Improved bending behaviour of steel fibres recycled aggregate concrete beams with a concrete jacket

Ali Anvari[1], Mansour Ghalehnovi[2*], Jorge de Brito[3], Arash Karimipour[4]

Abstract. The flexural behaviour and ductility ratio of reinforced concrete beams made with steel fibres and coarse recycled aggregate and strengthened after failure are studied. Eight reinforced concrete beams (cross-section 150 by 200 mm) and 1500 mm span, with various transverse reinforcement spacings, were manufactured and tested. Recycled aggregates from building demolition were used at 0% and 100% by mass to replace natural aggregates. Furthermore, steel fibres were added to improve the flexural behaviour of the beams at 0% and 2% (by volume). Both shear and flexural failures in a four-point bending test were analysed in specimens with various transverse reinforcement spacings. First, the specimens were tested to failure and then strengthened with a concrete jacket. In these tests, the flexural capacity, maximum displacement at mid-span and ductility before and after strengthening using the concrete jacket were measured. The effects of the steel fibres and of the transverse reinforcement spacing on the flexural behaviour of recycled aggregate concrete beams, with and without a concrete jacket, were determined. Concrete jacketing is an efficient method to strengthen recycled aggregate concrete beams and the ductility ratio increased when steel fibres, recycled aggregate and both of them were used by 160%, 24% and 146% respectively.

Keywords: beams & girders, failure, fibre-reinforced concrete.

Acronyms and symbols: CB - concrete beam; CJ - concrete jacket; DR - ductility ratio; NA - natural aggregates; RA - recycled aggregates; RC - reinforced concrete; SF - steel fibres; SFRC - steel fibres reinforced concrete; TR - transverse reinforcement; $\Delta_{0.85}$ - displacement at 85% of the maximum load; Δ_y - displacement at first yield; A_{s1} - cross-section area of tensile rebars in original beam; f_{s1} - tensile stress of tensile rebars in original beam; P_{ult} - ultimate load; M_u - ultimate moment strength; b - cross-section width; h - effective height of cross-section; ρ - percentage of steel rebars; f_{sc} - tensile yield strength of the rebars; f_{cc} - ultimate compressive strength of concrete.

Introduction

Cement, gravel, sand and water are the main materials to manufacture concrete members but using cement and natural aggregates (NA) represents high costs and environmental impacts (e.g. resulting from gases such as carbon dioxide that affect the environment and animals' life). Therefore, recycled aggregates (RA) and other waste materials help to protect natural resources and can be used to manufacture concrete members, replacing both cement and NA. Many studies have been done on the effect of waste materials on the behaviour of concrete (Patil and Sangle 2013, Boukour and Benmalek 2016, Ganjian et al. 2009, Saberian et al. 2018, Hunag et al. 2016and Asadi Shamsabadi et al. 2018). Blessen et al. (2015) studied the effect of scrap tire rubber on the mechanical behaviour of high-strength concrete. In their study, crumb rubber replaced NA at 0%, 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5% and 20%, respectively. Using RA led to a

---

[1] Department of Civil Engineering at Ferdowsi University of Mashhad, Mashhad, Iran; Email: A_anvari@yahoo.com
[2] Department of Civil Engineering at Ferdowsi University of Mashhad, Mashhad, Iran; Email: Ghalehnovi@um.ac.ir
[3] CERIS, Department of Civil Engineering, Architecture and Georresources, Instituto Superior Técnico, Universidade de Lisboa, Portugal; Email: jb@civil.ist.utl.pt
[4] PhD student at Department of Civil engineering at Texas University at El Paso and the member of Center for Transportation Infrastructure Systems (CTIS), Texas, USA, akarimipour@miners.utep.edu,
*Corresponding author: Mansour Ghalehnovi

reduction of the durability of concrete, but abrasion resistance and water absorption improved. Ganjian et al. (2009) used tire waste to replace NA and found a reduction (10-25%) of compressive strength. Aslani et al. (2017) tested the influence of rubber aggregate on concrete's compressive strength. In their study, NA were replaced at 10%, 20%, 30%, and 40% (in terms of volume). The obtained results showed that the compressive strength was not significantly affected. Furthermore, the effect of RA on the mechanical properties of materials used in the base and subbase layers of pavement has been analysed by Li et al. (2018) and Saberian et al. (2018).

Ramdani et al. (2018) studied the physical and mechanical behaviour of RA concrete. In their study, rubber waste replaced NA at 10%, 20%, 40% and 60%. Also, glass and natural sand powder replaced cement at 15%. Specimens were tested in the fresh and hardened state. The obtained results indicated that the compressive strength increased by about 10-20% by using glass powder and RA. Furthermore, the incorporation of RA improved concrete's workability. Usahanuntha et al. (2018) studied the mechanical properties and made recommendations on the application of Bakelite waste as aggregates in concrete. The obtained results indicated that RA of different sizes can replace both fine and coarse NA. Also, the optimal replacement content of RA was 20%. In another investigation, Awoyera et al. (2016) used ceramic waste as fine and coarse RA and investigated its effect on the behaviour of concrete. The compressive and splitting tensile strengths were determined after curing for 3, 7, 14 and 28 days. The results showed that that compressive and splitting tensile strengths increased more with the curing age more than in conventional concrete.

Wong et al. (2017) used brick aggregate and presented a review in this field. The mechanical behaviour and durability-related properties of concrete were the aims of the study. They concluded that the most feasible use of RA is in the form of brick dust, whereby up to 20% cement replacement may improve the strength and some durability properties of concrete. Arora and Singh (2015) studied the flexural fatigue behaviour of a concrete beam (CB) manufactured with 100% coarse RA. In their study, specimens with a cross-section 100 mm wide and 100 mm high, and a length of 500 mm, were manufactured and tested by four-point flexural loading. The obtained results were compared with those of CBs manufactured with NA. It was shown that using 100% RA in concrete mixes resulted in poor fatigue performance. Recently, Chaboki et al. (2018) evaluated the flexural behaviour and ductility ratio (DR) of CBs with different contents of steel fibers (SF) and coarse RA. Furthermore, the experimental flexural strength was compared with ACI, CSA and Eurocode 2 estimations. For this purpose, 27 reinforced concrete (RC) beams, with a cross-section 150 mm wide, 200 mm high, and with a length of 1500 mm, with various transverse reinforcement (TR) spacings, were manufactured and tested through a four-point bending test. RA from building demolition was used at 0%, 50% and 100% mass replacement of NA. Furthermore, SF was added at 0%, 1% and 2% (in terms of volume) to improve the flexural behaviour of the RC beams. In this test, the flexural capacity, maximum displacement at mid-span of the specimens and ductility were measured. The results showed that the individual effects on the DR and maximum loading capacity depend on the other parameters (e.g. the SF effect depends on the TR spacing and the effect of RA depends on both the SF content and the TR spacing).

Azad (2017) studied the flexural behaviour of RC beams made with recycled waste materials. In this study, polyethene terephthalate (PET) waste was used as recycled material. The compressive strength, maximum load capacity, load-deflection behaviour, stiffness and failure modes of the specimens were determined. The results showed that PET waste can be added in concrete up to 15%. Guo and Zhang (2014) evaluated the flexural performance of SF coarse RA concrete. In their study, SF was added at 0%, 0.5%, 1%, 1.5% and 2% (in terms of volume). Furthermore, coarse RA replaced NA at 0%, 30%, 50% and 100% (per volume). According to the results, the flexural strength, toughness and deflection dramatically increased with the SF content. Based on previous researches, it is clear that adding SF to RA CBs is an effective way of improving their flexural behaviour (Guo et al. 2014, Ghalehnovi et al. 2019 and Carneiro 2014). Also, previous studies confirmed the positive effect of SF on reducing crack propagation (Meda et al. 2012 and Soutsos et al. 2012). Furthermore, SF help to prevent brittle fracture by increasing the tensile strength and toughness.

Sometimes, it is necessary that beams are strengthened before or after concrete casting. Before manufacturing concrete, using materials such as SF helps to improve the flexural and shear behaviour of RC beams. SF are manufactured using high-strength steel in different sizes and shapes. Kim et al. (2008) investigated the behaviour of steel fibres reinforced concrete (SFRC) beams with SF at 0.4% and 1.2%. The specimens were tested under four-point bending test. The results showed that the bearing capacity and energy dissipation improved significantly in addition to a better control of multiple cracking. Altun and Aktas (2013) examined the effect of SF on the flexural performance of lightweight concrete (LWC) beams. Since LWC has a lower modulus of elasticity, cracks propagate faster in RC members manufactured with LWC than normal density and high-strength concrete. However, SF are used as an added material in concrete in order to increase the energy dissipation and control cracks propagation. Therefore, SF (at 0%, 1% and 2%) were added to LWC and its effect on the flexural performance of RC beams was investigated, through four-point bending tests. The results showed that SF increase the toughness capacity of prismatic CBs and their ductility.

Yoo et al. (2015)] studied the post-cracking of normal and high-strength SFC beams. In this research, specimens were manufactured and tested according to the Japan Concrete Institute (JCI) standard. The suggested models were confirmed through a comparison of the previous flexural test outcomes. The compressive strength and modulus of elasticity showed negligible changes with the incorporation of SF, while the strain capacity and post-peak behaviour improved. Furthermore, flexural resistance, post-peak ductility and deflection capacity significantly increased by using 1% SF. Also, Mertol et al. (2016) considered the effect of SF contents on the flexural behaviour of RC beams. In their study, 20 specimens with a cross-section width of 180 mm and height of 250 mm, 3500 mm length, and with different SF contents were manufactured and tested. 10 different longitudinal reinforcement ratios (ranging from 0.2% to 2.5%) were also used. The ultimate bearing capacity, ultimate displacement, service stiffness, post-peak stiffness, shear and flexural toughness were determined. Experimental load–deflection relationships were also compared with those from the strain compatibility theory and best fit stress-strain relationships of SFC in tension and compression were determined. The results showed that, for over-reinforced designed specimens, the post-peak stiffness of the SFC specimens is seen to be expressively lower than that of normal weight concrete (NWC) specimens. Luccioni et al. (2017) studied the static and dynamic behaviour of SFRC beams. Static classification tests were carried out on slabs and the obtained results of blast tests were calculated and analyzed. Improvements were found in static bending response at different fibres contents compared to those conducted under dynamic loading.

In another investigation, Lim and Paramasivam (2015) analysed the shear and flexural resistance of SFRC beams and an analytical formula was proposed by using the usual cross-section analysis and fully plasticized stress blocks and forces. For this aim, 22 CR beams were manufactured and tested under four-bending setup. During this research, the maximum flexural strength, load-displacement behaviour and maximum deflection of specimens were evaluated. The outcomes indicated that SF can replace TR partially or fully as long as parity in the TR factor is maintained. Dupont and Vandewalle (2015) analysed the flexural resistance of 28 SFRC beams with different SF contents under four-point bending test. The different tested parameters were SF content, concrete compressive strength, span to depth ratio and rebar ratio. Furthermore, the experimental load deflection outcomes were compared with theoretical load deflection results. The results demonstrated that the influence of the fibres on the flexural capacity is rather small.

Kuang and Bączkowski (2008) tested SFRC beams under monotonic loading. The ultimate shear resistance and post-peak load performance of the beams were investigated, as function of span-to-depth ratio, TR ratio, and SF content in concrete. The experimental outcomes indicated that SF enhance the post-cracking tensile strength of concrete, and increase the shear capacity of RC beams. Jain and Singh (2014) used SF at a minimum TR content in order to improve the shear behaviour of RC beams. Two kind of SF (crimped and hooked-end) were used. The specimens were conventionally detailed according to the ACI building code and Indian code formulas for the minimum TR content. The beams reinforced with hooked-end fibres had about 50% higher shear strengths than those containing crimped fibres. You et al. (2017) evaluated the effect of SF on the shear performance of T-beams. Specimens were subjected to four-point flexural test for various SF contents. The results showed that SF can significantly improve the ultimate shear resistance of RC beams. On the other hand, the ultimate experimental shear load was compared with the value obtained from the proposed equation in order to estimate the shear behaviour of SFRC T-beams.

Lee et al. (2018) determined the structural response of SFRC beams under different loading rates. In their study, the specimens were subjected to static, impact, and blast loading. Using SF enhanced the ductility of RC beams regardless of the strain rate. Furthermore, the SF contribution to shear resistance was evaluated under various loading types. The results showed that the static shear resistance of SFRC beams effectively improved. In another study, Mahmod et al. (2018) considered SF self-compacting concrete as a new material that can flow under its own weight in the fresh state. In this research, the effect of SF on the splitting tensile strength, compressive strength, and modulus of elasticity were studied. 14 RC beams were manufactured and tested under monotonic loading. The results indicated that the flexural strength increased by increasing the SF content. According to previous researches, using SF is an effective method of improving the behaviour of RC beams before failure. On the other hand, in some cases, it is necessary to improve the behaviour of RC beams after failure. Repairing damaged CBs is often needed and one of the primary methods to do it is by using a concrete jacket (CJ). On the other hand, using concrete, brick, stone and rubber wastes can help protect the environment. These materials can replace cement or aggregate or be added to a concrete mix as additions. Many researches have been done on repairing CBs using CJs under given load combinations.

Chalioris and Pourzitidis (2012) used self-compacting JCs in order to rehabilitate the shear-damaged RC beams. Three shear-conditioned beams were initially subjected to monotonic four-point bending loading. Then, the damaged beams were repaired using CJs, applied to the bottom width and both vertical sides of the beams. Furthermore, the small diameter steel bars and U-formed stirrups used in the jacket were designed in order to increase the shear capacity of the initially tested beams and to change their brittle failure mode and gain ductility. The results showed that jacketing is a promising rehabilitation method since the strength and overall performance of the jacketed beams was better than those of the initial specimens. In another study, Altun (2004) studied jacketed RC beams under bending. In this study, SFRC was used in jackets to repair damaged CBs. To measure the effect of jacketing, the flexural behaviour of the initial and the strengthened RC beams (after the former were loaded to full plastic yield under bending) were analysed. According to the results, the mechanical behaviour of the jacketed RC beams was slightly better than the original RC beams. Behara et al. (2016) investigated the torsional behaviour of RC beams with ferrocement mesh layers U-jacketing. The "U" jackets were found to provide better carrying capacity under all states of torsion. Similarly, over reinforced beams (beams reinforced with more reinforcement than strictly needed) have greater torsion capacity than those reinforced with the design reinforcement content or below.

Ruano et al. (2014) used SF as a retrofitting material of RC beams, repaired and strengthened with SFRC jacketing and tested for shear. For this purpose, the RC beams were designed with a high amount of longitudinal steel rebars and minimum TR content. Some of the beams were strengthened with very fluid high-strength SFRC jacketing and some others were first tested for shear until failure and then were jacketed. CJs were manufactured in both plain concrete and SFRC with two different SF contents (30 kg/m^3 and 60 kg/m^3). The results showed that the repaired beams had excellent strength and deformation capacity recovery. However, the undamaged jacketed beams had higher load-bearing capacity than those tested and then jacketed. Monir et al. (2017) analysed the flexural behaviour of RC beams strengthened by using CJs. The analysis of jacketed RC beams considering the interfacial slip effect is a complicated problem. In their study, the slip between jacket and beam was neglected in the analysis and monolithic behaviour. Therefore, a simplified method was developed to analyse jacketed RC beams taking into account the interfacial slip distribution and the actual nonlinear behaviour of both concrete and steel rebars. This method provides an evaluation of the bond slip and shear stress distributions, which allows assessing the influence of the surface's roughness condition. In another study, Monir et al. (2018) assessed again the flexural behaviour of RC beams strengthened with CJs. In this study, an iterative calculation algorithm was developed to determine the moment-curvature relationship of a jacketed beam with different cross-sections. This new method allows the evaluation of the interfacial slip and shear stress distributions in ductile RC beams, and is was also used to conduct an extensive parametric study, which resulted in modification factors that can be used to calculate the bearing capacity and deformations of a strengthened beam considering the interfacial slip.

The ductility index of specimens is a suitable parameter to evaluate the flexural behaviour of RC beams. Cohn and Bartlett (1982) proposed a relatively more appropriate definition of a displacement ductility index. Based on their definition, this index can be estimated as the ratio between the displacement at 85% of the maximum load in the post-peak portion of the curve and the displacement at first yield of the beam (Eq. 1 and Fig. 1).

(1) $\mathrm{i} = \frac{\Delta_{0.85}}{\Delta_y}$

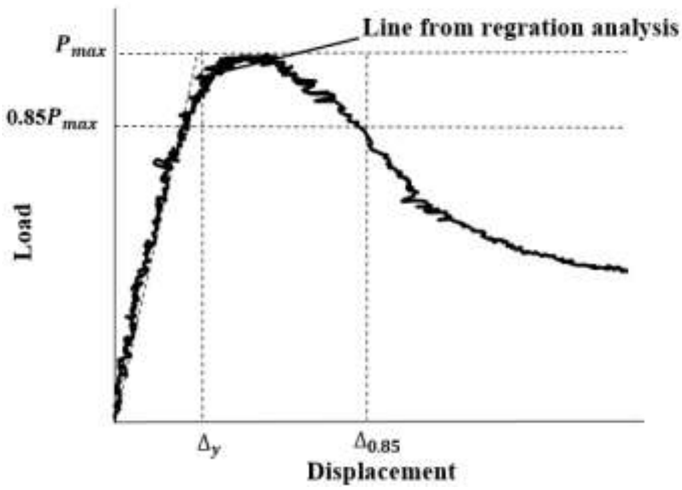


Fig. 1. Definition of the displacement-DR relationship (Cohn and Bartlett 1982)

Research significance

A review of the literature indicates that considerable research work has been carried out to investigate the flexural behaviour of RA CBs and repairing beams using CJs. According to previous studies, using CBs improves the flexural and shear behaviour of RC beams. Therefore, in this study, the effect of CJs on the flexural and shear behaviour of coarse RA RC beams was studied focusing on both shear and flexural failure mode according to the TR's spacing. Also, the obtained outcomes are compared with the presented equations in order to determine the behaviour of RC beams strengthened with CJs.

Materials and specimen's specifications

Geometry and properties of the specimens

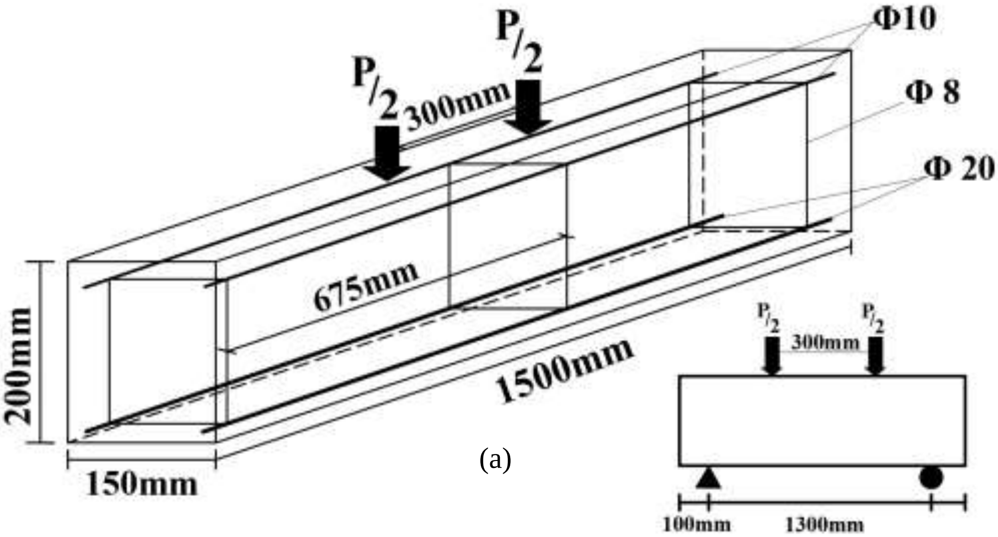
In this research, a total of nine RC beams, with a cross-section 150 mm wide and 200 mm high, and a length of 1500 mm, were manufactured using different volumetric contents of SF and replacement ratios of NA with RA. In these specimens, TR was used with two spacings: 675 mm and 100 mm. Two of these specimens were used as control with no SF and RA. First, the manufactured beams were tested under four-point bending until failure. Then, the specimens were turned back approximately to the initial shape and repaired with a CJ 50 mm thick. The geometry, different components of concrete mix composition and layout of the longitudinal and TR in beams with and without CJs are given in Fig. 2. In all specimens, the distance of the tension and compression bars from the most compressed fibre of the sections is 162 mm and 25 mm, respectively.

Rebars with diameters of 20 mm, 10 mm and 8 mm were used in the tensile region, compressive region and TR, respectively. There is no reinforcement in the CJs. The arrangement of the bars is constant in all the specimens and the compressive and tensile bar areas are 157 mm^2 and 628 mm^2, respectively. Rebars were subjected to direct tension tests and their characteristics are presented in Table 1.

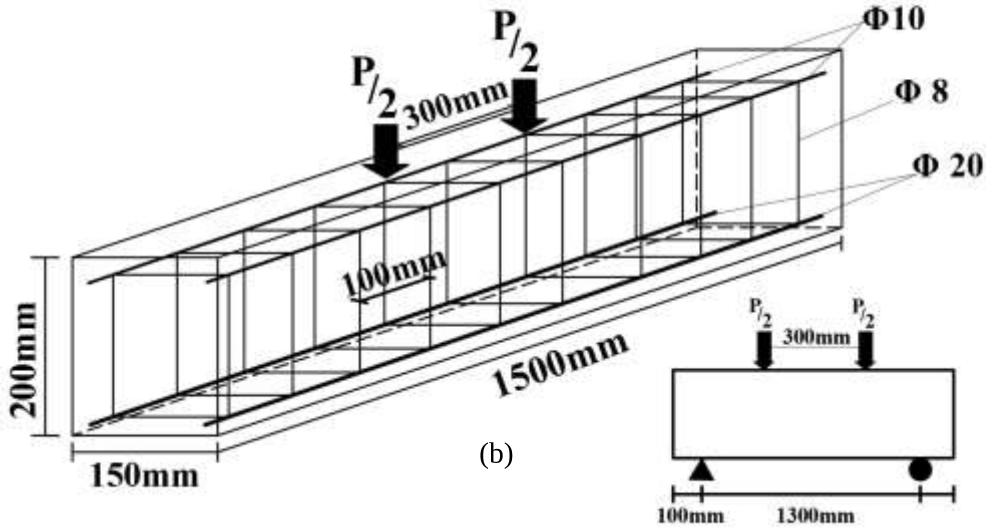
Table 1. Rebars test results

Rebars diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Yield strain (%)	Ultimate strain (%)	Modulus of elasticity (GPa)
8	371	560	12.94	24.93	209.28

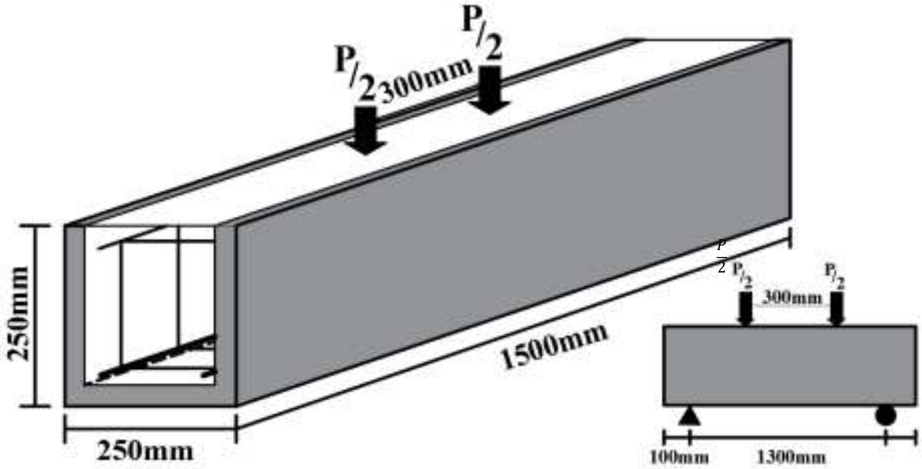
10	408	677	13.04	25.51	210.10
20	371	561	15.27	25.82	213.17



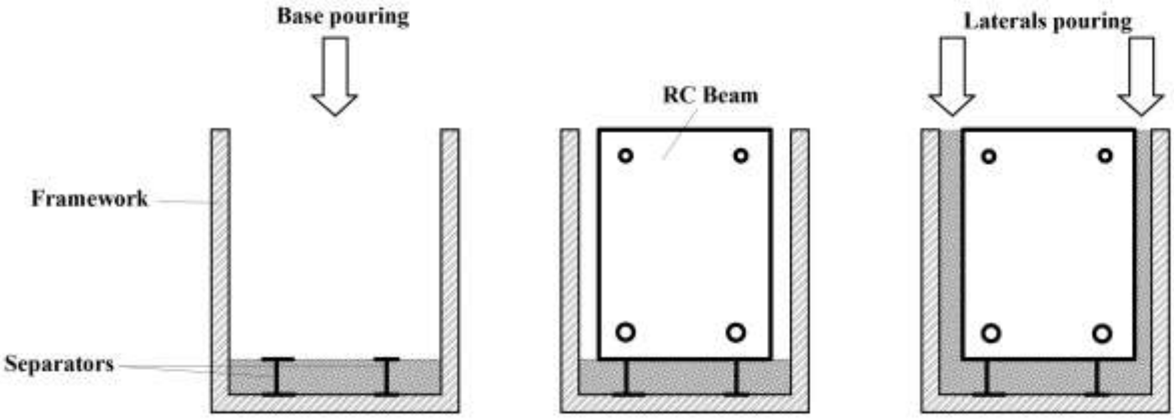
(a)



(b)



(c)



(d)

Fig. 2. Geometry of the beams, layout of the reinforcement a) with no TR b) TR spacing 100 mm c) jacketed specimen d) casting concrete jacket

The NA and RA were characterized using different standards (Chaboki et al. 2018 and Chaboki et al. 2019). In this study, RA and NA were used in the CBs and the CJs were manufactured with no SF and RA. Coarse RA were sourced from building demolition and replaced NA at two mass ratios in the CBs: 0% and 100%. The grading curves of the coarse RA and NA are shown in Fig. 3. The physical and chemical properties of both kinds of aggregates are presented in Tables 2 and 3, respectively.

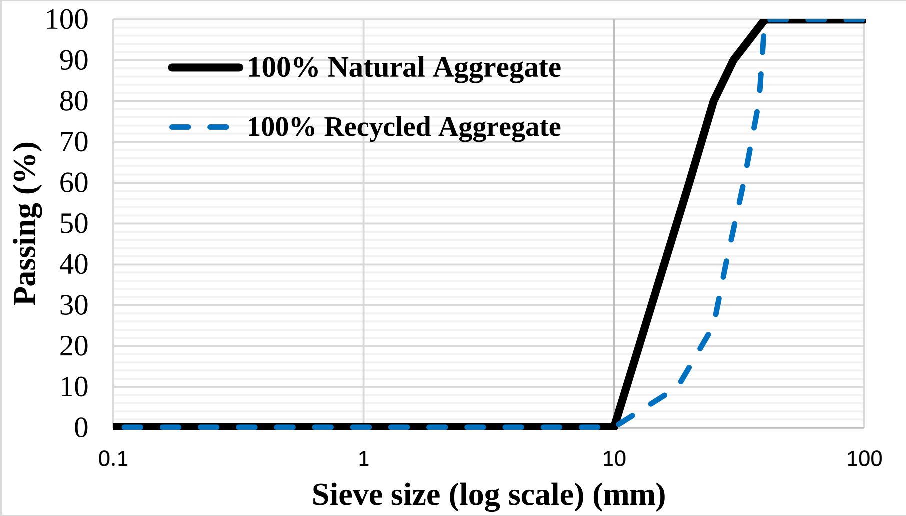


Fig. 3. Grading curves of the coarse NA and RA used in this study

Table 2. Physical properties of the coarse NA and RA

Aggregate type	Apparent density (g/cm^3)	Bulk density (g/cm^3)	Water absorption (wt%)	Crushing index (%)	Porosity (%)
NA	2.76	2.65	1.441	31.0	3.88
RA	2.66	2.56	1.519	46.1	3.76

Table 3. Chemical properties of the coarse NA and RA

Chemical composition	Aggregate type	
	NA	RA
$Ca(CO_3)$ (%)	72.2	-
SiO_2 (%)	27.8	-
$Ca\ Mg(CO_3)_2$ (%)	-	-
$Ca\ Mg(CO_3)$ (%)	-	100
Overall diffraction profile (%)	100	100
Background radiation (%)	22.53	25.12
Diffraction peaks (%)	77.65	74.88
Peak area belonging to selected phases (%)	16.09	47.15
Peak area of phase A (calcium carbonate calcite) (%)	11.14	-
Peak area of phase B (silicon oxide) (%)	4.87	-
Peak area of phase A (calcium magnesium carbonate)	-	47.15

As mentioned before, to produce the CBs, SF with two bent ends were used. These fibres are manufactured with high strength steel. The properties of SF are presented in Table 4.

Table 4. Properties of the SF

Properties	Length (mm)	Tensile strength (GPa)	Elastic modulus (GPa)	Failure strain
SF	8	200	2	3%

Concrete

To manufacture the CBs, cement was mixed with gravel, sand and SF (at 0% and 2%) and then water and a high-performance superplasticizer were added until the SF were uniformly distributed in the concrete matrix. Furthermore, coarse RA replaced NA at 0% and 100%. To manufacture the CJs, the concrete mix was the same as for the CBs with no SF and RA. The concrete mixes and the obtained results of the compressive and tensile test are shown in Table 5.

Table 5. Concrete mixes composition and strength of the concrete mixes

Specimens	B-0R-0S	B-100R-0S	B-0R-2S	B-100R-2S	J-0R-0S
Water (kg/m^3)	165	165	165	165	165
Cement (kg/m^3)	400	400	400	400	400
Steel fibres (kg/m^3)	0.0	0.0	156	156	0.0
Coarse RA (kg/m^3)	0.0	840	0	685	0
Coarse NA (kg/m^3)	840	0	685	0	840
Fine NA (kg/m^3)	950	950	950	950	950
Average tensile stress (MPa)	3.78	4.04	5.01	4.99	3.95
Tensile stress coefficient of variation	0.17	0.09	0.27	0.13	0.21
Average compressive strength (MPa)	37.4	36.1	36.9	35.6	36.8
Compressive strength coefficient of variation	1.01	1.65	1.38	36.8	1.54

Due to the close physical properties of RA and NA, the total water/cement ratio of all samples was kept constant at 0.41. To evaluate the compressive and tensile strength of concrete in each CB and CJ mix, six cylinders with a diameter of 150 mm and height of 300 mm were manufactured and tested under a hydraulic jack. For each mix, the average compressive and tensile strength of three of those cylinders was used. The tensile and compressive concrete strength was determined according to ASTM C293-08 (2008), BS EN 12390-1 (2008), 12390-2 (2000) and 12390-3 (2009).

In Table 5, B, J, R and S indicate the CBs (concrete beams with no concrete jacket), CJs (concrete beams strengthened with concrete jacket), RA and SF's mixes/content, respectively.

Results and discussion

Flexural behaviour and bearing capacity

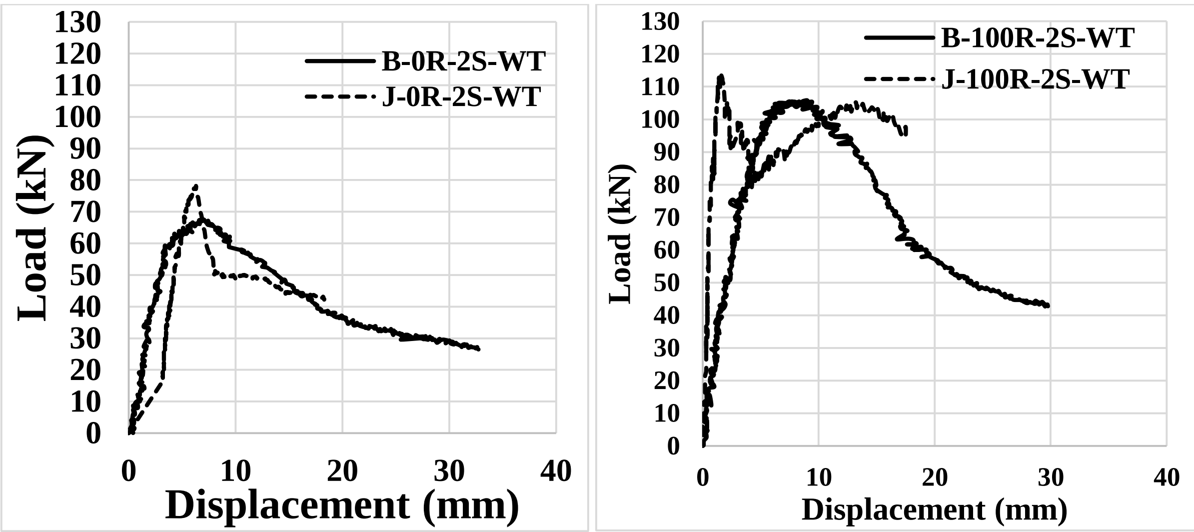
Eight SF coarse RA CBs were manufactured and tested until failure and the effect of TR was considered for both shear and flexural failure. Then, the damaged beams were strengthened using CJs 50 mm thick. The load-displacement relationship of mid-span of specimens, maximum loading capacity, flexural cracks propagation, DR and concrete shear-strain were evaluated.

Test setup and loading condition

The specimens were subjected to a flexural strength test after 28 days. The 1500 mm span beams were supported by round bars and two concentrated linear loads were applied as seen in Fig. 4. These loads were 300 mm apart. The test was performed under displacement control conditions and the stopping condition was set to be the failure of the specimen. The deflection of the beam was recorded at each load step by using LVDTs. Furthermore, vibrating wire strain gauges (VWSG) were used to measure concrete strains. The strain gauges were set up at the bottom concrete surface. The purpose of this test was to determine the flexural and shear behaviour of the beams.

Fig. 4. Test setup

Therefore, in Figs. 5 to 7, the effect of CJs was investigated. According to Fig. 5, reinforcing beams by CJs generally leads to increasing their flexural capacity, as expected. The effect of the CJ on specimens with shear failure (with no TR) is more than on specimens with flexural failure (with TR spaced 100 mm). Furthermore, the maximum displacement of the specimens declined in beams with CJ and specimens failed suddenly. Conversely, reinforcing specimens prevented a significant reduction of the flexural capacity after the maximum load was reached. Also, using 100% RA leads to improving the flexural behaviour when specimens strengthened by using a CJ after failure. Furthermore, SF lead to increasing maximum displacement, also as expected.



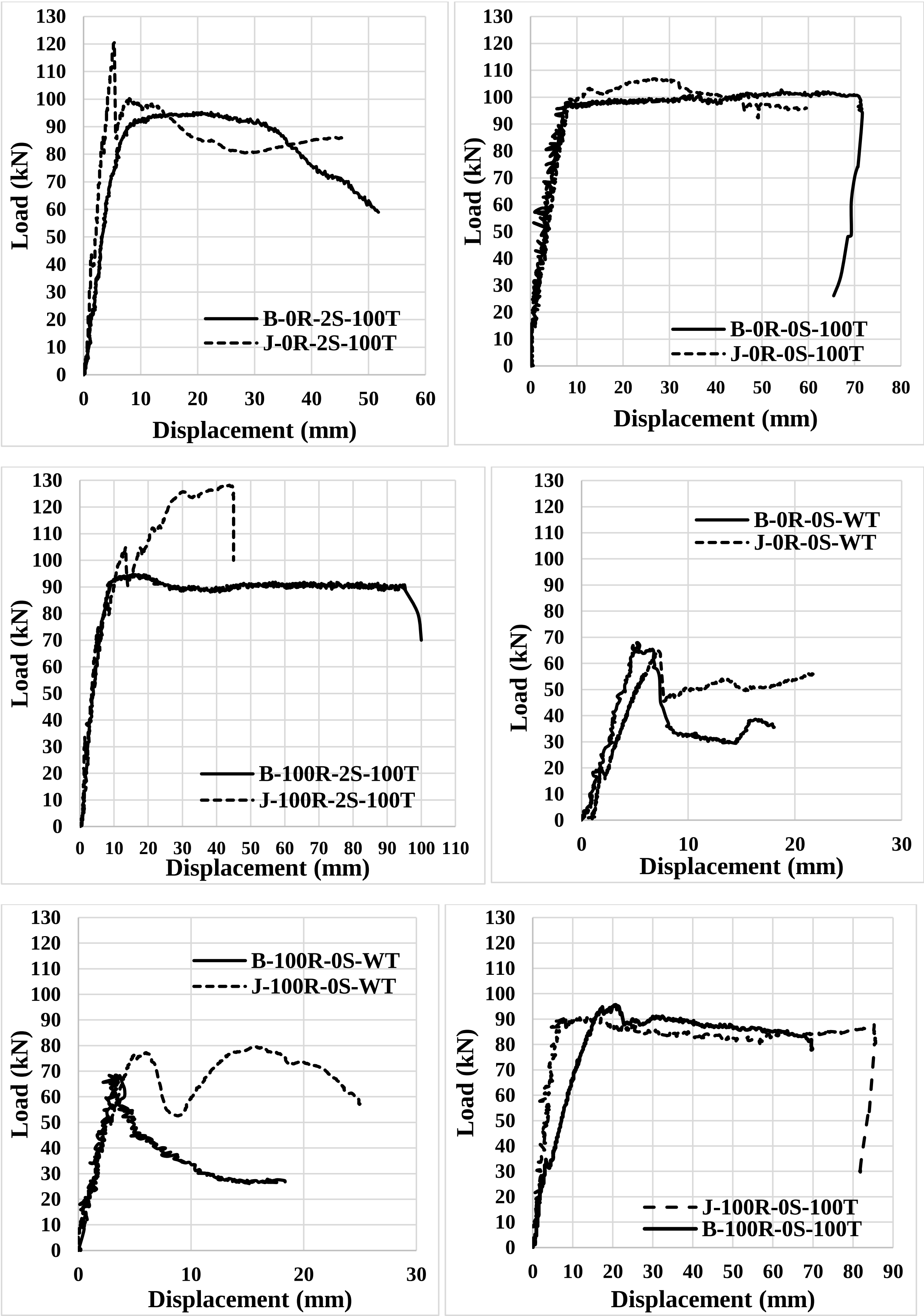


Fig. 5. Load-displacement relationship of specimens

To further investigate the effect of the CJ on the behaviour and failure mode of RA CBs, cracking and cracks propagation in specimens before and after strengthening by using CJ are presented in Fig. 6. In specimens with no TR, failure occurred by shear mode before and after strengthening but cracks propagation considerable declined when specimens were strengthened with the CJ. Furthermore, cracks width decreased in the CJ when SF were used in the beams.

In specimens with TR spaced 100 mm (Fig. 7), there is no significant difference in failure mode in specimens with and without CJ. Cracks propagation in the CJ is less developed compared with CBs without CJ, especially when 100% RA and 2% SF were used.

Ductility ratio

In order to investigate the influence of CJs on the flexural strength and ductility of the specimens with different RA content, SF, TR spacing and JC, the DR was determined for the different specimens as presented in Figs. 8 to 23.

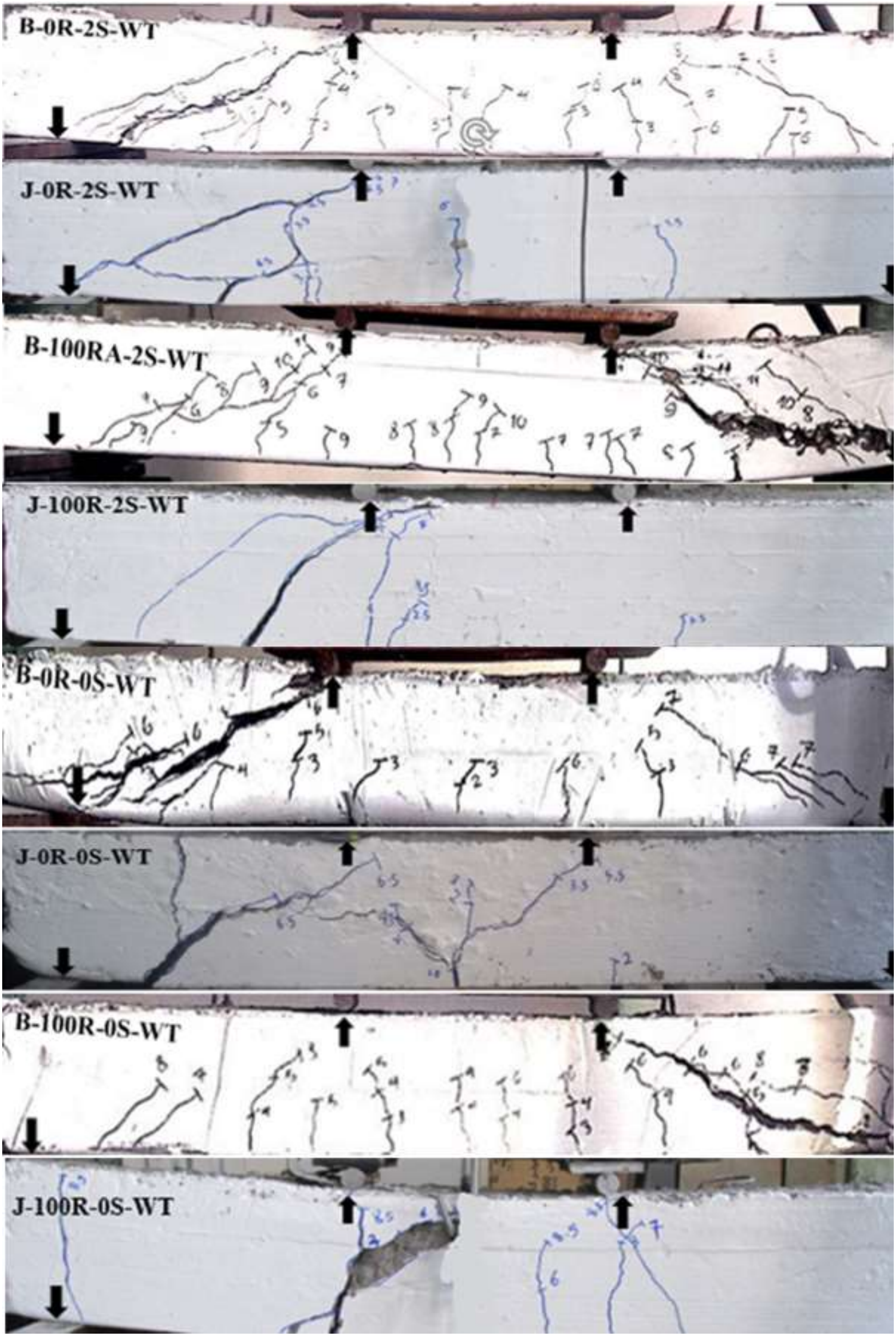


Fig. 6. Failure in specimens with no shear reinforcement and cracks propagation during loading

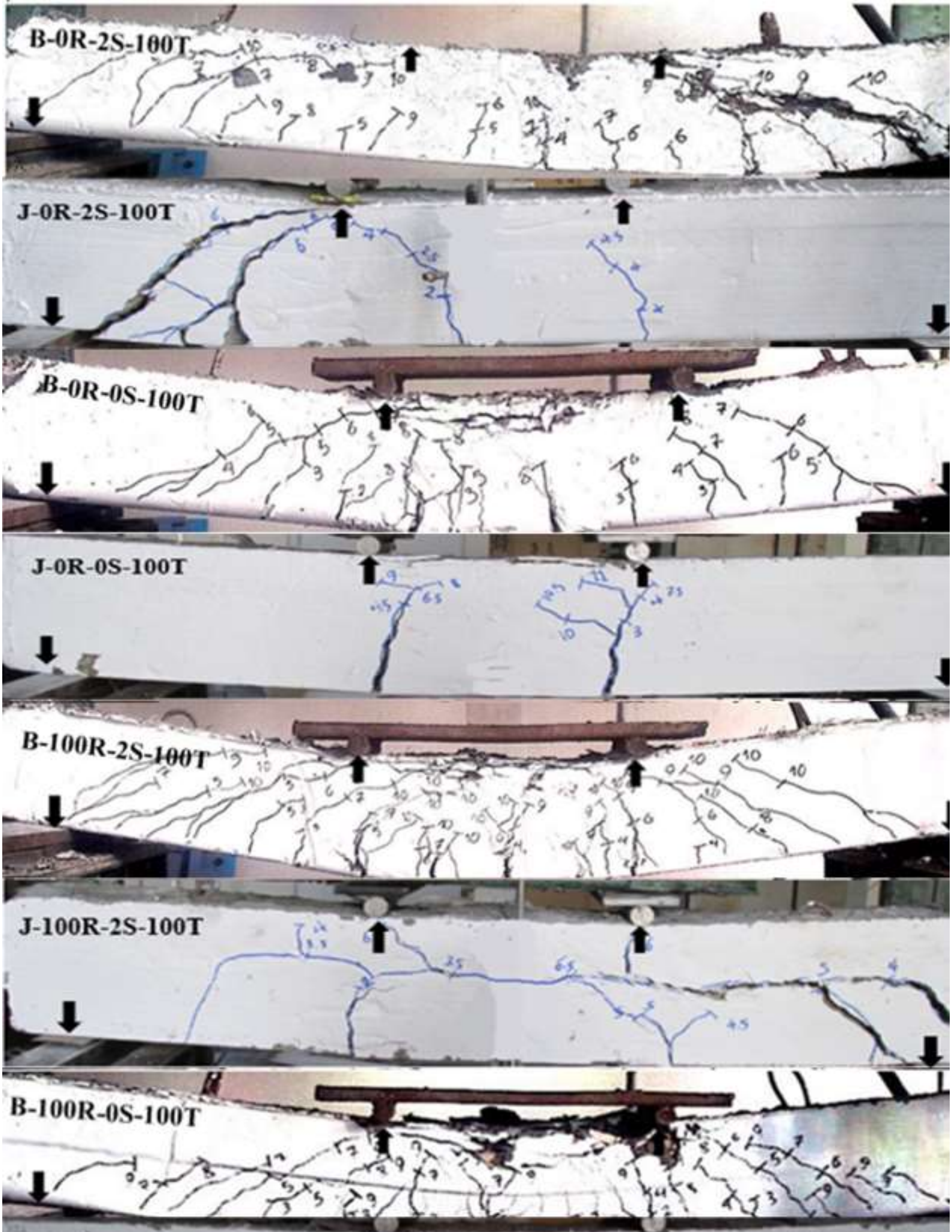

B-0R-2S-100T
J-0R-2S-100T
B-0R-0S-100T
J-0R-0S-100T
B-100R-2S-100T
J-100R-2S-100T
B-100R-0S-100T
J-100R-0S-100T

Fig. 7. Failure in specimens with TR spaced 100 mm and cracks propagation during loading

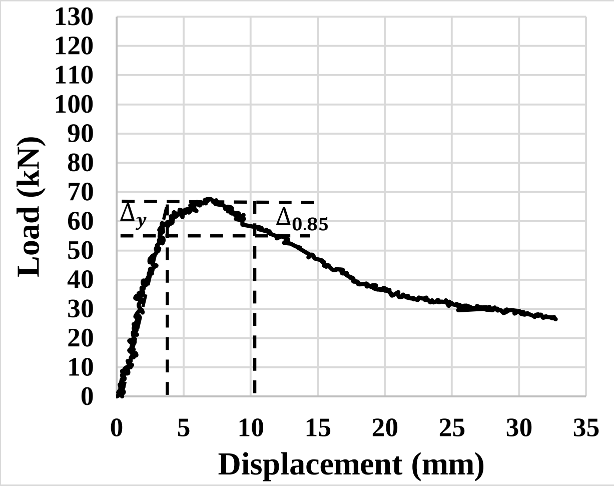


Fig. 8. DR of B-0R-2S-WT

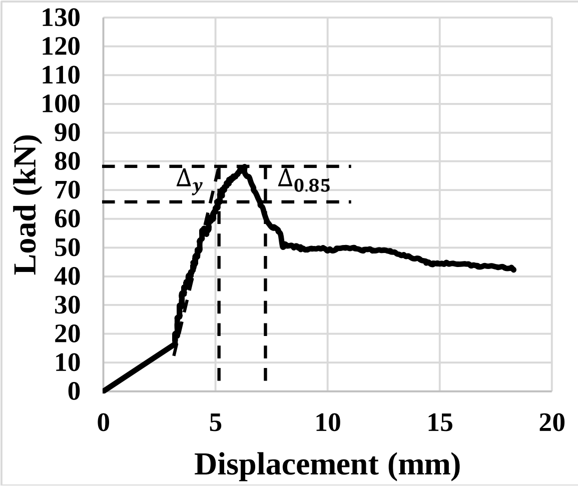


Fig. 9. DR of J-0R-2S-WT

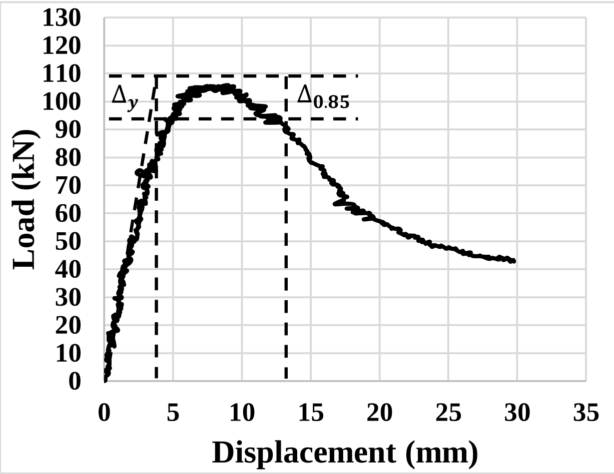


Fig. 10. DR of B-100R-2S-WT

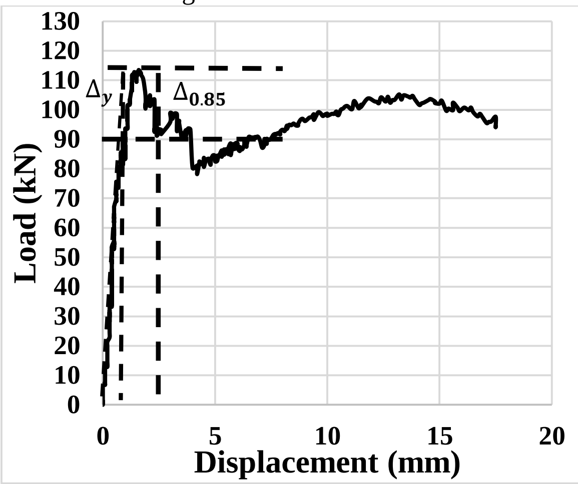


Fig. 11. DR of J-100R-2S-WT

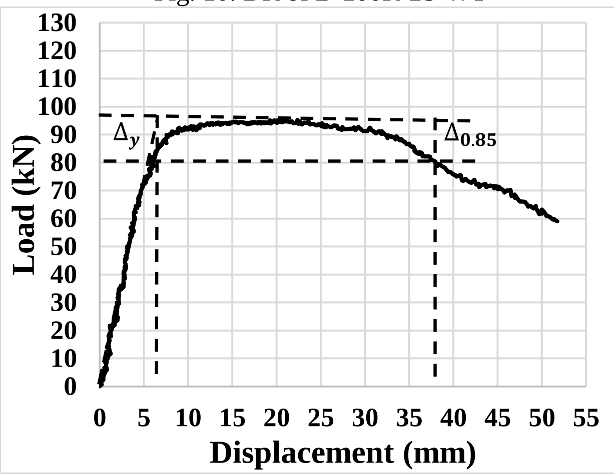


Fig. 12. DR of B-0R-2S-100T

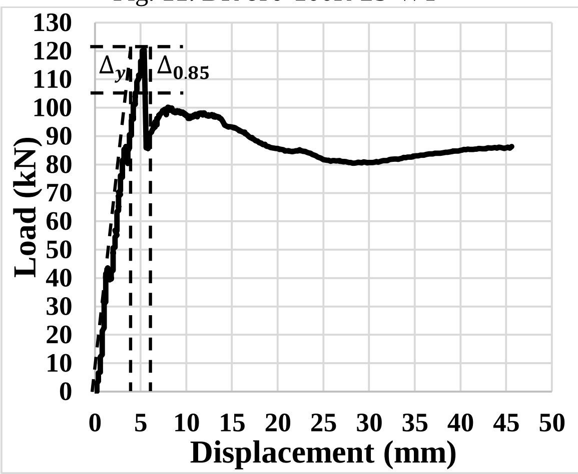


Fig. 13. DR of J-0R-2S-100T

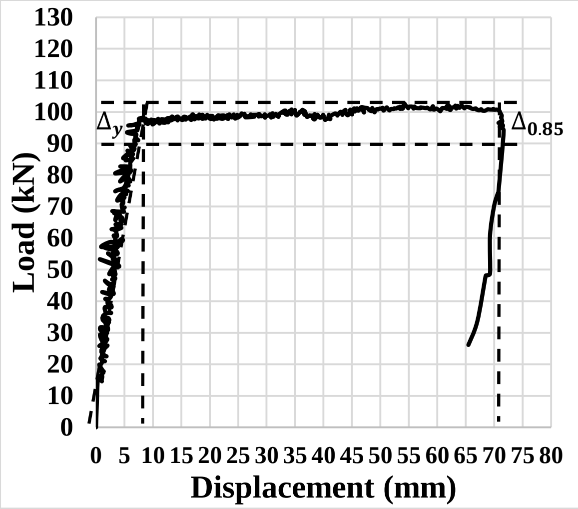


Fig. 14. DR of B-0R-0S-100T

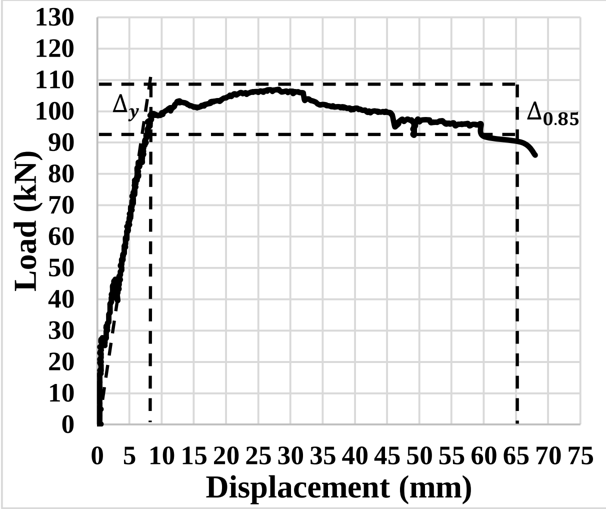


Fig. 15. DR of J-0R-0S-100T

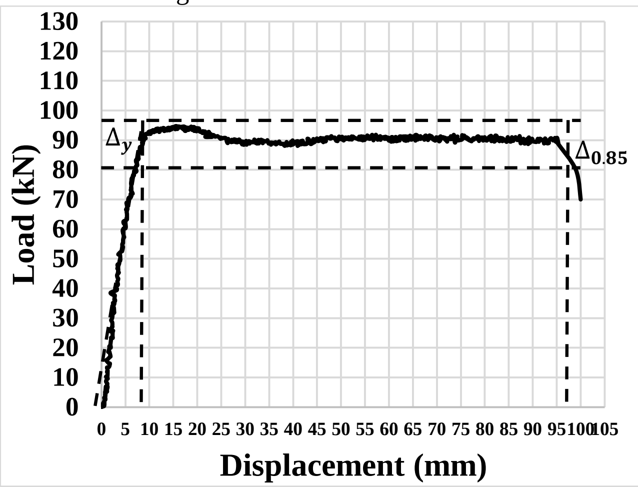


Fig. 16. DR of B-100R-2S-100T

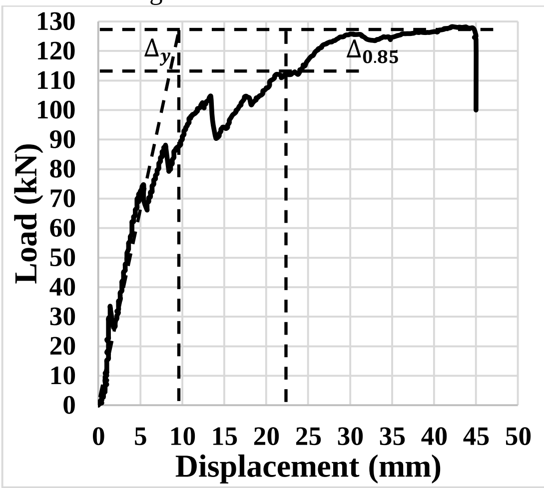


Fig. 17. DR of J-100R-2S-100T

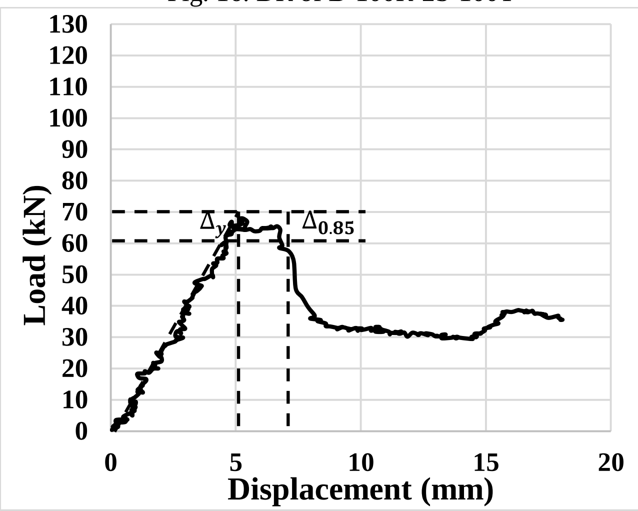


Fig. 18. DR of B-0R-0S-WT

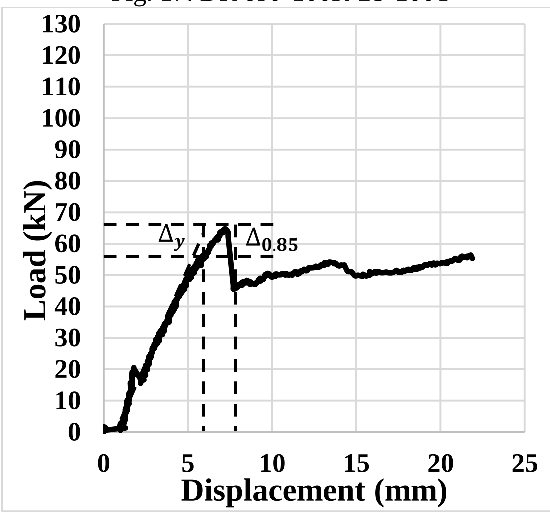


Fig. 19. DR of J-0R-0S-WT

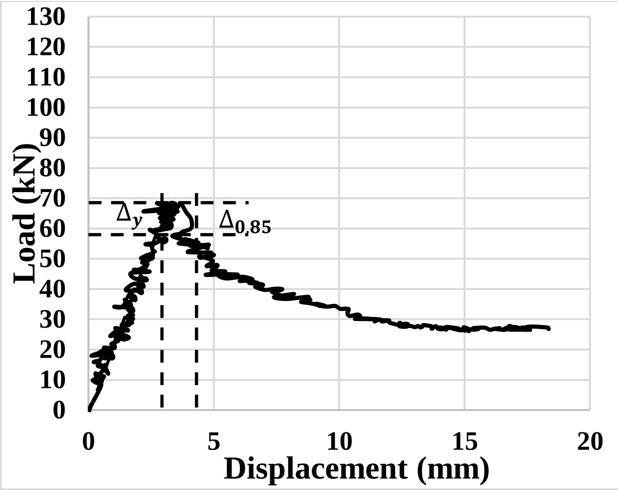


Fig. 20. DR of B-100R-0S-WT

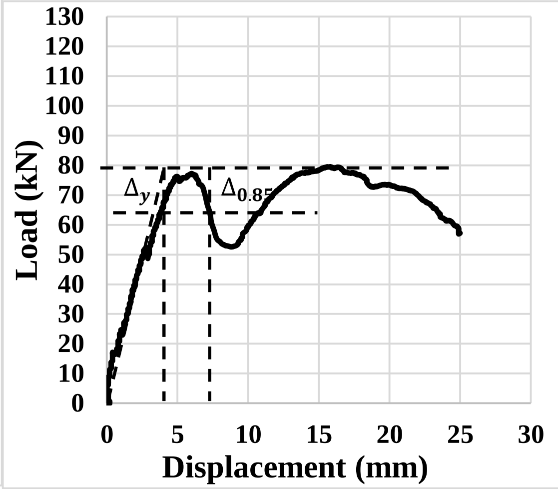


Fig. 21. DR of J-100R-0S-WT

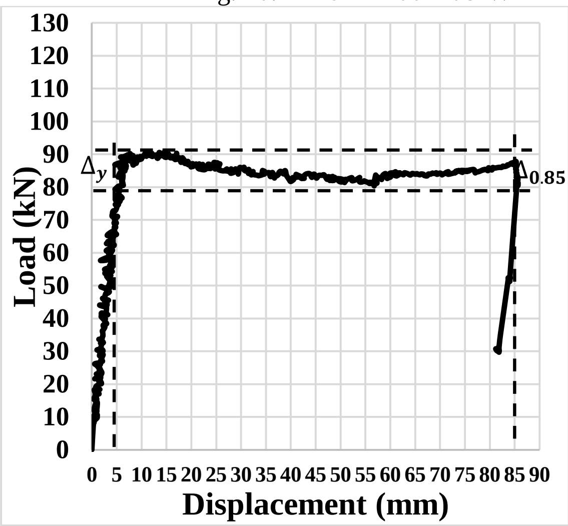


Fig. 22. DR of B-100R-0S-100T

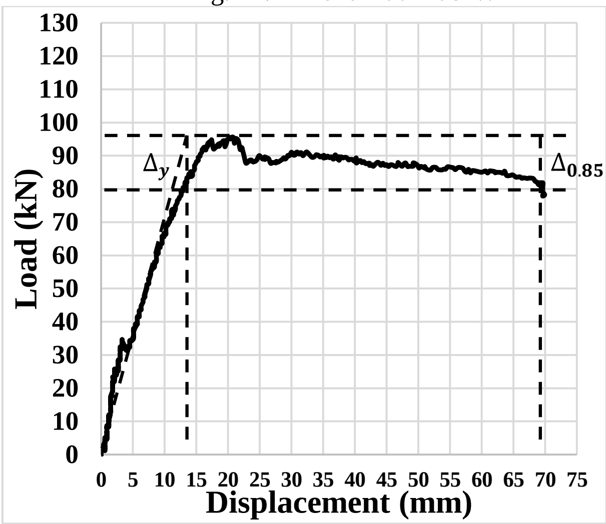


Fig. 23. DR of J-100R-0S-100T

According to Figs. 8 to 23, the DR of the specimens improved by increasing the SF's content. Furthermore, SF can enhance the flexural behaviour of the specimens with no TR. On the other hand, SF can improve the flexural behaviour and ductility of RA CBs. In this study, specimens were tested until complete failure and then strengthened using a CJ. Therefore, the DR in strengthened beams significantly improved in addition to the increase in flexural capacity. The DR of all specimens is given in Table 6.

Table 6. DR of all specimens

Specimens	Ductility ratio (DR)	Specimens	Ductility ratio (DR)
B-0R-2S-WT	3.4	J-0R-2S-WT	2.5
B-100R-2S-WT	3.2	J-100R-2S-WT	2.5
B-0R-2S-100T	6.0	J-0R-2S-100T	1.5
B-0R-0S-100T	7.8	J-0R-0S-100T	7.3
B-100R-2S-100T	8.1	J-100R-2S-100T	2.3
B-0R-0S-WT	1.3	J-0R-0S-WT	1.3
B-100R-0S-WT	1.6	J-100R-0S-WT	1.7
B-100R-0S-100T	11.7	J-100R-0S-100T	7.9

To further investigate the effect of the CJs on the flexural behaviour of the RA CBs with and without TR and SF, the concrete strain at mid-span of the specimens was measured with strain gauges, which were set up below beams on the outer layer of the concrete tensioned side. Therefore, the shear-strain relationship of the concrete was obtained as shown in Fig. 24. In this figure, the effect of the CJ in the different specimen was evaluated. According to this figure, in specimens with no RA, using SF caused an increase in the specimens' strain. Furthermore, the shear behaviour of the beams improved by increasing the RA's content. On the other hand, the shear strength increased by strengthening using CJ, but the strain declined. Therefore, the ductility decreased and failure became brittle. On the other hand, in reinforced specimens, the strain further reduced when 2% SF was used. Furthermore, in the beam with 100% RA, the strain increased relative to a specimen with no RA when strengthening by using a CJ.

Theoretical considerations, the test setup and the experiments

The longitudinal tensile and compressive rebars and TR of the original eight RC beams were 20 mm, 10 mm and 8 mm, respectively. There is no reinforcement in the CJs. The loading condition of both the original and the jacketed RC beams is presented in Fig. 24. The design of flexural and shear rebars was considered for this loading condition. The ultimate single load capacity should be determined as a simply-supported beam following the next formula:

(2) $P_{ult} = 3M_{ult}/L$

M_{ult}, P_{ult} and L are the ultimate mid-section bending moment at mid-section, the calculated maximum load, and the span width. The distribution of the compressive and tensile stress in a cross-section of an original RC specimen before the ultimate failure and the equivalent compressive stress block was adopted as presented in Fig. 25a. According to this method, the equilibrium of internal resisting forces can be stated as:

(3) $F_c = F_s$

So, the resisting moment can be assumed as in the next equation:

(4) $0.85 f_{cc} k_1 b \times (d - 0.5a) = A_s f_{sc} (d - 0.5a)$

Consequently, the ultimate resisting moment is equal to:

(5) $M_u = \rho b d^2 f_{sc} (1 - \frac{0.59 \rho f_{sc}}{f_{cc}})$

Where b, d and ρ is the cross-section width, the effective height of cross-section and the percentage of steel rebars.

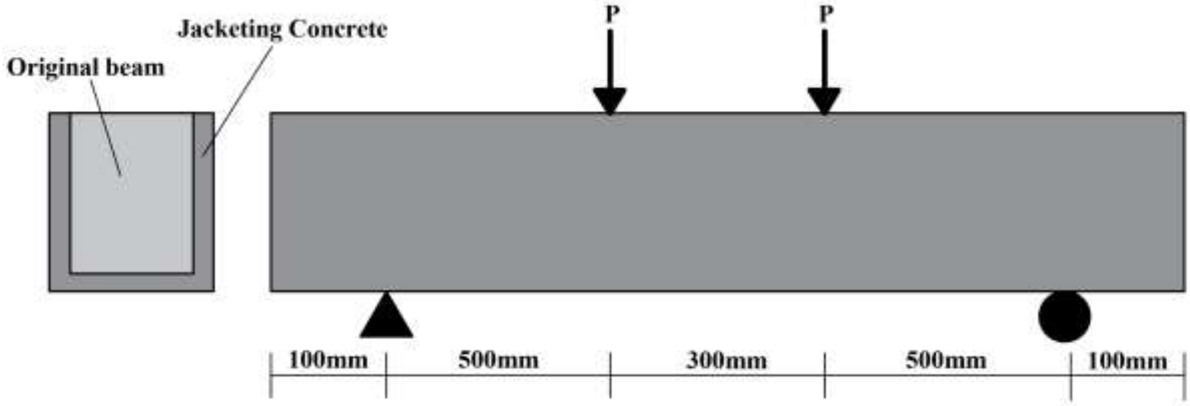
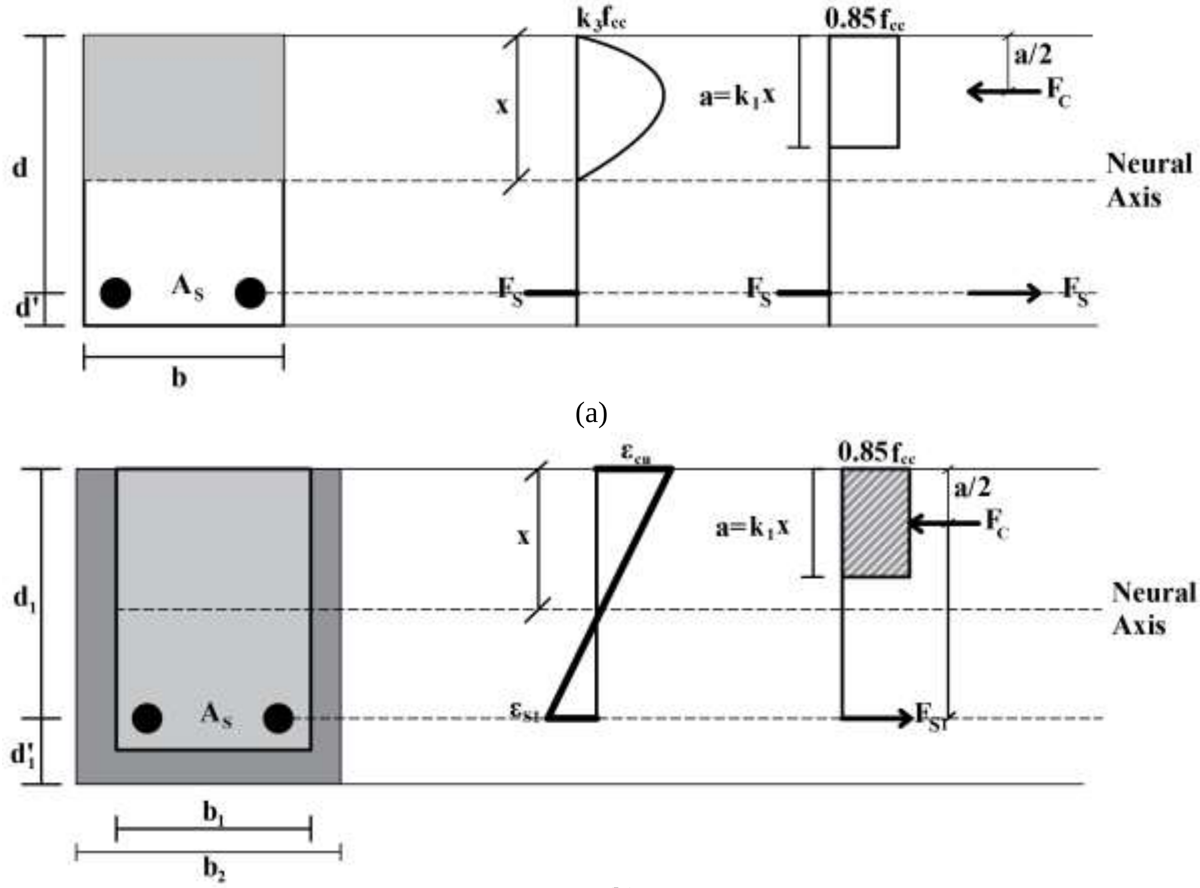


Fig. 24. Dimensions and loading condition



(a)

(b)

Fig. 25. Distribution of strains and internal stresses in a) original and b) jacketed RC beam

According to this study, the tensile rebars will reach their plastic limit while the stress in the compressive part of concrete is reasonably lower than its ultimate strength. In order to consider any probable difference between numerical and experimental outcomes, more analysis was done which will be summarized in the ensuing sections. It should be mentioned that a significant bond between original and jacketing beams was performed during manufacturing specimens. Furthermore, it should be considered a positive contribution to the flexural strength and the performance of jacketed beam. Therefore, the next equation should be considered to determine the presented stress in the longitudinal rebars.

$$(6) \quad F_c = F_{s1} + F_{s2}$$

When the jacketing concrete is not reinforced, F_{s2} is considered zero. Also, the internal moment strength can be written as in the next formula:

$$(7) \quad M_{ult} = A_{s2}f_{s2}(d_2 - 0.5a) + A_{s1}f_{s1}(d_1 - 0.5a)$$

So, eq. 7 in unreinforced CJ can be rewritten:

$$(8) \quad M_{ult} = A_{s1}f_{s1}(d_1 - 0.5a)$$

Where A_{s1}, f_{s1} are cross-section area and the tensile stress of tensile rebars in the original beam, respectively.

Algebraic manipulations performed on Equations (5) and (6) in light of Fig. 25b result in the following expression for the ultimate bending moment

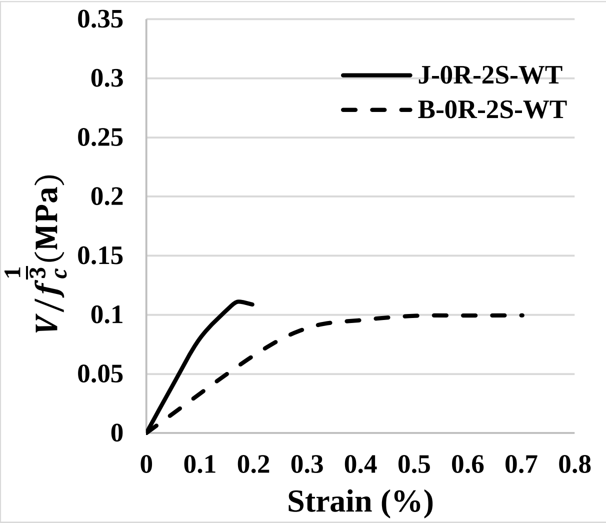
$$(9) \quad M_{ult} = A_{s2}f_{sc}d_2\left[1 - 0.59\rho\left(\frac{f_{sc}}{f_{cc}}\right)\right] + A_{s1}f_{sc}d_1\left[1 - 0.59\rho\left(\frac{f_{sc}}{f_{cc}}\right)\right] + (d_1 - 0.5a)$$

In this study, in order to compute the ultimate moment strength in unreinforced CJ beams, the first part is zero. Furthermore, f_{sc} and f_{cc} are the tensile yield strength of the rebars is and the ultimate compressive strength of concrete. So the obtained outcomes are compared and represented in Table 7.

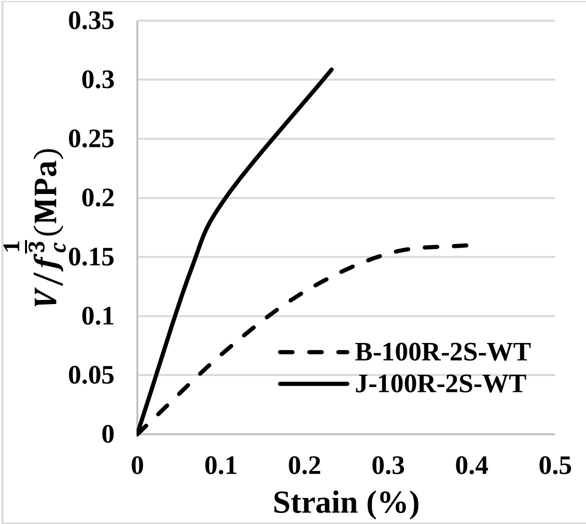
Table 7. Experimental and numerical outcomes

Specimens	Experimental ultimate load (kN)	Calculated ultimate load (kN)	Experimental moment strength (kN.m)	Calculated moment strength (kN.m)	Difference between the calculated and experimental ultimate moment	Difference between the calculated and experimental ultimate load
J-0R-2S-WT	79.00	61.22	39.50	26.53	0.48	0.29
J-100R-2S-WT	118.00	60.90	59.00	26.39	1.23	0.93
J-0R-2S-100T	120.00	61.23	60.00	26.53	1.26	0.95
J-0R-0S-100T	108.00	61.33	54.00	26.58	1.03	0.76
J-100R-2S-100T	130.00	60.90	65.00	26.39	1.46	1.13
J-0R-0S-WT	65.00	61.34	32.50	26.58	0.22	0.05
J-100R-0S-WT	80.00	61.04	40.00	26.45	0.51	0.31
J-100R-0S-100T	98.00	61.03	47.50	26.45	0.79	0.60

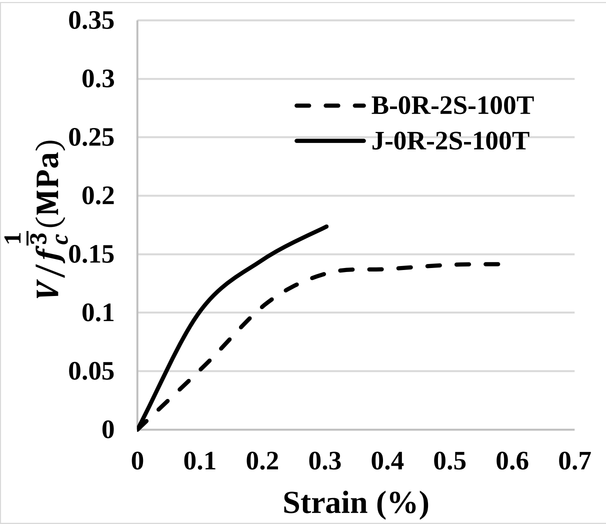
As per Table 7, the presented equation can be used for CJ beam with no TR. Furthermore, these formulas apply to specimens with only RA or SF and no RA and SF. On the other hand, the presented equations are not valid for RA SFRC beams strengthened with unreinforced CJ. To further investigate the effect of CJs on the flexural behaviour of the RA CBs with and without TR and SF, the concrete strain at mid-span of the specimens was measured with strain gauges that were set up below the beams on the outer layer of the concrete's tension face. Therefore, the shear-strain relationship of concrete was obtained as shown in Fig. 26, where the effect of the CJs in the different specimens was evaluated. In specimens with no RA, using SF caused an increase in their strain. Furthermore, the shear behaviour of the beams improved by increasing the RA content. On the other hand, the shear resistance increased by strengthening using CJs, but the strain declined. Therefore, the ductility decreased and brittle failure occurred. On the other hand, in reinforced specimens, the strain further reduced when 2% of SF were used in the beam. Furthermore, in the beam with 100% RA replacement content, the strain increased compared with a specimen with no RA when the specimen was strengthened by CJs.



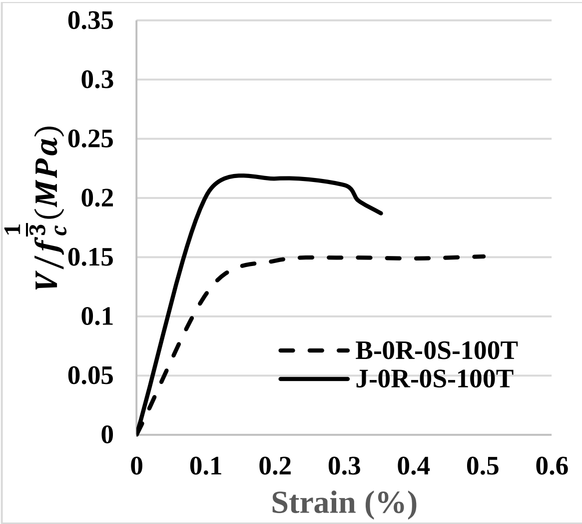
(a)



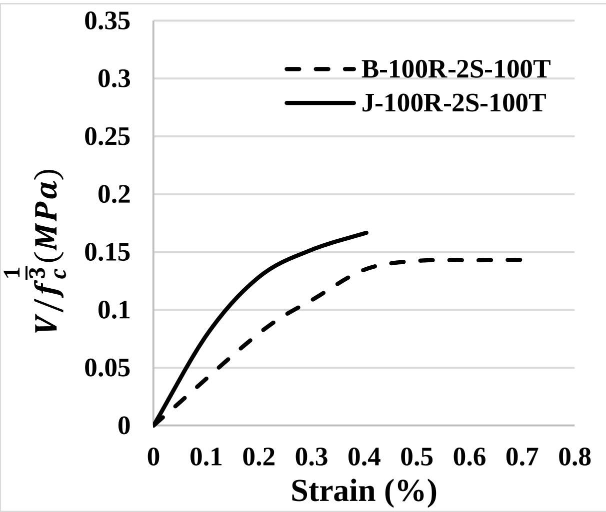
(b)



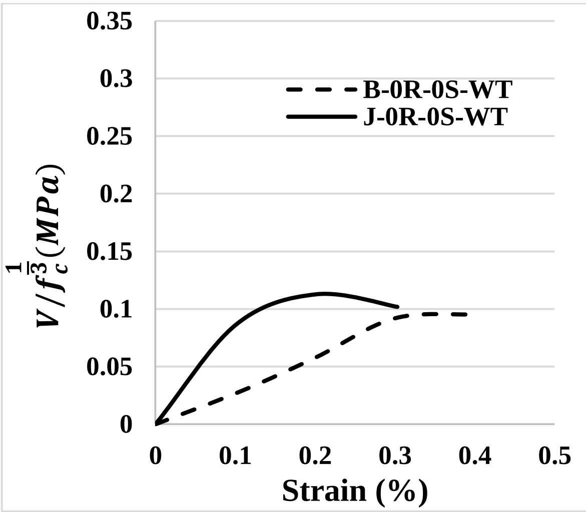
(c)



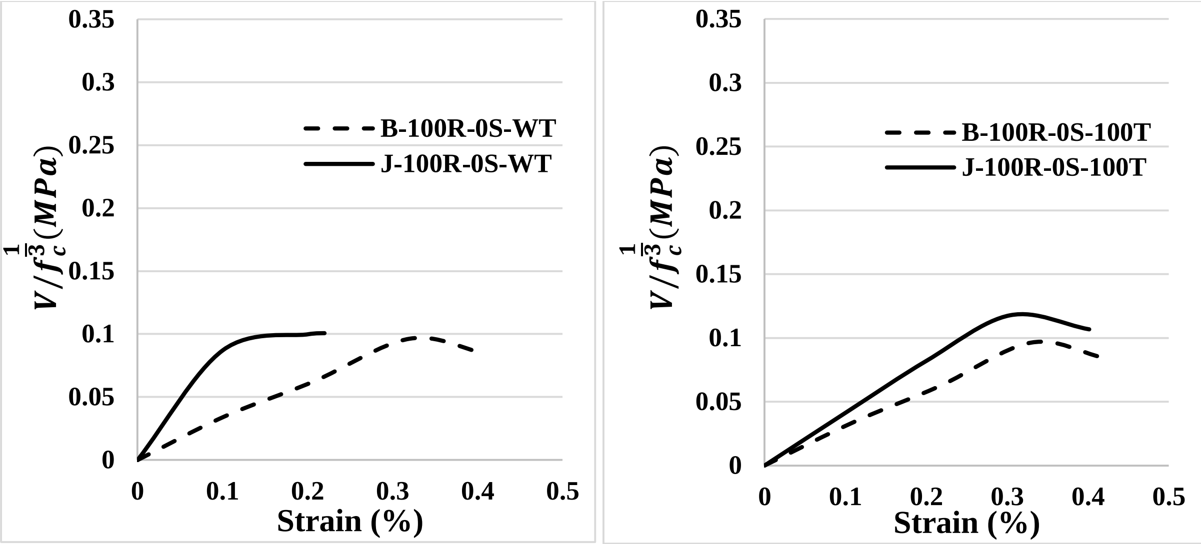
(d)



(e)



(f)



(g) (h)

Fig. 26. Shear-strain relationship of the specimens

Conclusions

In this research, the flexural behaviour and ductility of SF coarse RA CBs before and after strengthening by using a CJ were investigated. The research included tests of 16 RC beam specimens. SF contents varied between 0% and 2%. Furthermore, RA were used with mass replacement ratios of 0% and 100% of NA and two TR spacings were used: no TR and 100 mm. Firstly, the specimens were tested until failure and then repaired and strengthened using a CJ and tested again. In the test, the bearing capacity, deformation at the mid-span of the specimens, the DR and concrete shear-strain relationship were measured.

According to the results of the tests, the following conclusions can be drawn:

1- The CJ is an effective method for retrofitting RA CBs. Generally, strengthening RA CBs using a CJ leads to increasing the flexural capacity;

2- SF improved the flexural behaviour of RA RC beams by using a plain CJ. In a strengthened specimen with no TR, the DR increased 90% when 2% SF were added;

3- The maximum displacement of specimens declined when a CJ was used and the specimens failed suddenly. On the other hand, reinforcing specimens prevents a significant reduction in the flexural capacity after the maximum load is reached;

4- Using 100% RA leads to improving the flexural behaviour of specimens strengthened using CJ after failure (by about 20%). Furthermore, SF lead to increasing the maximum displacement by about 40%;

5- In specimens with no TR, failure occurred by shear mode before and after strengthening, but cracks propagation considerable declined when the specimens were strengthened using a CJ. Furthermore, the cracks' width decreased in the CJ when SF were used in the beams. On the other hand, in specimens with TR spaced 100 mm, there is no significant difference in the failure mode in specimens with and without a CJ. Cracks propagation in CJ was smaller compared with CBs without CJ, especially when 100% RA and 2% SF were used;

6- The DR in strengthened beams significant improved, in addition, to the increase in flexural capacity. In specimens with no TR, the DR increased by 160%, 24% and 146% when SF, RA and both SF and RA were used;
7- The shear strength increased by strengthening using CJ, but the strain declined. Therefore, the ductility decreased and failure became brittle;
8- The presented formulas are valid only for RA RC beams or SFRC beams with no TR. Therefore, for RA SFRC beams, new equations must be calibrated.

References

Aslani. F., Ma. G., Law. D. & Wan. Y. 2017. Experimental investigation into rubber granules and their effects on the fresh and hardened properties of self-compacting concrete, *Journal of Cleaner Production* 12.003.

Awoyera. P. O., Ndambuki. J. M., Akinmusuru. J. O. & Omole. D. O. 2016. Characterization of ceramic waste aggregate concrete, *Housing and Building National Research Centre HBRC Journal* 10: 1687-4048.

Arora S. & Singh S. P. 2016. Analysis of flexural fatigue failure of concrete made with 100% coarse recycled concrete aggregates, *Construction and Building Materials* 102: 782–791.

Azad A. M. 2017. Flexural behaviour and analysis of reinforced concrete beams made of recycled PET waste concrete, *Construction and Building Materials* 155: 593–604.

Altun, F. & Aktas. B. 2013. Investigation of reinforced concrete beams behaviour of steel fibre added lightweight concrete, *Construction and Building Materials* 38. 575–581.

Altun F. 2004. An experimental study of the jacketed reinforced-concrete beams under bending, *Construction and Building Materials* 18: 611–618.

ASTM C293-08, 2008. Standard test method for flexural strength of concrete (Using simple beam with center-point loading), *ASTM International*.

Asadi Shamsabadi E., Ghalehnovi M., De Brito J. & Khodabakhshian A. 2018. Performance of Concrete with Waste Granite Powder: The Effect of Superplasticizers, *Applied Sciences*, 8: 10.

Boukour. S. & Benmalek. M. L. 2016. Performance evaluation of a resinous cement mortar modified with crushed clay brick and tire rubber aggregate, *Construction and Building Materials* 120: 473–481.

Beheraa G. C., Gunneswara T. D. & Raob C. B. K. 2016. Torsional behaviour of reinforced concrete beams with ferrocement U-jacketing—Experimental study, *Case Studies in Construction Materials* 4: 15–31.

BS EN 12390-1, 2000. Testing hardened concrete: shape, dimensions and other requirements for specimens and moulds, *British Standards Institution*.

BS EN 12390-2, 2000. Testing hardened concrete: Making and curing specimens for strength tests, *British Standards Institution*.

BS EN 12390-3, 2009. Testing hardened concrete: Compressive strength of test specimens 19, *British Standards Institution*.

Chaboki H. R., Ghalehnovi M., Karimipour A. & de Brito J. 2018. Experimental study on the flexural behaviour and ductility ratio of steel fibres coarse recycled aggregate concrete beams, *Construction and Building Materials* 186: 400-422.

Chalioris C. E. & Pourzitidis C. N. 2012. Self-compacting concrete jacketing - Tests and analysis, *AASRI Procedia* 3: 624-629.

Carneiro J.A., Lima P.R.L., Leite M.B. & Filho R.D. 2014. Compressive stress-strain behaviour of

steel fibre reinforced-recycled aggregate concrete, *Cement and Concrete Composites* 46: 65–72.
Cohn M. Z. & Bartlett M. 1982. Computer-simulated flexural test of the partially pre-stressed concrete section, *ASCE Journal of Structural Division* 5: 2747-2765.
Chaboki. H. R., Ghalehnovi. M., Karimipour. A., de Brito. J. & Khatibinia. M. 2019. Shear behaviour of concrete beams with recycled aggregate and steel fibres, *Construction and Building Materials* 204: 809-827.
Dupont. D. & Vandewalle. L. 2015. Bending capacity of steel fibres reinforced concrete (SFRC) beams, *Magazine of Concrete Research* 39: 105-121.
Ganjian. E., Khorami. M. & Maghsoudi. A 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete, *Construction and Building Materials* 23: 1828–1836.
Ghalehnovi M., Karimipour A. & de Brito J. 2019. Influence of steel fibres on the flexural performance of reinforced concrete beams with lap-spliced bars, *Construction and Building Materials* 229: 116853.
Hunag. L. J., Wan. H. Y. & Wu. Y. W. 2016. Properties of the mechanical in controlled low-strength rubber lightweight aggregate concrete (CLSRLC), *Construction and Building Materials* 112: 1054–1058.
Guo Y., Zhang J., Chen G. & Xie Z. 2014. Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fibre, subjected to elevated temperatures, *Journal of Cleaner Production* 72: 193-203.
Jain. K. & Singh. B. 2014. Deformed steel fibres as minimum shear reinforcement – a comparative appraisal, *Magazine of Concrete Research* 66 (22): 1170-1182.
Kim, D. J., Naaman, A. E. & El-Tawil, S. 2008. Comparative flexural behaviour of four fibre reinforced cementitious composites, *Cement and Concrete Composites* 30: 917–928.
Kuang. J. S. & Bączkowski. B. J. 2008. Steel-fibre-reinforced concrete coupling beams subjected to monotonic loading, *Magazine of Concrete Research* 24: 178-190.
Li. J., Saberian. M. & Bao Thach Nguyen. B. T. 2018. Effect of crumb rubber on the mechanical properties of crushed recycled pavement materials, *Journal of Environmental Management* 218: 291-299.
Luccioni B., Isla F., Codina R., Ambrosini D, Zerbino R, Giaccio G. & Torrijos M.C 2017, Effect of steel fibres on static and blast response of high strength concrete, *International Journal of Impact Engineering* 107: 23-37.
Lim. T. Y. & Paramasivam. P. 2015. Shear and moment capacity of reinforced steel-fibre-concrete beams, *Magazine of Concrete Research* 39 (140): 148-160.
Lee. J. Y., Shin. H. O, Yoo. D. Y. & Yoon. Y. S 2018. Structural response of steel-fibre-reinforced concrete beams under various loading rates, *Engineering Structures* 156: 271-283.
Mahmod. M., Hanoon. A. N. and Abed. H. J. (2018) "Flexural behaviour of self-compacting concrete beams strengthened with steel fibre reinforcement" *Journal of Building Engineering* 16: 228-237.
Meda A., Minelli F. & Plizzari G.A. 2012. Flexural behaviour of RC beams in fibre reinforced concrete, *Composites, Part B* 43: 2930–2937.
Monir A. M., Maged A. & Youssef A 2017. Analysis of reinforced concrete beams strengthened using concrete jackets, *Engineering Structures* 132: 172–187.
Monir A. M., Maged A. & Youssef A 2018. Assessment of the flexural behaviour of reinforced concrete beams strengthened with concrete jackets, *Engineering Structures* 167: 108–120.
Patil. D. M. & Sangle. K. K. 2013. Experimental investigation of waste glass powder as partial replacement of cement in concrete, *International Journal of Advanced Technology in Civil Engineering* 2(1): 2231-5721.
Ramdan. S., Guettala. A., Benmalek. M. L. & Aguiar. J. B. 2018. Physical and mechanical

performance of concrete made with waste rubber aggregate, glass powder and silica sand powder, *Journal of Building Engineering* 21: 302-311.

Ruano. G., Isla F., Pedraza R. I., Sfer D. & Luccioni B. 2014. Shear retrofitting of reinforced concrete beams with steel fibre reinforced concrete, *Construction and Building Materials* 54: 646–658.

Saberian. M., Li. J. & Nguye. B. 2018. Permanent deformation behaviour of pavement base and subbase containing recycle concrete aggregate, coarse and fine crumb rubber, *Construction and Building Materials* 178: 51–58.

Saberian. M., Jie Li. J. & Nguyen. B. 2018. Permanent deformation behaviour of pavement base and subbase containing recycle concrete aggregate, coarse and fine crumb rubber, *Construction and Building Materials* 178: 51–58.

Soutsos M. N., Le T. T. & Lampropoulos A. P. 2012. Flexural performance of fibre reinforced concrete made with steel and synthetic fibres, *Construction and Building Materials* 36: 704–710.

Thomas. B. S. & Gupta. R. C. 2015. Properties of high strength concrete containing scrap tire rubber, *Journal of Cleaner Production*. 113: 86-92.

Usahanuntha. N., Tuprakaya. S., Kongsonga. W. & Tuprakay. S. R. 2018. Study of mechanical properties and recommendations for the application of waste Bakelite aggregate concrete, *Case Studies in Construction Materials* 8: 299–314.

Wong. C. L., Mo. K. H., Yap. S. P., Alengaram. U. J. & Ling. T. C. 2017. Potential use of brick waste as alternate concrete-making materials: A review, *Journal of Cleaner Production* 195: 226-239.

Yoo. D. Y., Yoon. Y. S. & Banthia. N. 2015. Predicting the post-cracking behaviour of normal- and high-strength steel-fibre-reinforced concrete beams, *Construction and Building Materials* 93. 477–485.