Scientific Review Engineering and Environmental Sciences (2022), 31 (4), 225–237

Sci. Rev. Eng. Env. Sci. (2022), 31 (4) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.4253

Received: 13.09.2022
Accepted: 17.10.2022

Hussein M. DUHAIM

Mohammed A. MASHREI✉ https://orcid.org/0000-0002-5909-756X

University of Thi-Qar, College of Engineering, Iraq

STRESS–STRAIN RELATIONSHIP OF DUCTILE MATERIALS AND FLEXURAL BEHAVIOR OF DUCTILE OVER-REINFORCED CONCRETE BEAMS

Key words: ductile materials, SFRC, SIFCON, UHPFRC, over-reinforced beam, flexural behavior, ductility

Introduction

According to ACI 318 (American Concrete Institute [ACI], 2014) and based on the reinforcement ratio, the flexural reinforced concrete beams can be classified to balanced reinforced, under-reinforced, and over-reinforced sections. When the tensile reinforcement ratio is less than the balance reinforcement ratio, the under-reinforced failure occurs by the yielding of steel before the crushing of concrete. This mode of failure is characterized by significant deflection and wide cracks. Balanced failure occurs by the yielding of steel in tension and crushing of concrete in the compression zone at the same time. However, the over-reinforced failure occurs suddenly by crushing of concrete in the compression zone before yielding of steel reinforcement in tension zone with little deflection and few cracks.

To avoid the brittle compression failure, many codes limit the use of over-reinforced sections (Ziara, Haldane & Hood, 2000; Siddiqi, 2016). However, a high tensile reinforcement ratio is often used to decrease the size of the beam and to provide adequate stiffness (Whitehead & Ibell, 2004; Ahmed, Farghal, Nagah & Haridy, 2007; Ali & Tarkhan, 2015; Mohamed, 2018; Deng, Zhang, Ma, Li & Sun, 2021). By reducing the beam's size, the formwork dimensions reduce and save time, material, and labor during construction. Furthermore, reducing the beam's size boosts the structure's efficiency by providing more rentable space. In recent years, the construction industry that requires the use of over-

✉mamashrei@utq.edu.iq

-reinforced sections in large projects, such as high-rise buildings and bridges has been employed (Ali & Tarkhan, 2015).

To change the failure mode of concrete from brittle to ductile failure for over-reinforced concrete beams, there are different techniques used in previous studies to improve the ductility of concrete in the compression zone, such as using a steel plate bolted with a compression zone of concrete (Alasadi, Shafigh & Ibrahim, 2020), addition confinement in the compression zone (Priastiwi, Imran, Nuroji & Hidayat, 2014; Tee, Al-Sanjery & Chiang, 2017), a block or precast block can be cast in compression zone (Liu & Wu, 2007; Wu, 2008), and using ductile materials, this can do by replacing the concrete in the compression zone with a layer of material that has both high strength and ductility.

A few studies have been carried out to use ductile materials in the compression zone. Thus, this paper aimed to study the effect of using ductile materials in compression zone on the flexural performance of over-reinforced concrete beams as well as to study the mechanical properties of the materials. The ductile materials used in this study were steel fiber reinforced concrete (SFRC), slurry infiltrated fiber concrete (SIFCON), and ultra-high performance fiber reinforced concrete (UHPFRC). To achieve the goal of the study, four composite beams were cast and tested to investigate the flexural capacity, failure modes, crack patterns, load-deflection relationships, ductility index, and toughness.

Background

Steel fiber reinforced concrete (SFRC)

This type of FRC is made of cement, fine and coarse aggregates, water, and steel fibers that are actually randomly distributed in the concrete. The purpose of randomly distributed discontinuous steel fibers is to bridge across the cracks that formed inside concrete to provide ductility after cracking through the pullout resistance of steel fibers (Kobayashi, 1976). The SFRC has a higher strain capacity than normal concrete (NC), making it ideal for usage in members that are subjected to large plastic deformation demands. Also, SFRC has durability and serviceability more than NC (Germano, Plizzari & Tiberti, 2013). The FRC has many applications, such as applications in ground slabs, precast members, and shotcrete tunnel linings (Orouji, Zahrai & Najaf, 2021).

Slurry infiltrated fiber concrete (SIFCON)

This type of concrete is different from traditional FRC in respect of composition and fabrication. The fiber content in FRC usually ranges from 1 to 3% by volume, whereas fiber content in SIFCON typically ranges from 5 to 20% by volume (Balaji & Thirugnanam, 2018).

The SIFCON matrix has a high cement content. It may contain fine or coarse sand, as well as mineral and chemical admixture, but no coarse aggregates. Therefore, the SIFCON matrix is either cement paste or flowing cement mortar as opposed to the traditional FRC (Salih, Frayyeh & Ali, 2018). Also, SIFCON production differs from FRC, in SIFCON fibers are placed in a casting mold, and then a slurry of cement is infiltrated over the rich fiber layers. Fibers are placed in the mold by hand or with the use of fiber-dispersing units (Shelorkar, 2021). Vibration is often required to achieve proper slurry infiltration of the fiber bed (Khamees, Kadhum & Alwash, 2020). While in FRC, fibers are added to the dry or wet concrete mix.

Ultra-high performance fiber reinforced concrete (UHPFRC)

This type of concrete is a cementitious composite with a high cement content, small aggregate size, and binder (pozzolana, fly ash, silica fume, reactive powder) as well as a low water to cement ratio.

Because of the low water to cement ratio, UHPC mixes are characterized by low workability. One method to improve the workability of UHPC is using a super--plasticizer. Furthermore, using silica fume in UHPC can fill spaces between coarser particles due to its smaller size and spherical form, so enhancing the strength properties via pozzolanic reactions. Despite enhancing the stiffness and strength, the failure mode of plain UHPC is very brittle; therefore, post-cracking behavior is limited (Qadir, Faraj, Sherwani, Mohammed & Younis, 2020). Fibers can change the failure mode of plain UHPC from brittle to ductile mode and increase the tensile strength, toughness, and deformation ability of the resultant composite, the name of this type of concrete is UHPFRC (Khalil & Tayfur, 2013).

Experimental program

Materials preparation

All materials used were conformed to the requirement of the American Association State Highway and Transportation (ASTM) standards. The NC mix consists of cement, sand, gravel, and water in addition to a super--plasticizer. The SFRC mix differs from the NC mix by containing steel fibers. The UHPFRC and SIFCON mix consist of cement, quartz sand, water, super-plasticizer, and steel fibers. Furthermore, mineral admixtures such as silica fume are used as a partial replacement (10%) of cement weight in the UHPFRC mix.

The materials used throughout the work are Portland cement 42.5 grade, natural sand as fine aggregate with a maximum size of 4.75 mm, crushed coarse aggregate (gravel) with a maximum nominal size of 14 mm, high-performance super-plasticizer concrete admixture, densified silica fume with grading below 1 μm, and quartz sand with small grading 0.3–0.7 mm to ensure complete infiltration of the slurry over the dense steel fiber (Abeer, Dawood & Ghalib, 2020). Finally, hooked-end steel fiber with volume fractions of 1.5, 1.5 and 7.5% were used in the SFRC, UHPFRC, and SIFCON mixes, which has a length of 30 mm and diameter of 0.5 mm with an aspect ratio (*l*/*d*) of 60 and ultimate tensile strength of 1,200 MPa based on the manufacturer company requmdations.

Compressive strength and stress–strain relationship

The uniaxial compressive strength of NC and ductile materials was determined by the compressive test of cylinder specimens of size 100 × 200 mm. Cylinder specimens for each material were cast from the same batch of beams. The stress–strain relationship and crack pattern of NC and ductile materials under the uniaxial compressive test are shown in Figure 1.

As depicted in Figure 1, the presense of hooked-end steel fiber (V_f 1.5%) with NC increased the strain capacity of concrete from 0.0032 to 0.0080 as well as increased compressive stress, which means the ductility and toughness of SFRC were higher than those of NC. The UHPFRC and SIFCON showed high strength and strain

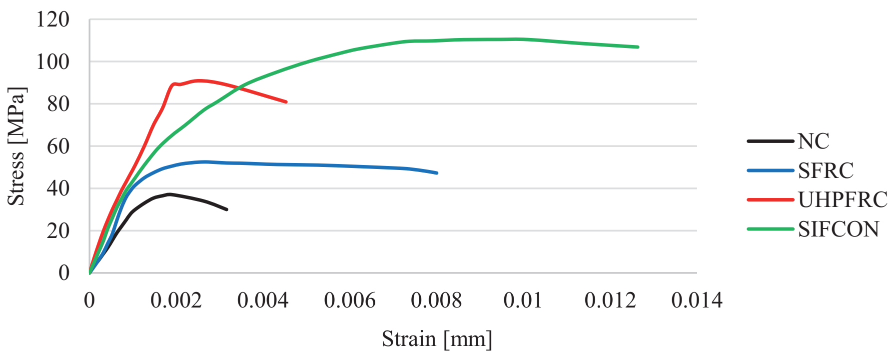

FIGURE 1. Uniaxial compression stress–strain relationships for different concrete types

capacity when compared to NC. Noting that despite using the same *Vf* 1.5% of steel fiber, UHPFRC exhibited strain capacity less than SFRC, which was 0.0045. This may be related to the fact that the behavior of UHPC is more brittle, which led to reduced deformation ability in comparison to SFRC. While SIFCON exhibited strain capacity greater than other types of FRC, which was 0.01263. This is attributed to the high content of steel fibers in SIFCON, which led to increased deformation ability.

Details of reinforcement

Figure 2 shows details of the over-reinforced beam. Based on the cross-section assumption, the critical thickness of partial replacement of NC with ductile materials

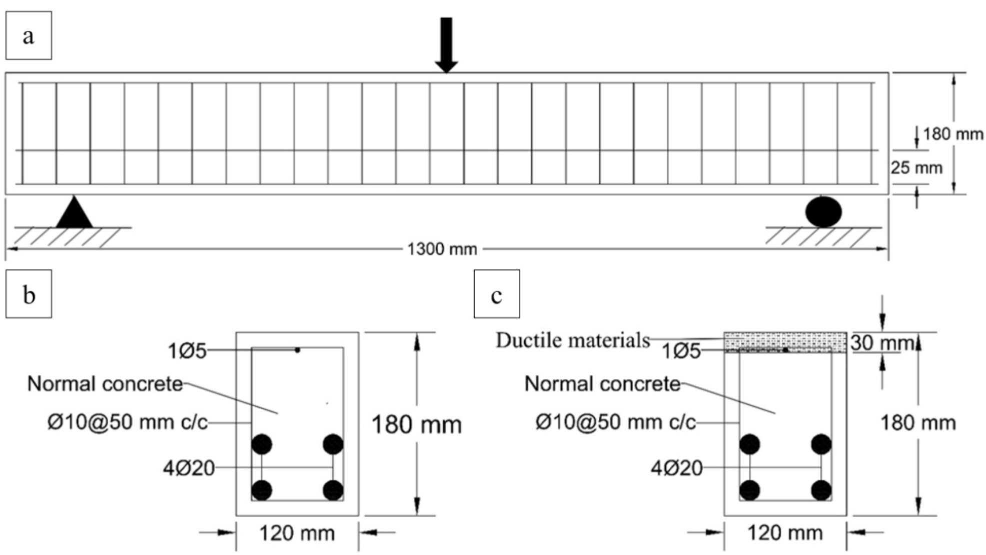

FIGURE 2. Details of reinforcement and cross-section of over reinforced concrete beams: (a) beam reinforcement; (b) cross section of reference beam; (c) cross section of composite beams

layer in the compression zone was around 30 mm (more than 10% of the beam depth), based on findings by Deng, Ma, Ye and Li (2021).

Table 1 illustrates the mechanical properties of deformed steel rebars that conformed to the requirements of ASTM A615/A615M (American Association State Highway and Transportation [ASTM], 2015).

Each beam has a tensile reinforcement ratio of 8.548%. It is more than the balancing limit which is 1.988% according to ACI 318 (ACI, 2014), in order to obtain heavily reinforced beams and to ensure the mode of failure is compression failure.

Mix proportions

Based on trial mixes for various proportions of constituents in order to determine the required strength, the final mix proportions of NC, SFRC, UHPFRC, and SIFCON slurry are presented in Table 2. The workability was checked as the control test for the fresh concrete properties, as shown in Figure 3.

TABLE 1. Mechanical properties of deformed steel rebars

Bar diameter [mm]	Yield strength (*Ys*) [MPa]	Tensile strength (*Ts*) [MPa]	*Ts*/*Ys* [-]	Total elongation [%]	Bending test pass/fail
10	618	773	1.25	10.00	pass
20	599	713	1.19	13.50	pass

TABLE 2. Mix proportions of NC, SFRC, UHPFRC, and SIFCON slurry for 1 m^3 of concrete

Concrete type	Cement [kg]	Silica fume [kg]	Sand [kg]	Quartz sand [kg]	Coarse aggregate [kg]	w/c or w/b ratio	Steel fiber [%]	Super-plasticizer [%]
NC	410	–	750	–	1 100	0.45	–	0.4
SFRC	410	–	750	–	1 100	0.45	1.5	0.4
UHPFRC	900	90	–	990	–	0.19	1.5	1.8
SIFCON	850	–	–	850	–	0.31	7.5	1.6

FIGURE 3. Trail mix and fresh concrete test

Casting and curing

The casting of the beams in this study contains four over-reinforced concrete beams, three of them were composite beams created by using NC and one layer of ductile materials (SFRC, UHPFRC, and SIFCON) in the compression zone, while the last beam was cast with NC only to use as a reference beam. The casting of the ductile materials layer in the compression side was immediately after casting the NC to increase the bond strength between different concrete parts. Each part was compacted using an electric vibrating table to ensure removing the entrapped air and increasing the bond between parts, allowing them to behave as one part. After casting all specimens, it was covered with plastic sheets and demolded at the age of two days and all specimens were immersed in water until testing.

Endurance test

After curing, the over-reinforced concrete beams were tested up to failure under three-point loading with a clear span of 1,100 mm. Figure 4 shows the test setup and instrumentation that were used to monitor the beams during the testing.

Test results and discussion

Crack pattern and modes of failure

The first crack in NC beam was flexural type and initiated at the early stage of loading in the tension zone. With increasing load, a few cracks with small width were formed and propagated in their length toward the compression zone. When the load approximately reached its maximum capacity, the number and width of final cracks were comparatively small, the cover of concrete in the compression zone began to collapse, and concrete crushing failure occurred. This type of failure is a brittle compression failure without sufficient warning before failure.

For other beams that had ductile materials layer (SFRC, UHPFRC, and SIFCON) in the compression zone, their experimental phenomenon was similar to that of the NC at the initial stage of loading. As the load approximately reached its maximum capacity, the cracks extended toward the compression zone and widened rapidly. Also, the flexural crack length and deflection at midspan significantly increased with the increase of load as compared to the NC beam. Finally, the beam failed by crushing of ductile materials layer in the compression zone. The

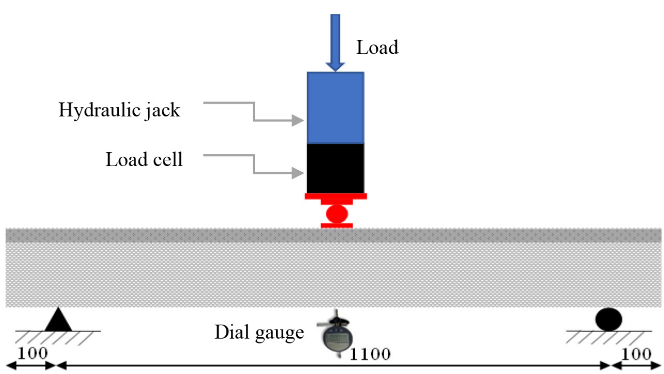

FIGURE 4. Details of the test setup (all dimensions in mm)

modes of failure of composite beams stayed flexural compression failure, but these beams have ductile behavior. Therefore, the use of the ductile materials layer at the compression zone changed the failure mode of over--reinforced concrete beams from brittle to ductile failure and led to an increase in their load-carrying capacity.

Although the ultimate load carried by the SIFCON beam is higher than the other beams, the SIFCON layer maintained the beam's integrity. This can be attributed to the high content of steel fibers in the SIFCON layer compared to SFRC and UHPFRC layers. Also, it should be mentioned that despite using the same volume fraction of steel fibers (1.5%) for UHPFRC and SFRC layers, the deformation ability of the SFRC beam was more than the UHPFRC beam. This may be due to the presence of steel fibers, which led to an increase the contact between the particles of aggregates when the cracks formed, and this is may not found in the UHPFRC beam.

The crack pattern and failure modes of all tested beams are shown in Figure 5. No debonding between NC and ductile materials layers in the composite beams even at the failure state has been observed.

This can be attributed to the fact that good bond strength is achieved between the surfaces of the ductile material and NC, in addition to the presence of stirrups in beams that work as effective shear connectors (Atta & Khalil, 2016).

Load deflection relationships

To investigate the effect of using ductile materials on improving the flexural performance of over-reinforced concrete beams used in this study, the relation of applied load versus deflections at mid-span for all beams are plotted in Figure 6 to show their structural behavior, flexural capacity, deformation ability of beams, ductility, and toughness.

All over-reinforced concrete beams exhibited flexural compression failure noting that the failure of the composite beams was through the crushing of the concrete after an obvious large deflection compared to the reference beam. Therefore, the composite beams exhibited load–deflection behavior more ductile than that of the reference beam under the same load conditions because using ductile materials leads to an increase in both load-carrying capacity and ductility. However, the curve of UHPFRC rapidly drops after reaching peak load and then continues to deform up to failure. Figure 6 shows that the using a layer of SFRC, UHPFRC, or SIFCON in the compression zone gives higher deflection at failure than that of NC by 133.70, 55.84 and 81.92%, respectively,

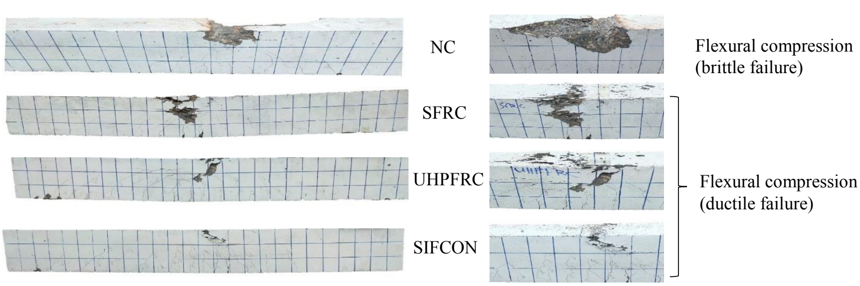

FIGURE 5. Crack pattern and failure modes of over-reinforced concrete beams

Duhaim, H. M., Mashrei, M. A. (2022). Stress–strain relationship of ductile materials and flexural behavior of ductile over-reinforced concrete beams. *Sci. Rev. Eng. Env. Sci.*, *31* (4), 225–237. DOI 10.22630/srees.4253

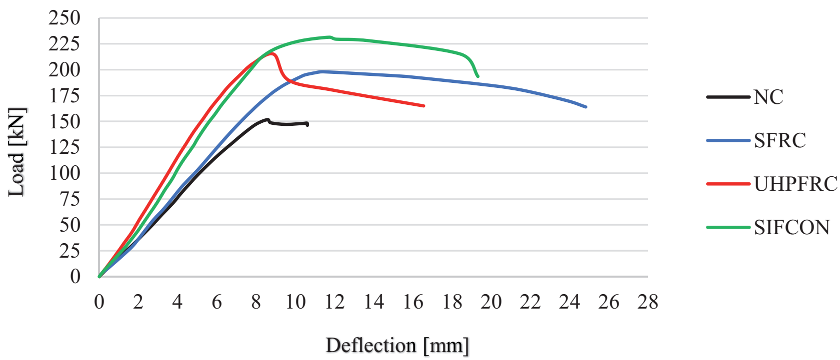

FIGURE 6. Load deflection relationships for over-reinforced beams

and enhances load-carrying capacity by 30.45, 41.65 and 52.46%, respectively. Noting that the increases in load-carrying capacity of UHPFRC and SIFCON beams were more than the SFRC beam. This may be due to the high compressive strength and the different production of UHPFRC and SIFCON compared to SFRC, where the high fiber content in SIFCON led to the strong bond between steel fibers and matrix interfaces. In contrast, the increase in deflection at failure for the SFRC beam was greater than that of UHPFRC and SIFCON beams. This may be related to increasing the contact between the particles of aggregates when the cracks form due to the presence of steel fibers as compared to the UHPFRC beam without coarse aggregate in the UHPFRC layer. Therefore, it is possible that if using steel fibers content greater than 1.5% in the UHPFRC mix, the ductility results of beams would have been better, which needs to be investigated further in future studies. While in the case of SIFCON beams, the lack of ductility compared to SFRC beam may be attributed to using a strengthening layer with a small thickness, so it needs to be investigated using SIFCON in the compression zone with a layer thickness greater than 30 mm in future studies.

Flexural capacity

As shown in Table 3, the ultimate loads of composite beams containing a layer of SFRC, UHPFRC, and SIFCON in the compression zone improved by 30.45, 41.65 and 52.46%, while the corresponding deflections improved by 33.30, 3.61 and 36.44%, respectively, compared to those of NC beam.

TABLE 3. Experimental results of all beams

Beam type		Ultimate load [kN]	Ultimate deflection [mm]	Mode of failure
Reference beam	NC	151.78	8.59	flexural compression (brittle)
Composite beam	SFRC	198.00	11.45	flexural compression (ductile)
	UHPFRC	215.00	8.90	flexural compression (ductile)
	SIFCON	231.40	11.72	flexural compression (ductile)

The improvement in the ultimate load and the corresponding deflection is attributed to the significant effect of the high compressive strength and high ultimate compressive strain capacity of ductile materials, respectively, compared to those of NC that was used in the reference beam. These results indicate that using ductile materials in the compression zone of concrete has a considerable effect on improving the flexural capacity of over--reinforced beams.

Ductility

The ability of any material or member to experience plastic deformation and energy absorption is measured by its ductility, which also refers to the ability of the material or member to resist applied loads after yielding without critical failure. There are many forms of ductility, such as curvature, rotational, and deflection ductility (Deng et al., 2018). The definition of deflection ductility is investigated in this study. As defined by Pam, Kwan and Islam (2001), the deflection ductility index (μΔ) is the ratio of maximum deflection (Δ_{max}) to yield deflection (Δ_y). Several various definitions have been suggested by Park (Park, 1989) to estimate yield and maximum deflections. The definition adopted here for yield deflection is by using the secant stiffness method at 75% of the ultimate load (P_u), while the definition of maximum deflection is related to how the failure point is defined. The most realistic definition of maximum deflection is when the load-carrying capacity has undergone a small reduction after ultimate load or when the material fractures, whichever occurs first. For more details, see reference (Park, 1989). Noting that the reduction in load-carrying capacity after ultimate load was adopted by 15%, according to reference (Pam et al., 2001). Figure 7 shows the definition of yield and maximum deflections.

In order to reveal the effect of ductile materials layers on ductility, the ductility index ratio (R) is calculated, which is the ratio of the deflection ductility index of the composite beam to that of the corresponding reference beam. The obtained main results of loads and the deflection ductility indexes with the ductility index ratio for the tested beams are presented in Table 4. It emerged that the use of ductile materials layer (SFRC, UHPFRC, and SIFCON) in the compression zone of over-reinforced concrete beams showed a considerable increase in ductility as compared to that of the reference beam.

Based on the above, composite beam with SFRC or SIFCON layer exhibited

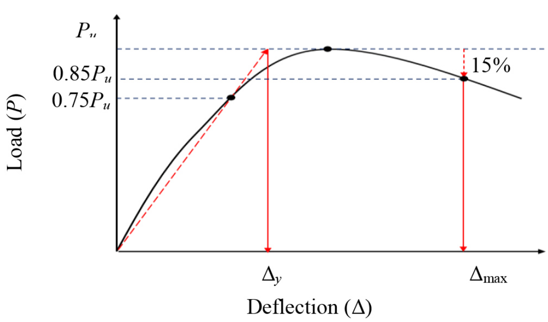

FIGURE 7. Definition of yield and maximum deflections

TABLE 4. The deflection ductility indexes and the ductility index ratio of tested beams

Beam type		Δ_y [mm]	Δ_{max} [mm]	$\mu\Delta$ [-]	R [%]
Reference beam	NC	7.68	10.60	1.38	–
Composite beam	SFRC	9.50	24.20	2.55	84.78
	UHPFRC	7.50	11.25	1.50	8.70
	SIFCON	8.75	19.25	2.20	59.42

better performance than that with the UHPFRC layer in deflection ductility. This may be related to the fact that the behavior of UHPC is brittle. Generally, the use of hooked-end steel fiber (*Vf* 1.5%) with NC increased the ductility of concrete by 84.78%. Finally, the ductility of the over-reinforced concrete beams has been improved using ductile materials in the compression zone.

Toughness

Toughness (*Ut*) is defined as the material's ability to absorb energy before failure. However, it is attached to combining both strength and ductility in a single measurable property and requires a delicate balance of strength and ductility (Abeer et al., 2020). The material must be strong and ductile in order to be tough. A strong material but has limited ductility as brittle material is not tough, and similarly, highly ductile material but has low strength is not tough. The material must be able to sustain high stresses as well as high strains to be considered tough. Flexure toughness is related to the area under the stress–strain or load–deflection curves and calculated using Equation (1).

$$Ut = \text{area under the load } (P) \text{ curve} – \text{deflection } (\Delta) \text{ curve} = P \times \Delta \qquad (1)$$

The toughness results of the tested beams are shown in Table 5. It emerged that the toughness of composite beams showed an acceptable increment when compared to the reference beam, which was 279.93, 146.05 and 235.13% for SFRC, UHPFRC, and SIFCON, respectively. This behavior may be explained by the fact that the ability of steel fibers to bridge across the cracks led to an increase in the ultimate load and deflection, which resulted in an increase in the area under the load–deflection curve.

TABLE 5. The toughness values of tested beams

Beam type		Toughness [$N \cdot m^{-1}$]	The increment in toughness over NC beam [%]
Reference beam	NC	996.18	–
Composite beam	SFRC	3 784.81	279.93
	UHPFRC	2 451.15	146.05
	SIFCON	3 338.55	235.13

Table 5 shows that the composite beam with SFRC exhibits a higher increment in toughness. In general, it can be concluded that the use of ductile materials in the compression zone of composite beams provides an improvement in the energy absorption and ductility for over-reinforced concrete beams.

Conclusions

Based on the results obtained in the current study, the following conclusions can be drawn:

- Using ductile materials layer in the compression zone of over-reinforced beams changed the failure mode from brittle compression failure to ductile flexural compression failure.
- Using ductile materials layers in the compression zone of over-reinforced concrete beams with tensile reinforcement ratio of 8.548% increased load-carrying capacity and deformation ability at failure by up to 52.46 and 133.70%, respectively.
- The load-carrying capacity of composite beams containing a layer of SFRC, UHPFRC, and SIFCON in the compression zone improved by 30.45, 41.65 and 52.46%, while the corresponding deflections improved by 33.30, 3.61 and 36.44%, respectively, compared to NC beam.
- The increase in ductility by using SFRC, UHPFRC, and SIFCON layers in the compression zone was 84.78, 8.70 and 59.42%, respectively, while the increase in toughness was 279.93, 146.05 and 235.13%, respectively.
- Finally, it can be stated that the acceptable compressive strength and high deformation ability of SFRC have the potential to enable economical and ductility together compared with UHPFRC and SIFCON.

References

Abeer, S. Z., Dawood, M. B. & Ghalib, M. H. (2020). Flexural behavior of continuous beams consisting of normal concrete and SIFCON under static and repeated loads. *IOP Conference Series: Materials Science and Engineering*, *870* (1), 1–14. https://doi.org/10.1088/1757-899X/870/1/012113

Ahmed, M. M., Farghal, O. A., Nagah, A. K. & Haridy, A. A. (2007). Effect of confining method on the ductility of over-reinforced concrete beams. *Journal of Engineering Sciences*, *35* (3), 617–633. https://doi.org/10.21608/JESAUN.2007.112873

Alasadi, S., Shafigh, P. & Ibrahim, Z. (2020). Experimental study on the flexural behavior of over reinforced concrete beams bolted with compression steel plate: Part I. *Applied Sciences (Switzerland)*, *10* (3), 1–20. https://doi.org/10.3390/app10030822

Ali, A. M. & Tarkhan, M. A. (2015). Experimental investigation of confining the compression zone in over-reinforced beams. *International Journal of Engineering Sciences and Research Technology*, *4* (11), 611–617.

American Association State Highway and Transportation [ASTM] (2015). *Standard specification for deformed and plain carbon-steel bars for concrete reinforcement* (ASTM A615/A615M). Washington: American Association State Highway and Transportation.

American Concrete Institute [ACI] (2014). *Building code requirements for structural concrete* (ACI 318). Farmington Hills: American Concrete Institute.

Atta, A. M. & Khalil, A. E. H. (2016). Improving the failure mode of over-rinforced concrete beams using strain-hardening cementitious composites. *Journal of Performance of Constructed Facilities*, *30* (5), 04016003. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000857

Balaji, S. & Thirugnanam, G. S. (2018). Behaviour of reinforced concrete beams with SIFCON at various locations in the beam. *KSCE Journal of Civil Engineering*, *22* (1), 161–166. https://doi.org/10.1007/s12205-017-0498-9

Deng, M., Ma, F., Ye, W. & Li, F. (2018). Flexural behavior of reinforced concrete beams strengthened by HDC and RPC. *Construction and Building Materials*, *188*, 995–1006. https://doi.org/10.1016/j.conbuildmat.2018.08.124

Deng, M., Zhang, M., Ma, F., Li, F. & Sun, H. (2021). Flexural strengthening of over-reinforced concrete beams with highly ductile fiber-reinforced concrete layer. *Engineering Structures*, *231*, 111725. https://doi.org/10.1016/j.engstruct.2020.111725

Germano, F., Plizzari, G. A. & Tiberti, G. (2013). Experimental study on the behavior of SFRC columns under seismic loads. In J. G. M. Van Mier, G. Ruiz, C. Andrade, R. C. Yu & X. X. Zhang (Eds). *Proceedings of the 8th International Conference on Fracture Mechanics of Concrete and Concrete Structures, FraMCoS-8* (pp. 1171–1182). Barcelona: Cimne.

Khalil, W. I. & Tayfur, Y. R. (2013). Flexural strength of fibrous ultra high performance reinforced concrete beams. *ARPN Journal of Engineering and Applied Sciences*, *8* (3), 200–214.

Khamees, S. S., Kadhum, M. M. & Alwash, N. A. (2020). Effects of steel fibers geometry on the mechanical properties of SIFCON concrete. *Civil Engineering Journal (Iran)*, *6* (1), 21–33. https://doi.org/10.28991/cej-2020-03091450

Kobayashi, K. (1976). Steel Fiber Reinforced Concrete. *Zairyo/Journal of the Society of Materials Science, Japan*, *25* (277), 937–945. https://doi.org/10.2472/jsms.25.937

Liu, K. & Wu, Y. F. (2007). Compression yielding by sifcon block for FRP-reinforced concrete beams. *Proceedings of the 1st Asia-Pacific Conference on FRP in Structures*, *1*, 411–416.

Mohamed, H. A. (2018). Improvement in the ductility of over-reinforced NSC and HSC beams by confining the compression zone. *Structures*, *16* (2), 129–136. https://doi.org/10.1016/j.istruc.2018.09.005

Orouji, M., Zahrai, S. M. & Najaf, E. (2021). Effect of glass powder & polypropylene fibers on compressive and flexural strengths, toughness and ductility of concrete: an environmental approach. *Structures*, *33*, 4616–4628. https://doi.org/10.1016/j.istruc.2021.07.048

Pam, H. J., Kwan, A. K. H. & Islam, M. S. (2001). Flexural strength and ductility of reinforced normal- and high-strength concrete beams. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, *146* (4), 381–389. https://doi.org/10.1680/stbu.2001.146.4.381

Park, R. (1989). Evaluation of ductility of structures and structural assemblages from laboratory testing. *Bulletin of the New Zealand Society for Earthquake Engineering*, *22* (3), 155–166. https://doi.org/10.5459/bnzsee.22.3.155-166

Priastiwi, Y. A., Imran, I., Nuroji & Hidayat, A. (2014). Behavior of ductile beam with addition confinement in compression zone. *Procedia Engineering*, *95*, 132–138. https://doi.org/10.1016/j.proeng.2014.12.172

Qadir, H. H., Faraj, R. H., Sherwani, A. F. H., Mohammed, B. H. & Younis, K. H. (2020). Mechanical properties and fracture parameters of ultra high performance steel fiber reinforced concrete composites made with extremely low water per binder ratios. *SN Applied Sciences*, *2*(9), 1594. https://doi.org/10.1007/s42452-020-03425-3

Salih, S., Frayyeh, Q. & Ali, M. (2018). Fresh and some mechanical properties of sifcon containing silica fume. *MATEC Web of Conferences*, *162*, 1–7. https://doi.org/10.1051/matecconf/201816202003

Shelorkar, A. P. (2021). Slurry Infiltrated Fibrous Concrete (SIFCON) – a review. *International Journal of Research Publication and Reviews*, *2* (8), 780–787.

Siddiqi, Z. A. (2016). *Concrete Structures*. Part 1 (3rd ed.). Lahore: Help Civil Engineering Publisher.

Tee, H. H., Al-Sanjery, K. & Chiang, J. C. L. (2017). Behaviour of reinforced concrete beams with confined concrete related to ultimate bending and shear strength. *AIP Conference Proceedings*, *1*, 020060. https://doi.org/10.1063/1.4976924

Whitehead, P. A. & Ibell, T. J. (2004). Deformability and ductility in over-reinforced concrete structures. *Magazine of Concrete Research*, *56* (3), 167–177. https://doi.org/10.1680/MACR.2004.56.3.167

Wu, Y. F. (2008). Ductility demand of compression yielding fiber-reinforced polymer-reinforced concrete beams. *ACI Structural Journal*, *105* (1), 104–110. https://doi.org/10.14359/19074

Ziara, M. M., Haldane, D. & Hood, S. (2000). Proposed changes to flexural design in BS 8110 to allow over-reinforced sections to fail in a ductile manner. *Magazine of Concrete Research*, *52* (6), 443–454. https://doi.org/10.1680/MACR.2000.52.6.443

Summary

Stress–strain relationship of ductile materials and flexural behavior of ductile over-reinforced concrete beams. This paper aimed to investigate the effect of using ductile materials in the compression zone on the flexural performance of over-reinforced concrete beams. In order to avoid brittle compression failure, partial replacement of concrete with ductile materials layer in the compression zone was used. Four over-reinforced concrete beams of size 120 × 180 × 1,300 mm were cast and tested under three-point loading conditions. The steel fibers reinforced concrete (SFRC), slurry infiltrated fiber concrete (SIFCON), and ultra-high performance fiber reinforced concrete (UHPFRC) were used as ductile materials. The flexural capacity of the beams, failure modes, crack patterns, load-deflection relationships, ductility index, and toughness were investigated. The results showed that using ductile materials in the compression zone is an effective technique to increase the ultimate load, ductility, and toughness by up to 52.46, 84.78 and 279.93%, respectively, compared to the reference beam. In addition, the failure mode changed from brittle to ductile failure. Noting that the use of SFRC layer enhanced the ductility of over-reinforced concrete beams more than using UHPFRC and SIFCON layers. Also, one of the main advantages of this technique is led to increase the tensile reinforcement ratio up to 8.548% without needing the compressive reinforcement. Thus, ductile composite beams with a high flexural capacity were generated using an economical amount of ductile materials.