the first cycle, where as it is clear from Figure 8, the differences in the dissipated energy between the last four cycles were relatively small in a comparison with the difference between the first and the second cycles. The same observation was for the principal strains Figure 9. The absorbed energy of the repeated load slabs is shown in Table 9. The calculated values of the absorbed energy in the case of repeated load were compatible with those of the corresponding static tested specimens, still the difference in the absorbed energy between the cases of (0.5 and 1) % steel fibers volume ratio is greater than the cases of (1 and 1.5) %.

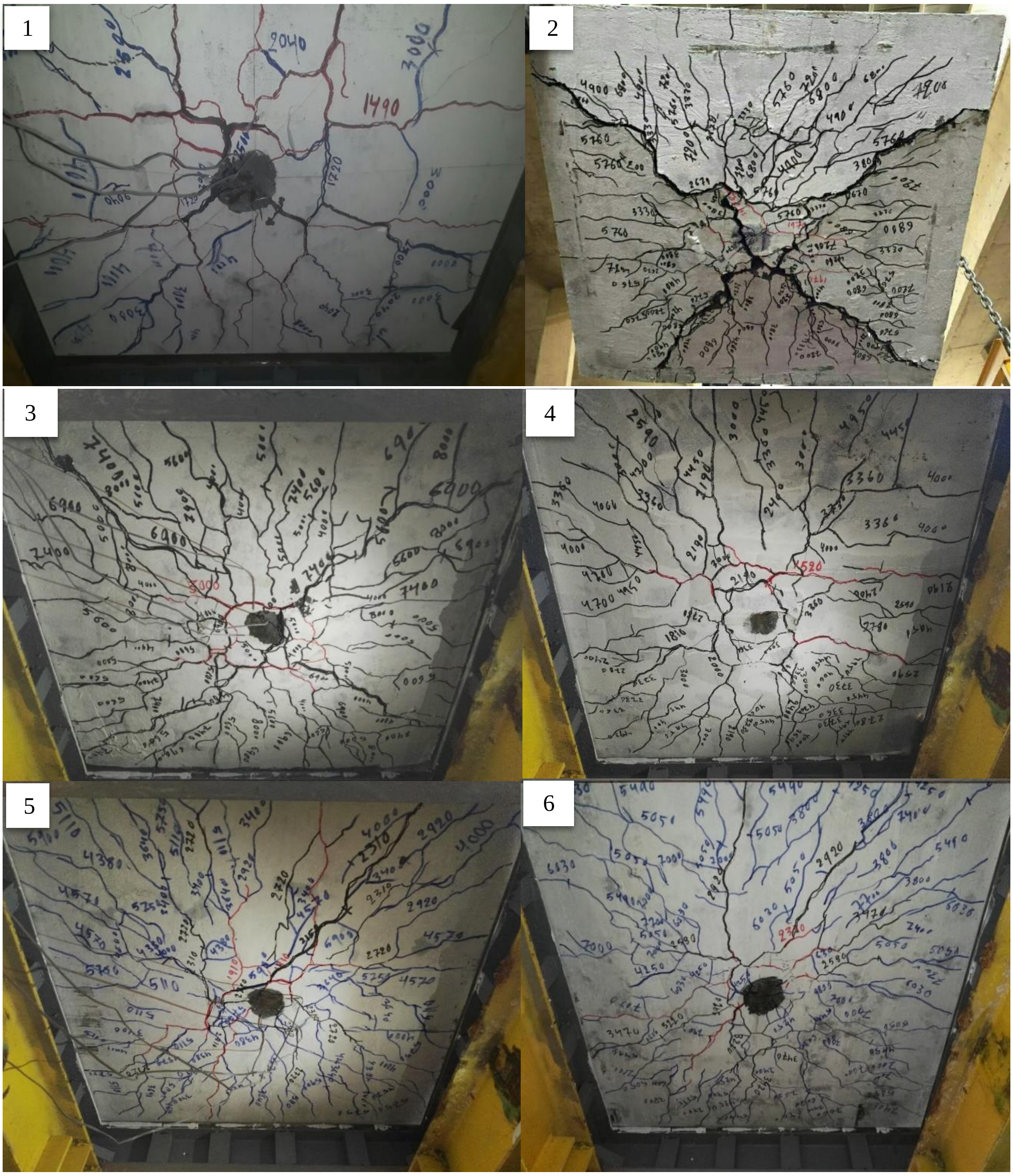


Figure 4. Crack pattern of the tension face for the experimental specimens after failure; (1-3) static test specimens, (4-6) repeated test specimens

3.3. Comparison between Static and Repeated Test Results

Test results revealed that applying five cycles of repeated load to the steel fiber reinforced RPC two-way slab specimens led to a decreasing in the ultimate load capacity as it is clear in Table 10., and that loading-unloading process caused a fluctuation of stresses and more damages in concrete in a comparison with the static or monotonic load. Repeated load also affected the ultimate deflection of the specimens, where the ultimate deflections of R0.5 %, R1 %, and R1.5 % specimens were lower than that of S0.5 %, S1 %, and S1.5 % by 1.1 %, 21.1 %, and 17.6 % respectively as it is shown in Figure 10. The mode of failure of the repeated specimens was similar to that of static specimens, where a flexural failure occurred in all specimens. It was also observed that the ultimate strains of the specimens under repeated load were lower than that of the corresponding specimens tested under static load by 9.2 %, 10.32 %, and 7.1 % respectively. As it is clear from Table 11, the repeated load significantly reduced the absorbed energy of the specimens, where the absorbed energy had been decreased by 49.6 % and 53.1 % for R1 % and R1.5 % respectively, in a comparison with the corresponding static tested specimens. While for R0.5 % specimen, the difference was relatively small (5.3 %), since the repeatedly tested specimen was stiffer than the corresponding statically tested specimen, where the compressive strength of the cubic control specimens of R0.5 % specimen was greater than that of the corresponding S0.5 % specimen, where the specimens were not identical. The load-strain behavior of the RPC specimens and the steel reinforcement under repeated load is shown in Figure 11 and 12 respectively.

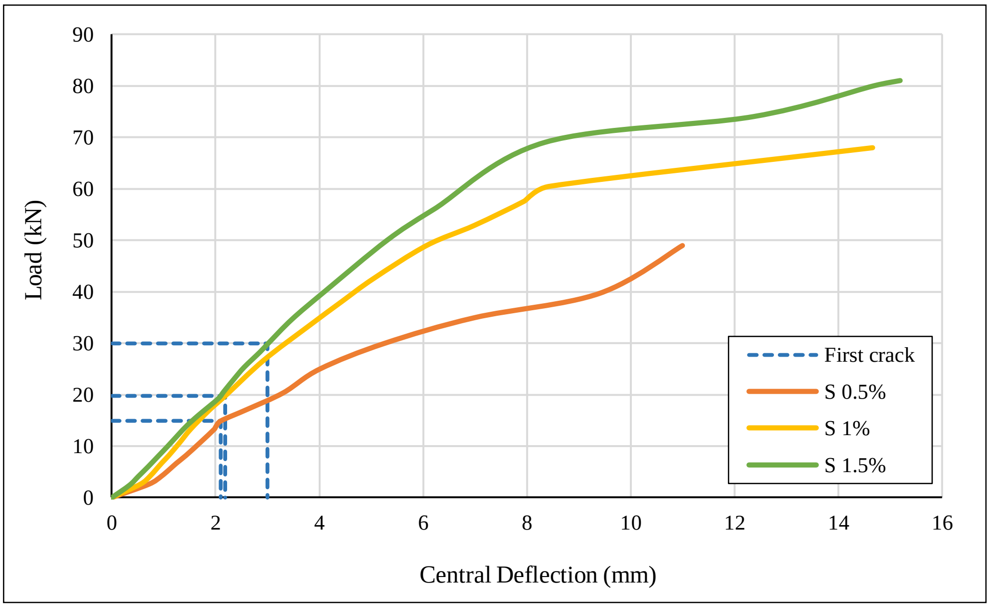


Figure 5. Load-Defection curves of the static test specimens

Table 5. Principal strain at first crack and ultimate load for the static load test specimens

Specimen	Principal strain at first crack	Ultimate principal strain	% Increase in ultimate principal strain
S0.5%	0.005	0.01690	-
S1%	0.00023	0.01708	1.1 %
S1.5%	0.00015	0.01823	6.73 %

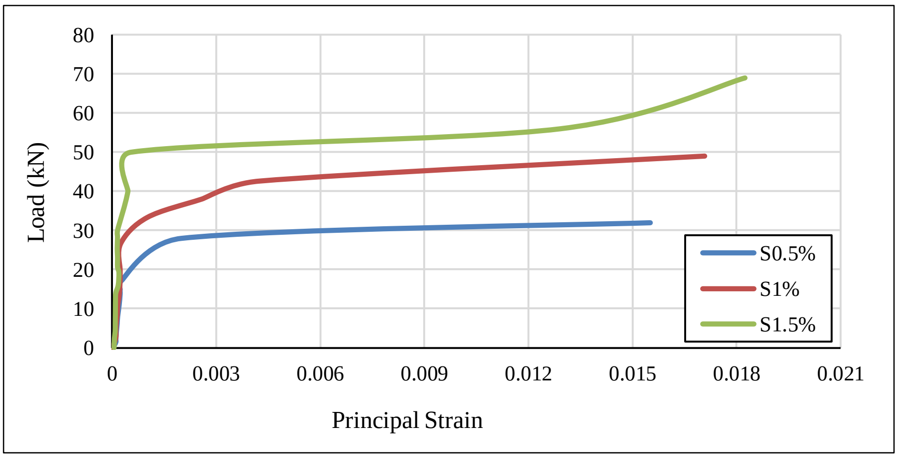
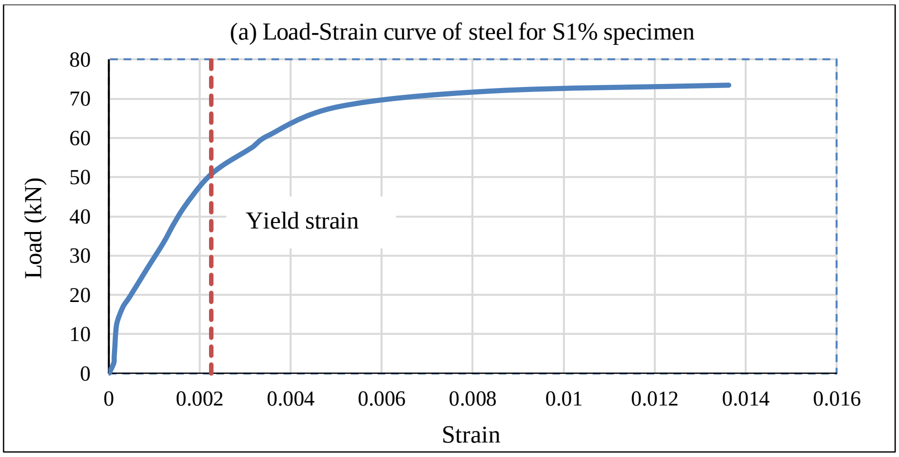


Figure 6. Load-strain curves of the bottom face for all RPC slab specimens of the static test



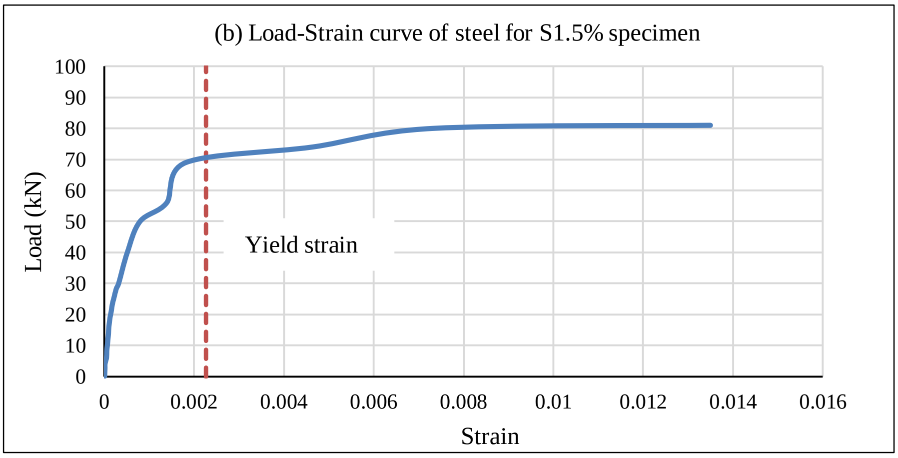


Figure 7. Load-Strain curves of the steel reinforcement of the static test specimens

Table 6. Absorbed energy of the static load test specimens

Specimen	Absorbed energy (kN . mm)	% Increase
S0.5%	300.8	-
S1%	685.9	128.0 %
S1.5%	824.5	20.2 %

Table 7. Central deflection for the repeated load test specimens

Specimen	Central ultimate deflection (mm)
R0.5%	10.88
R1%	12.14
R1.5%	12.93

Table 8. Dissipated energy of the repeated load test specimens at first load cycle

Specimen	Dissipated energy (mm)	% Decrease in dissipated energy
R0.5%	2	-
R1%	1.8	11 %
R1.5%	1.5	20 %

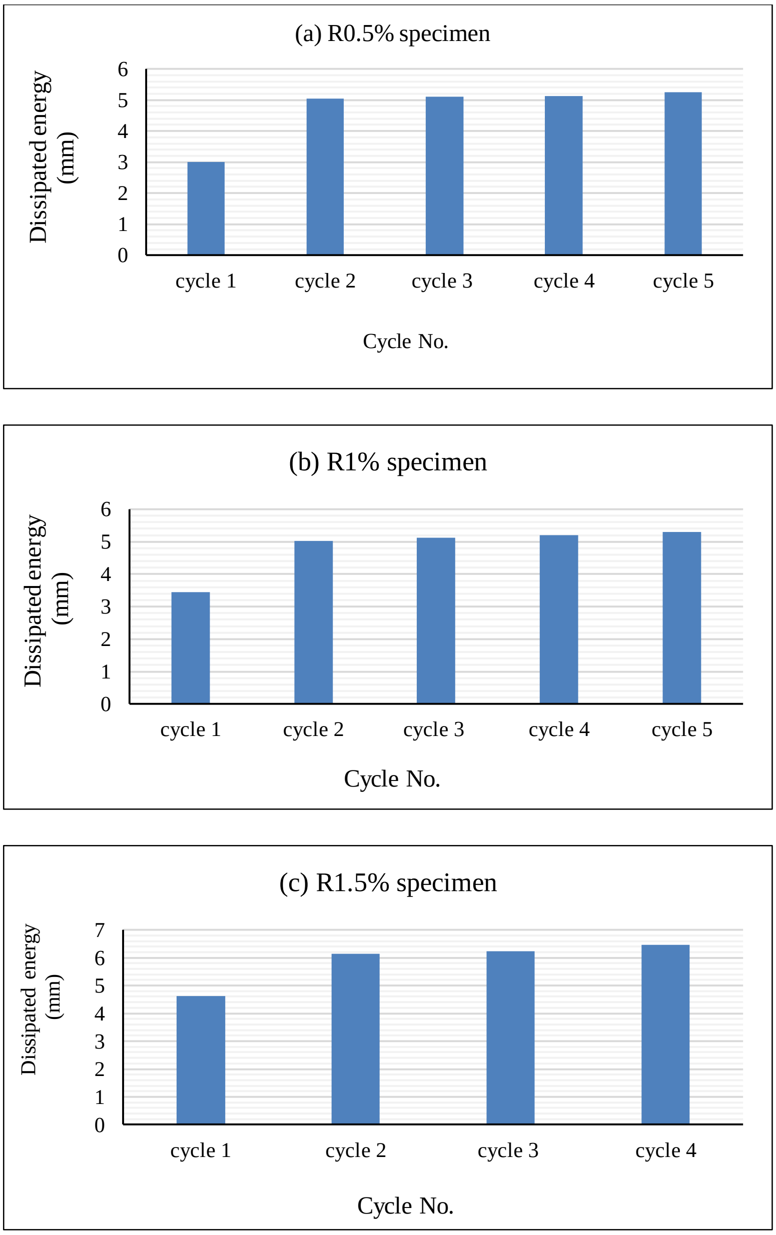


Figure 8. The dissipated energy at different cycles at the minimum loads of the repeated cycles (40 % ultimate load capacity)

Table 9. Absorbed energy of the repeated test specimens

Specimen	Absorbed energy (kN . mm)
R0.5%	285.6
R1%	458.6
R1.5%	538.7

Table 10. Comparison between the ultimate load capacity of static and repeated load tests

Static test		Repeated test		% Decrease in ultimate load capacity
Specimen	Ultimate load (kN)	Specimen	Ultimate load (kN)	
S0.5%	54.0	R0.5%	52	3.8 %
S1%	73.5	R1%	63	16.7 %
S1.5%	86.0	R1.5%	78	10.3 %

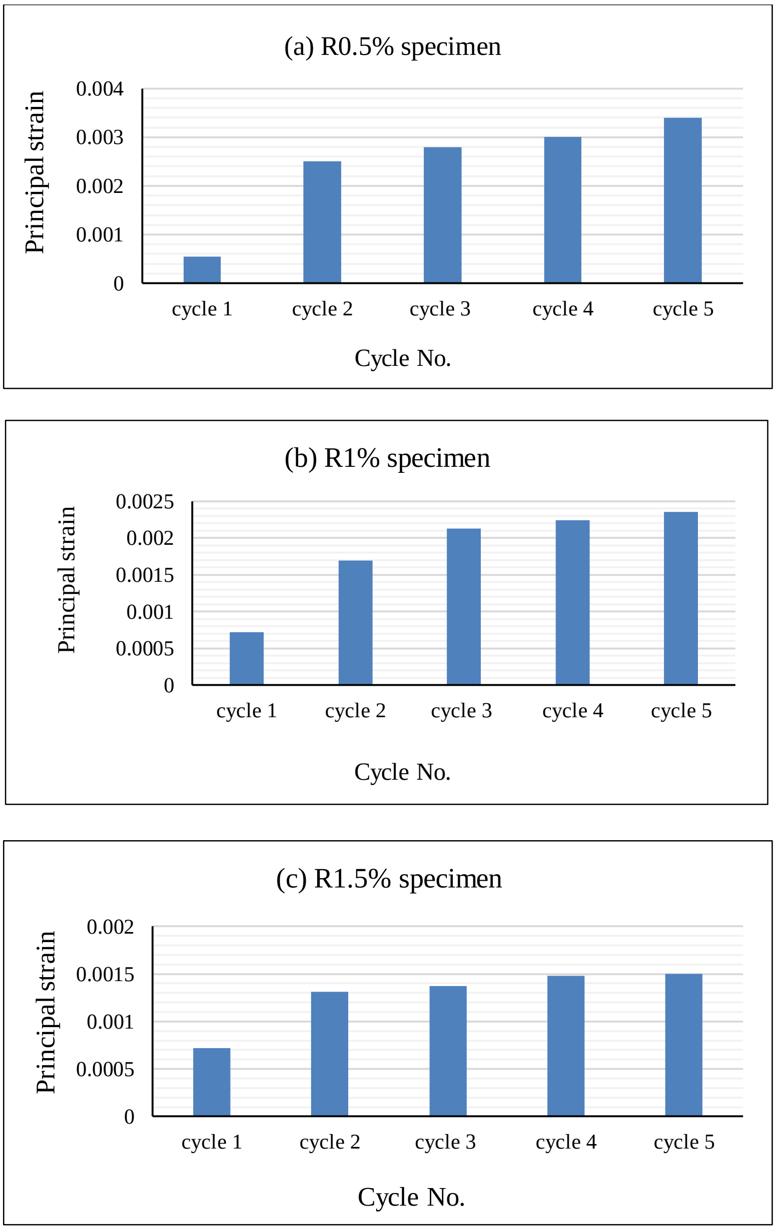
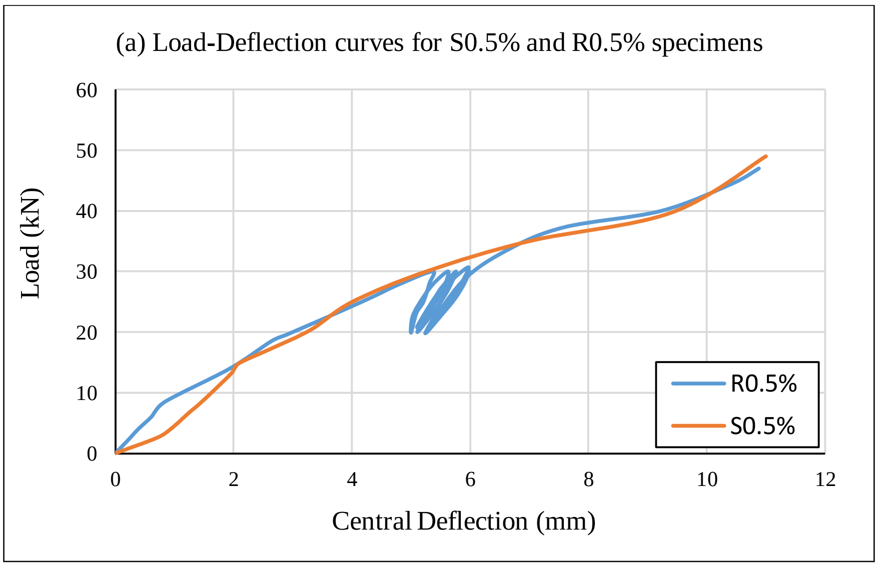
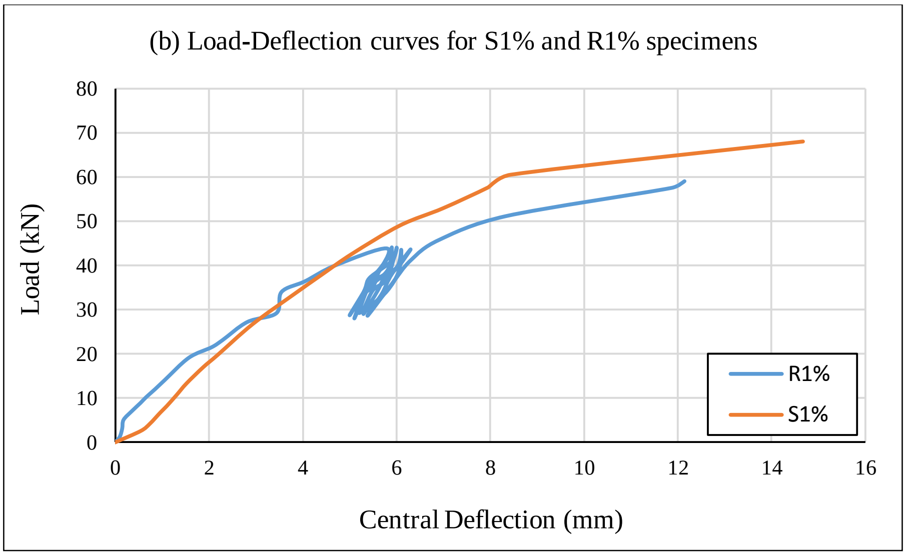


Figure 9. The principal strain at different cycles at the minimum loads of the repeated cycles (40 % ultimate load capacity)





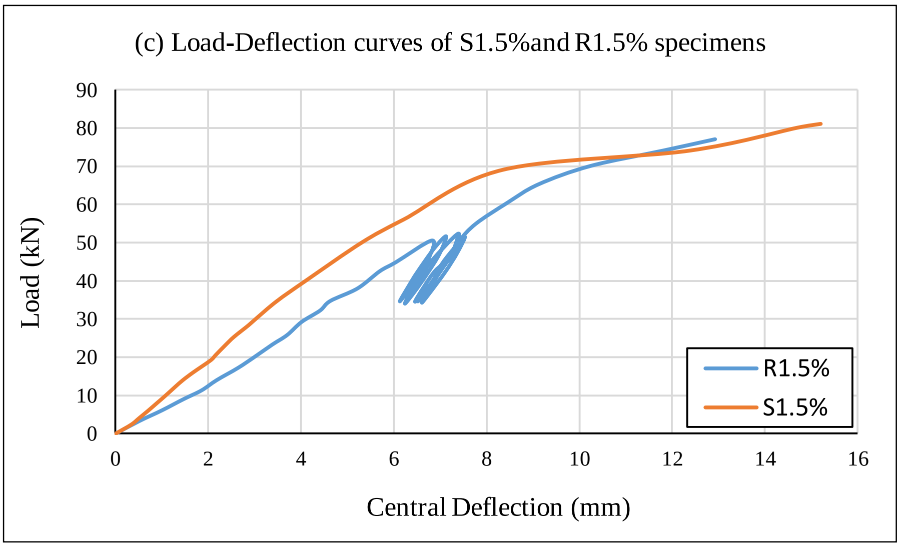
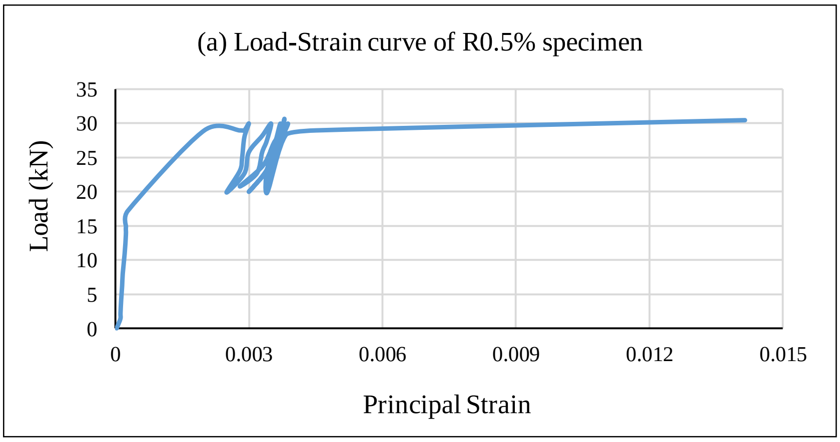


Figure 10. Comparison of the load-deflection curves for static and repeated load tests

Table 11. Comparison of the absorbed energy for static and repeated load tests

Static test		Repeated test		% Decrease in absorbed energy
Specimen	**Absorbed energy (kN.mm)**	**Specimen**	**Absorbed energy (kN.mm)**	
S0.5%	300.8	R0.5%	285.6	5.3 %
S1%	685.9	R1%	458.6	49.6 %
S1.5%	824.5	R1.5%	538.7	53.1 %



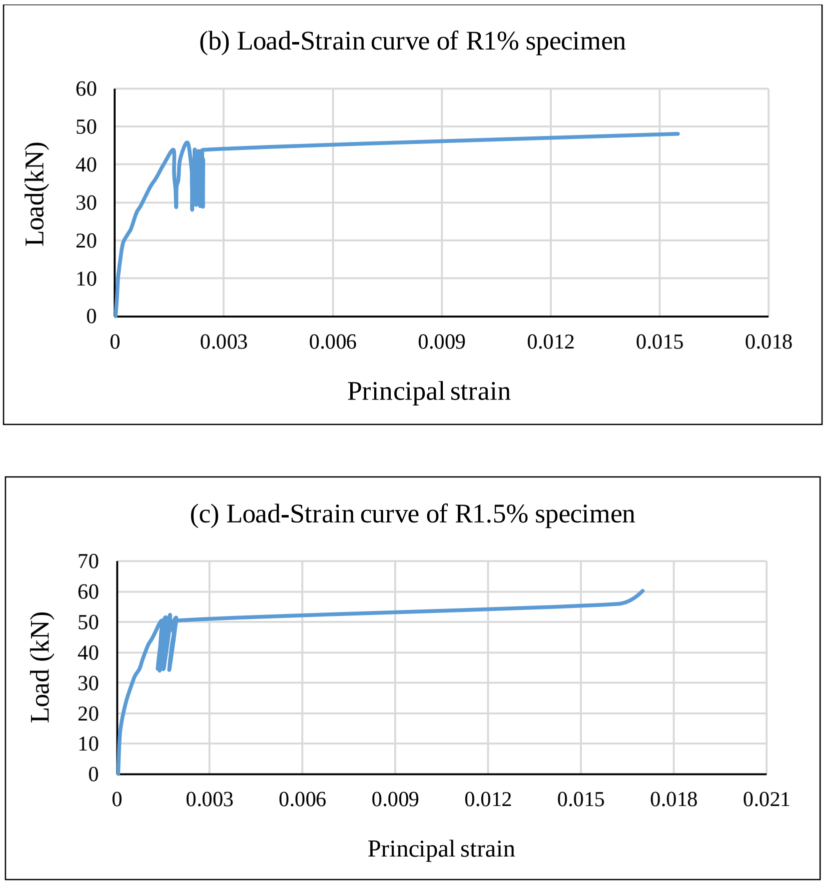
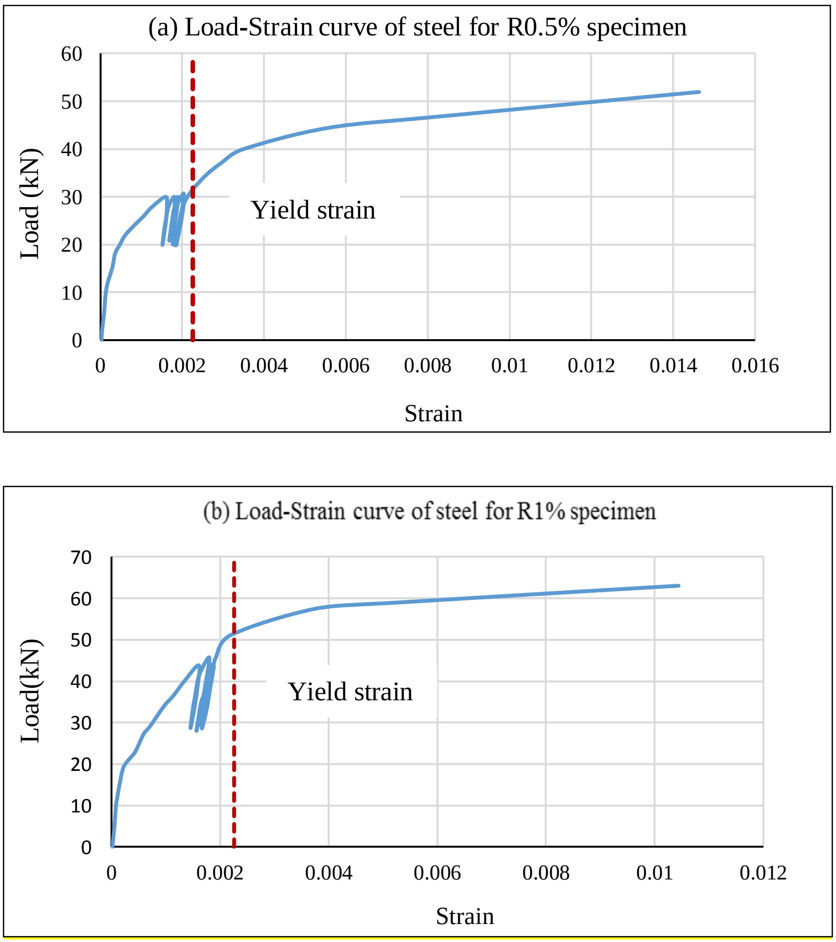


Figure 11. Load-strain curves of the repeated test specimens



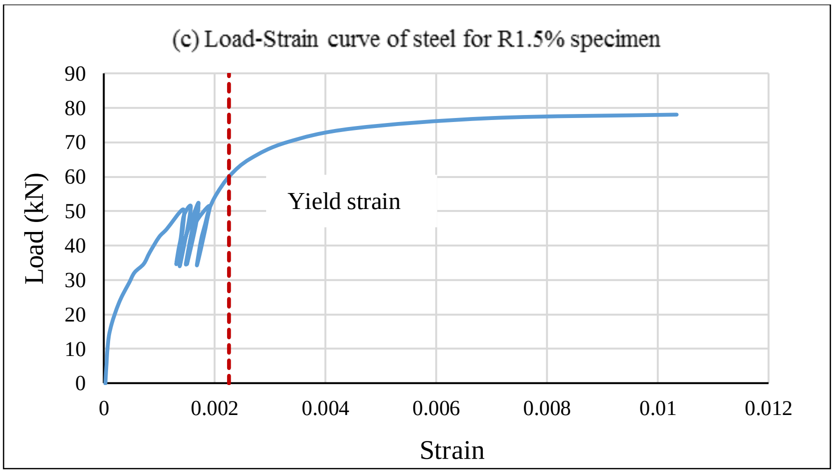


Figure 12. Load-Strain curves of the steel reinforcement of the repeated test specimens

4. Conclusion

- Static test results revealed that increasing steel fibres volume fraction from 0.5% to 1% and from 1% to 1.5%, led to an increase in the: first crack load by (32.2 %, 52.3 %), ultimate load by (36.1 %, 17.0 %), ultimate deflection by (33.6 %, 3.4 %), absorbed energy by (128 % and 20.2 %), and the ultimate strain by (1.1 %, 6.73 %). It also increased the stiffness and the ductility of the specimens especially at the final stages of loading. Additionally, it delayed the propagation of the cracks, controlled their growth, kept the integrity of the specimens at post cracking stage, and avoided their ruin at the failure stage through its "bridging" effect.
- Applying five cycles of repeated load to the steel fibre reinforced RPC two-way slab specimens leads to a decreasing in the ultimate load capacity, ultimate deflection, ultimate strain, and absorbed energy in a comparison with the corresponding static test specimens, and that because of the loading-unloading process which causes a fluctuation of stresses and more damages in concrete.
- The crack pattern of the slab specimens that subjected to the repeated load was nearly similar to that of the specimens under static load, however; further cracks had been developed and widened when the number of loading cycles was increased.
- Increasing the steel fibers volume fractions decreased the dissipated energy of the specimens that subjected to a repeated load, where the difference percent of dissipated energy between the first and second cycles of (S0.5%, S1%, and S1.5%) specimens were (68.0 %, 46.2%, and 32.4%) respectively, this could be caused by the positive effects of increasing the steel fibres volume fraction which are increasing the ductility of concrete and decreasing the permanent deformations (dissipated energy).
- The greatest effect of the repeated load happened at the first cycle, where the differences in the dissipated energy and the principal strain between the last four cycles were relatively small in a comparison with the difference between the first and the second cycles. For example, the difference percent between the first and second cycles of the dissipated energy and the principal strain for S1 % specimen, were (46.2 %, and 134.7 %) respectively, while the average difference between the last four cycles were (1.8 %, and 12%) respectively.

5. References

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