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Behaviour of functionally graded reinforced-concrete beams under cyclic loading

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Original scientific paper

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Behaviour of functionally graded reinforced-concrete beams under cyclic loading

Over the past decade, the functional grading has been applied as a new method for the manufacturing of reinforced-concrete elements. The objective of this investigation is to evaluate performance of the functionally graded reinforced-concrete beams exposed to cyclic loading. The steel and polypropylene fibres are used for the preparation of samples. Concrete beams with full composite action are strengthened with 0.5 to 2 % of steel fibres, and functionally graded RC beams contain 1.3 % of steel fibres. The use of the functionally graded method to reinforce concrete increases the dissipated energy due to the applied cyclic loading.

Key words:
functionally graded RC beams, fully reinforced cross-section, cyclic loading

Izvorni znanstveni rad

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Ponašanje slojevito mikroarmiranih betonskih greda izloženih cikličkom opterećenju

Tijekom zadnjih deset godina primjenjuje se slojevito mikroarmiranje kao nova metoda za proizvodnju armiranobetonskih elemenata. U radu su prikazani rezultati ispitivanja svojstava slojevito mikroarmiranih betonskih greda izloženih djelovanju cikličnog opterećenja. Za pripremu uzoraka primijenjena su čelična i polipropilenska vlakna. Betonske grede s potpunim kompozitnim djelovanjem ojačane su sa 0,5 do 2 % čeličnih vlakana, a slojevito mikroarmnirane grede sadrže 1,3 % čeličnih vlakana. Dobiveni rezultati pokazuju da se primjenom slojevitog mikroarmiranja betona povećava disipacija energije uslijed cikličkog opterećenja.

Ključne riječi:
slojevito mikroarmiranje betonske grede, potpuno armirani poprečni presjek, ciklično opterećenje

Wissenschaftlicher Originalbeitrag

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Verhalten von geschichtet faserverstärkten Betonbalken unter zyklischer Belastung

In den letzten zehn Jahren wird geschichtete Faserverstärkung als neue Methode zur Herstellung von Stahlbetonelementen angewandt. Das Ziel dieses Forschungsvorhabens ist, die Eigenschaften von geschichtet faserverstärkten Betonbalken unter zyklischer Belastung zu erfragen. Zur Vorbereitung der Proben wurden Stahl- und Polypropylenfasern angewandt. Betonbalken mit voller Verbundwirkung sind mit 0,5 bis 2 % Stahlfasern verstärkt und geschichtet verstärkte Balken umfassen 1,3 % Stahlfasern. Die Resultate zeigen, dass durch eine geschichtete Faserverstärkung des Betons die Dissipationsenergie infolge zyklischer Belastung ansteigt.

Schlüsselwörter:
geschichtet faserverstärkte Stahlbetonbalken, vollständig bewehrter Querschnitt, zyklische Belastung

1. Introduction

In the last decade, various studies have been conducted on reinforced structural elements, with an emphasis on the use of fibres in the improvement of concrete behaviour. Fibre-Reinforced Composites (FRC) often aim to improve the strength to weight and stiffness to weight ratios (light-weight structures that are strong and stiff are desired). Glass or metal fibres are generally embedded in polymeric matrices. Fibres are available in three basic forms:

a) continuous fibres: long, straight and generally parallel to each other;
b) chopped fibres: generally short and randomly distributed (fibreglass);
c) woven fibres: which come in cloth form and provide multidirectional strength.

In the beginning, fibre-reinforced cement sheets were produced using asbestos fibres in the Hatschek process. Because of special features of asbestos fibres such as the high fibre strength and durability, high physical and chemical resistance, non-combustibility, resistance to weathering, and cost-effectiveness, it was used as a building material in various forms and styles during the last century to fulfill different requirements. However, the use of asbestos fibres was stopped due to its major health hazard [1-3]. Consequently, various types of synthetic fibres were produced as their replacement. The most common are organic fibres such as acrylic, polyvinyl alcohol (PVA), polyethylene (PE), polypropylene (PP)), natural cellulose (such as hardwood and softwood pulps), and inorganic fibres (such as glass and carbon) [4]. By considering different type of materials, fibres (for use in structural concrete) are classified into the following basic groups [5]:

- steel fibres of different shapes and dimensions and microfibres;
- glass fibres, used in cement matrices as alkali-resistant (AR) fibres only;
- Synthetic fibres made of different materials: polypropylene, polyethylene and polyolefin, polyvinyl alcohol (PVA), etc;
- carbon, pitch and Polyacrylonitrile (PAN) fibres.

Parameters affecting mechanical performance of cement are the type, geometry and orientation, and volume content of fibres used in the matrix [6]. Using fibres for reinforcing cementitious composites leads to an increase in toughness and mechanical strength [7].

To demonstrate the reinforcing efficiency of structural elements containing various fibre types, the structural elements were subjected to different tests such as the flexural, compression, tension, impact loading, and cyclic loading tests. In common studies on structural elements, these elements are entirely reinforced in cross-section, and the effects with regard to fibre type, fibre content and matrix properties are reported under flexural, tension, compression, cyclic, and impact loading.

In 2008, a new aspect of concrete reinforcement was developed. This advancement demonstrated that the reinforcement of concrete in different layers, and with different fibre contents, leads to a better flexural performance in the beams and slabs under monotonic load [8]. Iskhakov et al. investigated an innovative material to be used as a replacement in the repair of concrete structures [9]. They used two layers of materials in the beam, in which the plain concrete and the high performance concrete were used for the bottom and top layers, respectively. The aim of their study was to achieve an optimum fibre content with the highest Poisson's ratio and ductility for the repaired element sections [9]. Their experimental results show that the SFHSC layer depth should be equal to that of the beam's compressed zone section [9]. The fibre reinforcement was distributed randomly throughout the elements. The reinforced concrete layer can be used entirely in the element's section, or just in two-layers via composite elements [10]. The combination of the normal-strength concrete and the Steel Fibre High Strength Concrete (SFHSC), as a two-layer composite beam, results in effective and low-cost solutions. Additionally, this method can be proposed as a new method for the retrofitting of structural elements [11]. Ghasemi Naghibdehi et al. investigated, both experimentally and numerically, the effect of cross-section reinforcement with steel fibres, PP fibres, or both, in two separate layers. In their study, beams were reinforced by using 0.5 %, 1 %, and 2 % fibre volume fractions of steel and PP fibres. The reinforced cross-section beams with one or two fibre types were evaluated under flexural loading. The results showed that reinforcement of the entire cross-section with steel fibres could lead to a higher load-carrying capacity as compared to the reinforcement of cross-section with two fibre types in two separate layers. The best flexural performance for the single-type reinforcement of the entire cross-section was obtained for the 2 % fibre volume fraction with steel fibres. Also, the best performance of composite two-layer beams was achieved with the 1 % fibre volume fraction of steel fibres [12, 13]. Previous studies were performed by monotonic loading and, as far as the authors can tell, no study has been done on the reinforcement of structural elements by this method under cyclic loading. In this regard, we experimentally investigated behaviour of reinforced concrete beams. In doing so, PP fibres and steel fibres were utilized in different fibre volume fractions to better expose the performance of functionally graded reinforced concrete beams in comparison with entirely reinforced cross-section beams under the reverse cyclic loading. The current investigation is composed of two stages. In the first stage, the normal and reinforced concretes were studied under different kinds of loading, such as the compression, splitting tensile, and shear loading. Then, in the next stage, after obtaining the mechanical properties of concrete, the behaviour of multi-layered slabs was scrutinized under the reverse cyclic loading by considering different fibre types and fractions, and layer positions.

2. Experimental plan

In the first phase of the experimental plan, the compressive and splitting tensile tests were carried out to clarify mechanical properties of reinforced concrete layers with PP fibres and steel fibres. The tests were performed both for the entirely reinforced concrete beams and functionally graded reinforced concrete beams. After having measured mechanical properties of reinforced concretes, the functionally graded reinforced beams and entirely reinforced concrete beams were subjected to shear loading and then, in the last phase of the experimental plan, they were tested by reverse cyclic loading. In the present study, concrete beams were reinforced with PP fibres and steel fibres. The utilized PP fibre volume fractions were 0.25 % (2.3 kg/m^3), 0.5 % (4.6 kg/m^3), 0.65 % (5.98 kg/m^3), 0.75 % (6.9 kg/m^3), and 1 % (9.2 kg/m^3), while the utilized steel fibre volume fractions were 0.5 % (39.5 kg/m^3), 1 % (79 kg/m^3), 1.3 % (102.7 kg/m^3), 1.5 % (118.5 kg/m^3), and 2 % (158 kg/m^3).

2.1. Materials

The Portland cement 42.5R (Type 2), silica sand with two different diameters, micro silica, water, and a poly-carboxylate-based super plasticizer, were used to obtain the high-strength concrete with the mix proportions as presented in Table 1. The poly-carboxylate-based super plasticizer is a new generation of admixtures that is added in a relatively low proportion (0.15 - 0.3 % by cement weight). This super plasticizer allows water reduction of up to 40 %, due to its chemical structure enabling good particle dispersion. The mix design was achieved based on two components:

1. paste materials, which contain powders such as cement and lime stone filler;
2. stone skeleton, which contains sand and coarse aggregates, as well as fibres.

Table 1. Concrete mix proportions

Mix proportions		Portion in the mix [kg/m^3]
Cement		967
Micro silica		251
Silica sand	0.5-0.9 mm	405
	0.2-0.5 mm	270
Water		365.4
Super plasticizer		12.18

To obtain a good rheology of fresh concrete two items, i.e. the slump value and segregation, were considered and monitored visually (for paste materials). To obtain the mixture proportion presented in Table 1, paste materials were mixed with stone skeleton and assessed by slump test. Two different types of fibres were used. Their mechanical properties are sorted as shown in Table 2 and Figure 1. The reinforced concretes with different fibre contents were prepared by adding the following materials:

1. fine aggregate
2. cement
3. water + 40 % super plasticizer
4. 60 % super plasticizer
5. fibres.

To achieve the proposed goals, twenty six beams were reinforced with different fibre types, different fibre contents, and at different layer positions. The reinforced beam candidates are listed in Table 3.

Table 2. Properties of steel and PP fibres

Fibre	L/D	Young's modulus [GPa]	Tensile strength [MPa]
Steel	45	200	1100
Polypropylene (PP)	461	5	600

The ductility and technological aspects of laboratory tests of two-layer beams, consisting of fibred high strength concrete in a compressed zone, and normal strength concrete without fibres in the tensile zone, are explained in more details in literature [12, 14]. In the present study, three wooden moulds were used for

Table 3. Description of beams

Specimens	Fibre type [%]	Fibre content	Reinforcement method	Layer numbers	Layer thickness [mm]
Plain concrete	---	---	---	---	100
PP 0.25	0.25	PP	Entirely RC	1	100
PP 0.5	0.5	PP	Entirely RC	1	100
PP 0.65	0.65	PP	Entirely RC	1	100
PP 0.75	0.75	PP	Entirely RC	1	100
PP 1	1	PP	Entirely RC	1	100
FGRCPP	0.65 (Equivalent)	PP	Functionally graded RC	5	20
ST 0.5	0.5	Steel	Entirely RC	1	100
ST 1	1	Steel	Entirely RC	1	100
ST 1.3	1.3	Steel	Entirely RC	1	100
ST 1.5	1.5	Steel	Entirely RC	1	100
ST 2	2	Steel	Entirely RC	1	100
FGRCST	1.3 (Equivalent)	Steel	Functionally graded RC	5	20

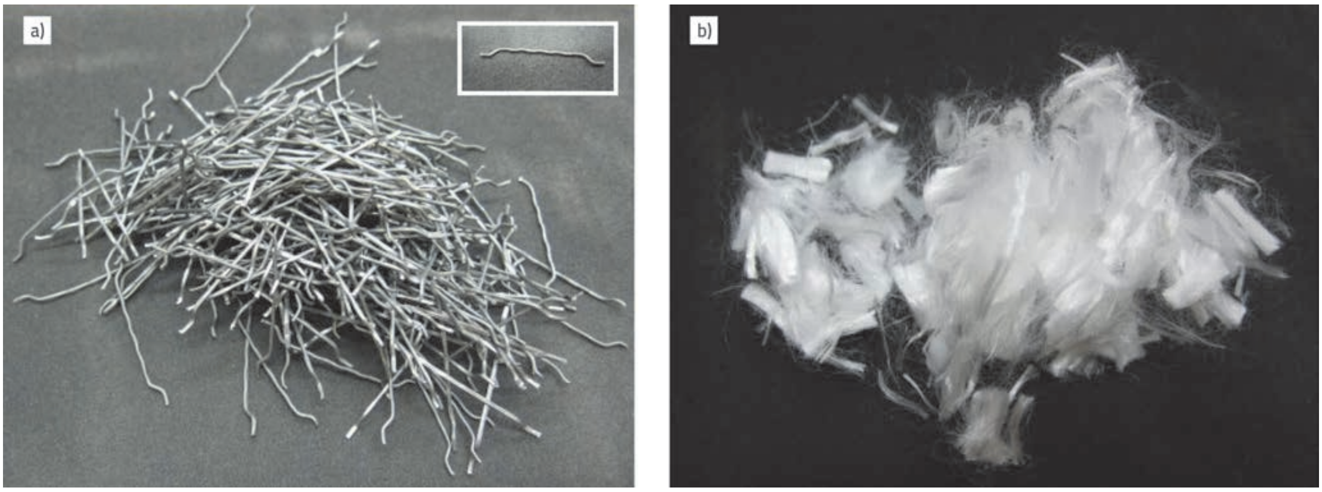

Figure 1. Materials used: a) Steel fibres; b) PP fibres

casting the functionally graded reinforced concrete beams in five layers. Two sides of moulds 20 mm in thickness, 400 mm in length, and 100 mm in width, were bolted to the bottom plate. At first, two 20 mm thick side moulds were placed into their position (for controlling the uniform thickness of each layer) and the fresh mixture was poured into the mould. After about 45 minutes (obtained by trial and error), the first layer could withstand the weight of the top layer and another layer poured onto it, and this continued to the fifth layer.

2.2. Compressive and splitting tensile strength

At the first stage of the study, the reinforced concretes were subjected to compressive and splitting tensile tests in order to obtain compressive and tensile strength values. In this regard, cubic specimens measuring 100 × 100 × 100 mm^3 were cast and tested to assess the effects of steel and PP fibres on compressive strength. Furthermore, three cylinders 150 mm in diameter and 300 mm in height were utilized for the splitting tensile test. The setup and cracking patterns are shown in Figure 2. The applied force rate was considered to be equal to 0.016 N/mm^2.sec based on the ASTM C496 [15].

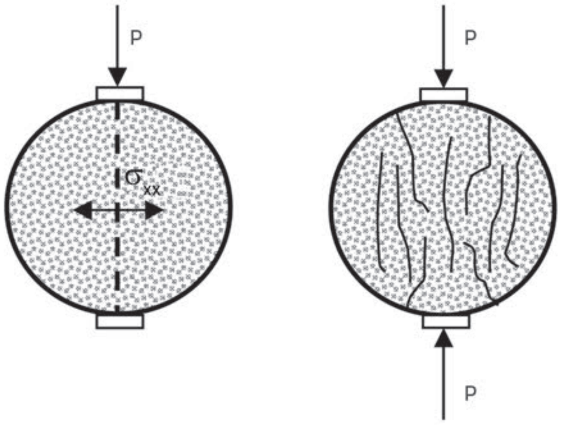

Figure 2. Schematic of splitting tensile test and cracking patterns

The splitting tensile strength is calculated using equation (1):

$$\sigma_{xx} = \frac{2P}{\pi D} \tag{1}$$

where D is the diameter of cylindrical specimens, while P is the magnitude of point loads.

2.3. Three Point Bending (TPB) tests

Ghasemi Naghibdehi et al. showed that reinforcement, in the functionally graded method, is significantly dependent on the fibre type, fibre content, and position of layers [12, 13]. On the other hand, using functionally graded method in the reinforcement of concrete provides options for choosing different layer positions, fibre types, and fibre volume fractions based on structural applications. During the reverse cyclic loading, the structural element is assessed under the positive and negative cyclic moments. Additionally, the reinforcement enhances the post-cracking properties of plain concrete and provides for a better ductile behaviour of material. The increased ductility results from the ability of fibres to transfer tensile stresses across a cracked section, which subsequently leads to crack width reduction. On the other hand, the plain concrete reinforcement provides better capability for transferring tensile stresses across a cracked section. This property is more effective when more fibres are used and localized in the tension part of the entire cross-section. Considering the aforementioned, reinforced layers with the same fibre content and fibre type were placed symmetrically in the functionally graded reinforced concrete beams under monotonic and reverse cyclic loading. The details of entirely reinforced beam sections, and functionally graded reinforced concrete beams, are presented in Figure 3 and Table 4.

Table 4. Details of reinforcement used in functionally graded RC beams

Layers / Type of fibres	Layer 1 [%]	Layer 2 [%]	Layer 3 [%]	Layer 4 [%]	Layer 5 [%]
Polypropylene	2	1	0,5	1	2
Steel	1	0,5	0,25	0,5	1

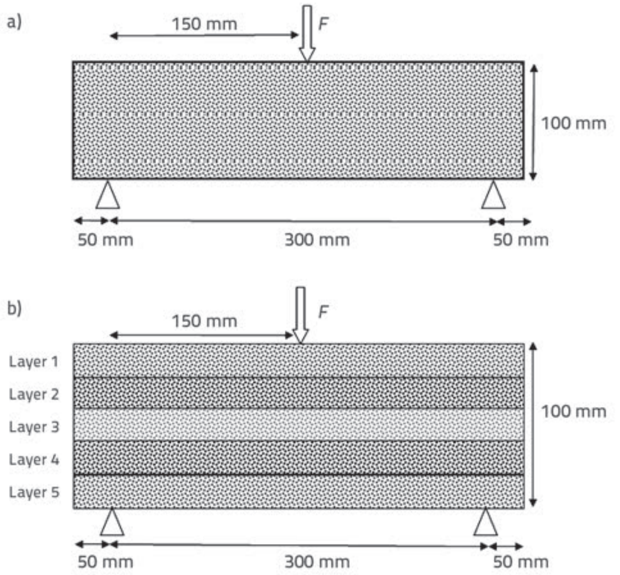

Figure 3. Schematic figures of reinforced concrete: a) entirely reinforced concrete beams; b) functionally graded reinforced concrete beams

To evaluate flexural properties of beams, thirteen beams measuring 100×100×400 mm^3 were cast and tested under TPB test conditions, at the load rate of 0.5 mm/min. According to previous findings [13], more layers with lower thickness lead to an enhanced flexural performance. This fact is derived from the lower thickness of reinforced concrete layer results obtained in aligning fibres as planar in the reinforced concrete layer. Hence, it is postulated that if the thickness of the reinforced concrete layer with steel and PP fibre decreases to a lower fibre length, the fibres are aligned as planar and, subsequently, the flexural performance will be improved. Since the steel and PP fibres measure 36 mm and 12 mm in length, respectively, the thickness of 20 mm was selected as the layer thickness to have planar fibre alignment in the reinforced concrete layer.

Additionally, a symmetric reinforcement was used in the layers due to the imposed reverse cyclic loading conditions. On the other hand, both top and bottom layers were subjected to compression and tension loading. Thus a symmetric reinforcement was employed in the layers with both types of fibres.

The proposed functionally graded reinforced concrete layers can be adopted as a composite RC element. The concept of the functionally graded reinforced concrete involves steady transitions in material microstructure and composition to meet functional requirements of an engineered component. Regarding this point, there are some interfacial transition zones (ITZ) among the layers. The interfacial transition zone properties are different for each layer due to the use of different fibre volume fractions for concrete reinforcement. Shear stresses between layers are transferred via the ITZ. As beams are loaded as cyclic, the maximum shear stresses are realized in the ITZ of the bottom and top reinforced concrete layers. Considering this fact, the use of a greater number of layers leads to the reduction of shear stresses in the ITZ and, subsequently, a better composite action can be observed in proposed functionally graded reinforced concrete elements. According to this fact, it will be shown that all layers work together up to the Ultimate Limit State (ULS), which is the evidence that a good bond was formed between the layers.

The minimum reinforced layers that could be considered as symmetric are three layers. However, it was assumed that three layers result in a shear stress distribution among the layers with high gradients. Regarding this point, five layers were adopted as the number of layers to be used in this experimental study.

2.4. Test setup and procedure

The test setup for performing the TPB test is presented in detail in Figure 3. To compare the results, a similar test setup had to be used for the reverse cyclic loading [16]. Therefore, the hydraulic jack was fixed by steel bolts so that the continuous cyclic loading can be applied. In addition, this fixing system was used to fix supports that prevented beams from moving upward during the reverse cyclic loading. The test setup is presented schematically in Figure 4.

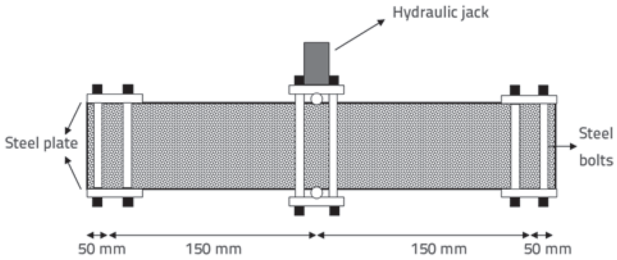

Figure 4. Schematic of test setup for cyclic test

The consequences of reverse cyclic loading are shown in Figure 5. In this regard, forty-four loading steps were employed to conduct the reverse cyclic loading. The displacement control was used to perform the test at the rate of 0.5 mm/min at mid-spans of beams. As shown in Figure 4, the defined displacement consequences were applied to mid-span by a hydraulic jack in order to conduct the reverse cyclic loading.

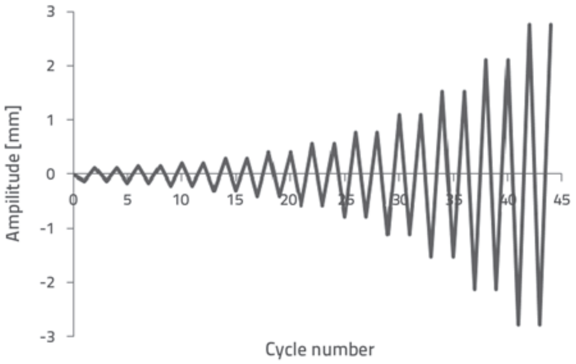

Figure 5. Cyclic load pattern used in testing

Table 5. Compressive and tensile strength values

Specimens		Compressive strength [MPa]				Splitting tensile strength [MPa]		
		SP 1	SP 2	SP 3	Average	SP 1	SP 2	Average
Polypropylene fibres (PP)	PP 0.25	108.80	101.10	102.20	104.03	5.39	4.45	4.92
	PP 0.5	97.60	100.60	100.70	99.63	5.12	4.55	4.83
	PP 0.65	83.50	84.70	85.70	84.63	4.47	3.25	3.86
	PP 0.75	77.80	75.10	78.60	77.16	4.22	4.48	4.35
	PP 1	52.90	64.60	68.80	62.10	4.43	3.64	4.03
Steel fibres (ST)	ST 0.5	97	95	89.50	93.83	7.19	6.10	6.64
	ST 1	98.5	83.8	103	95.10	6.85	6.92	6.88
	ST 1.3	77.60	83.70	88.40	83.23	7.88	8.15	8.01
	ST 1.5	88.10	93.60	74.80	85.50	7.40	7.40	7.40
	ST 2	92.80	100.70	94.20	95.90	8.30	9.19	8.74
CUN - plain concrete		92.20	85.40	85	87.53	2.53	2.67	2.60

3. Results and discussions

3.1. Compressive and splitting tensile tests

The compressive and splitting tensile tests were performed on cubic and cylindrical specimens, respectively. The measured compressive and splitting tensile strengths are given in Table 5.
According to the results presented in Table 5 and Figure 6, different results were obtained by adding both PP and steel fibres. For instance, using steel fibres in plain concrete reinforcement with 2 % (158 kg/m^3), the fibre volume fraction gives the maximum compressive and tensile splitting strengths, while it seems that reinforcement of plain concrete with PP fibres at 0.25 % (2.3 kg/m^3) fibre volume fraction results in maximum compressive and tensile splitting strengths. Since the use of 2 % (158 kg/m^3) of fibre volume fraction may seem a little high, and considering the main function of fibres - which is to increase the tensile capability of plain concrete, it can be stated that the plain concrete reinforcement with steel fibres at 1.3 % (102.7 kg/m^3) fibre volume fraction would be a good choice. According to results shown in Figure 6.a, when the compressive strength was increased by 9.56 % with the 2 % (158 kg/m^3) fibre volume fraction, the splitting tensile strength of reinforced concrete with the 2 % (158 kg/m^3) fibre volume fraction was 3.36 times greater than that of the plain concrete. Moreover, the addition of 0.25 % (2.3 kg/m^3) PP fibres resulted in the maximum tensile strength. This increment was by 1.86 times greater than that of the plain concrete. This fact reveals that both the steel and PP fibres are more effective with regard to the splitting tensile strength than in case of compressive strength.

3.2. Utilizing TPB test to assess flexural properties

The proposed functionally graded reinforced concrete, and beams with the entirely reinforced cross-section, were evaluated using the TPB test. The Force-Displacement responses and Flexural stress-Displacement diagrams are shown in Figure 7. According to the results, the addition of steel fibres improves the maximum load and post-cracking properties of reinforced concrete, while the addition of PP fibres as functionally graded reinforced concrete and entirely reinforced cross-section with the 0.65 % (5.98 kg/m^3) fibre volume fraction and the 0.75 % (6.9 kg/m^3) fibre volume fraction, respectively, could increase the maximum applied load as compared to plain concrete. This fact is derived

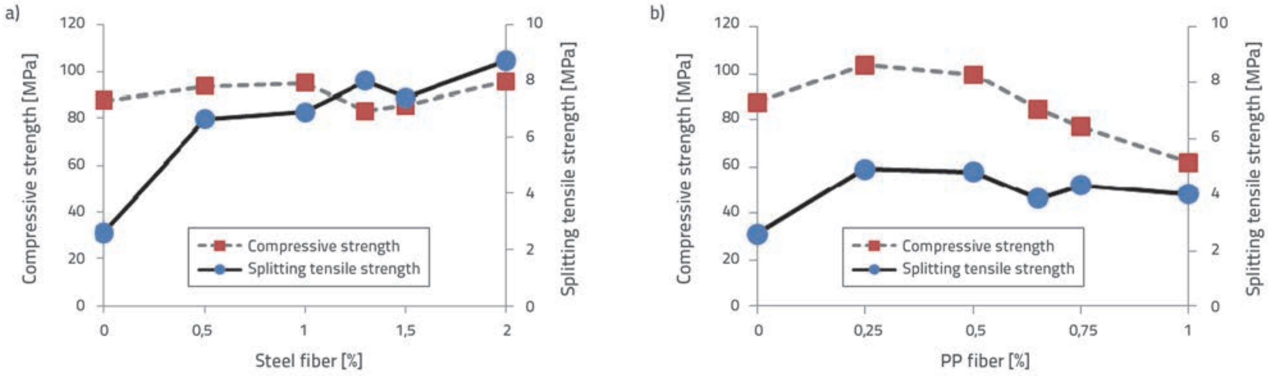

Figure 6. Effects of fibre addition on the compressive and splitting tensile test: a) Steel fibres; b) PP fibres

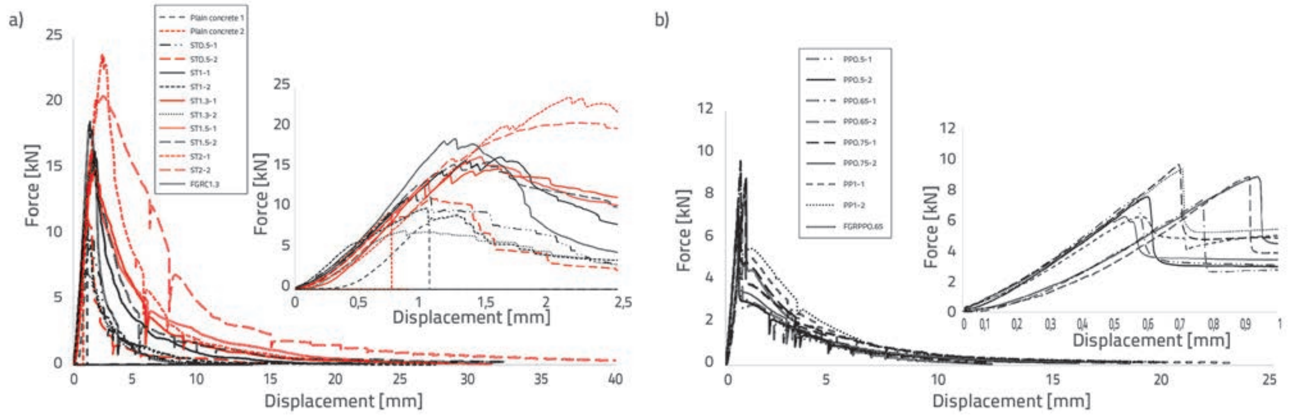

Figure 7. Force-Displacement and flexural responses: a) Force-Displacement of beams with steel fibres; b) Force-Displacement of beams with PP fibres; c) Flexural responses of beams with steel fibres; d) Flexural responses of beams with PP fibres

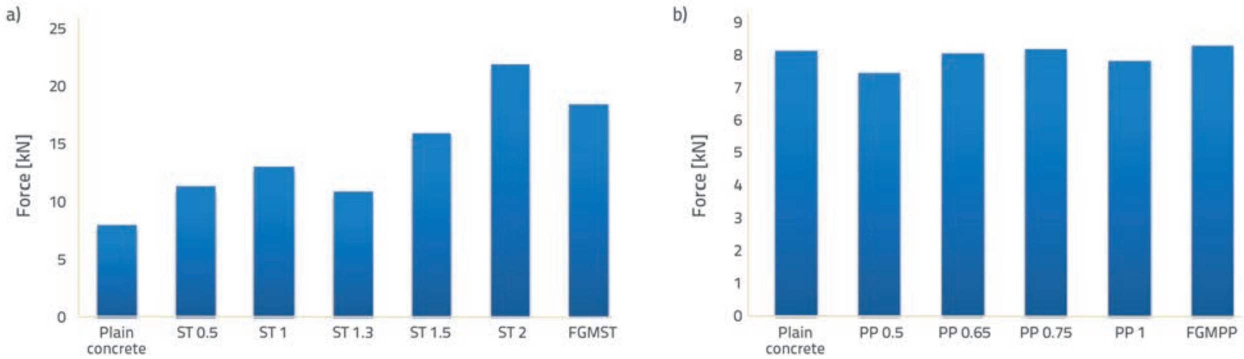

Figure 8. Maximum load applied in beams reinforced with: a) steel fibres; b) PP fibres

from the bond properties that formed among fibres and matrices. According to the results, it can be seen that the hard bond was formed between fibres and matrices. It seems that the hard bond that formed between PP fibres and matrices led to rupture of the fibres. In addition, no enhancement was observed with regard to the post peak properties.

It should be noted that, because of the steel fibre properties such as longer length, higher Young's modulus, and tensile strength, the bond that formed between the steel fibres and matrix does not lead to fibre rupture. So, the reinforcement of concrete beams with steel fibres enhanced post-crack properties, as compared to the concrete reinforcement with PP fibres. Also, the addition of steel fibres leads to significant increase of the maximum load and flexural strength, but this effect was much lower in the concrete reinforced with PP fibres. Previous studies have shown that the reinforcement of the entire cross-section with steel fibres leads to a higher load-carrying capacity, than the reinforcement of the cross-section with two fibre types in two separate layers. The best flexural performance for the single-type reinforcement of the entire cross-section was obtained for the 2 % (158 kg/m^3) fibre volume fraction with steel fibres. Additionally, the use of composite multi-layers as functionally graded reinforced concrete cross-sections has enough potential to achieve mechanical properties of the entirely reinforced concrete with a higher fibre content. Furthermore, the flexural performance of the functionally graded reinforced concrete is significantly governed by the fibre type, fibre content, and positions of reinforced layers. As shown in Figure 8, the reinforcement of concrete beams, functionally graded with the equivalent 1.3 % (102.7 kg/m^3) steel fibre volume fraction, led to a 1.67 times greater increment of the maximum load carrying capacity, as compared to the entirely reinforced cross-section beams with the 1.3 % (102.7 kg/m^3) steel fibre volume fraction. The use of concrete reinforcement beams as functionally graded with the 0.65 % (5.98 kg/m^3) of PP fibres increased by 2.85 % the maximum applied load, as compared to the entirely reinforced cross-section.

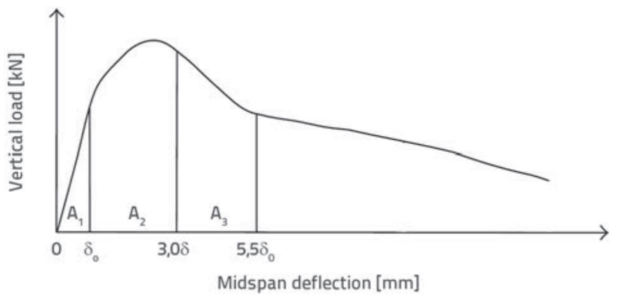

Figure 9. Calculation diagram for flexural toughness according to ASTM method [17]

Table 6. Flexural toughness of beams

Specimen	Fracture toughness and indices according to ASTM C1018 [17]				
	A_1	A_2	A_3	I_5	I_{10}
ST 0.5-1	2.42	5.51	1.88	3.27	4.05
ST 0.5-2	2.4	4.23	1.27	2.76	3.29
ST 1-1	3.28	10.58	3.77	4.22	5.37
ST 1-2	2.73	4.53	1.94	2.66	3.37
ST 1.3-1	2.11	10.98	7.4	6.20	9.71
ST 1.3-2	0.6	3.48	2.25	6.80	10.55
ST 1.5-1	2.64	10.95	6.03	5.14	7.43
ST 1.5-2	4	11.65	4.74	3.91	5.09
ST 2-1	6.71	21.58	6.89	4.21	5.24
ST 2-2	3.96	21.07	18.44	6.32	10.97
FGRC 1.3	4.08	8.19	1.39	3.00	3.34
PP 0.25-1	0.74	0.77	0.6	2.04	2.85
PP 0.25-2	1.02	0.95	0.75	1.93	2.66
PP 0.5-1	0.80	1.55	1.41	2.93	4.70
PP 0.5-2	0.81	1.53	1.3	2.88	4.49
PP 0.65-1	1.01	1.82	1.41	2.80	4.19
PP 0.65-2	1.40	2.70	1.86	2.92	4.25
PP 0.75-1	1.34	2.62	1.9	2.95	4.37
PP 0.75-2	0.72	1.55	1.49	3.15	5.22
PP 1-1	0.65	2.3	2.19	4.53	7.90
PP 1-2	1.34	3.25	2.6	3.42	5.36
FGPP 0.65	1.68	2.94	1.47	2.75	3.62

ST - steel fibres, PP - polypropylene fibres, FGRCST - functionally graded reinforced concrete with steel fibres, FGRCPP - functionally graded reinforced concrete with polypropylene fibres

The flexural toughness of beams was computed based on ASTM C1018 [17]. When the first crack appears, the midspan deflection of the beam specimen is defined as δ_0. The flexural toughness indices I_5 and I_{10} can be computed as follows:

$$I_5 = \frac{(A_1 + A_2)}{A_1} \tag{1}$$

$$I_{10} = \frac{(A_1 + A_2 + A_3)}{A_1} \tag{2}$$

The higher values of I_5, I_{10} indicate that the flexural toughness of concrete is much better. The flexural toughness of beams is calculated and presented in Table 6. In general, the reinforcement of concrete with fibres results in a higher flexural toughness.

3.3. Reverse cyclic loading

Thirteen beams were tested under the reverse cyclic loading conditions. The measured responses are shown in Figure 10 and Figure 11. According to the results, the specimen behaviour is significantly governed by the fibre type, fibre content, and reinforcement (entirely reinforced or functionally graded RC). Furthermore, it seems that just before the beam cracking and failure, the beams exhibit a similar behaviour under the reverse cyclic loading. To achieve a better perception of beam performance under the reverse cyclic loading, the peak point values of the hysteresis curve cycles in pushing are shown in Figure 12.a and Figure 12.b for the reinforced concrete beams with steel fibres and PP fibres, respectively.

According to the measured results shown in Figure 12, the use of steel fibres absorbs more energy due to the applied reverse cyclic loading in comparable PP fibres. The reason can be related to the bond behaviour among fibres and matrices. So, more energy absorption can be achieved in the reinforced concrete beams with steel fibres, as compared to the reinforced concrete beams with PP fibres. Also, it should be mentioned that an increase in the steel fibre content does not necessarily lead to greater energy absorption. For instance, the reinforced concrete beam with the 2 % (158 kg/m^3) steel fibre volume fraction absorbed less energy, in comparison with the reinforced concrete beam with the 1.5 % (118.5 kg/m^3) steel fibre volume fraction up to the measured point. The results achieved show that the reinforced beams with the best performance under monotonic loading do not necessarily exhibit the best cyclic performance. On the other hand, the best performance in the entirely reinforced cross-section beams was

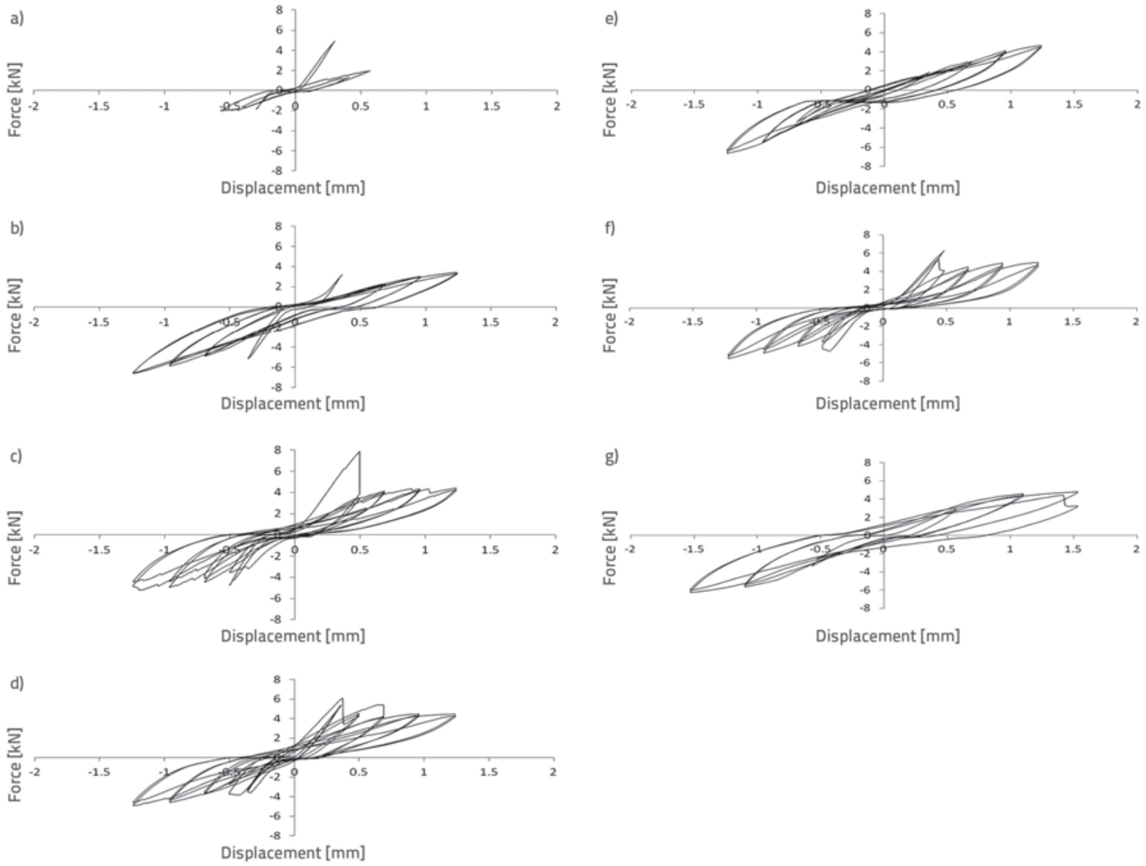

Figure 10. Load-displacement hysteretic responses of beams under reverse cyclic loading: a) plain concrete; b) PP0.25; c) PP0.5; d) PP 0.65; e) PP0.75; f) PP1; g) FGRCPP

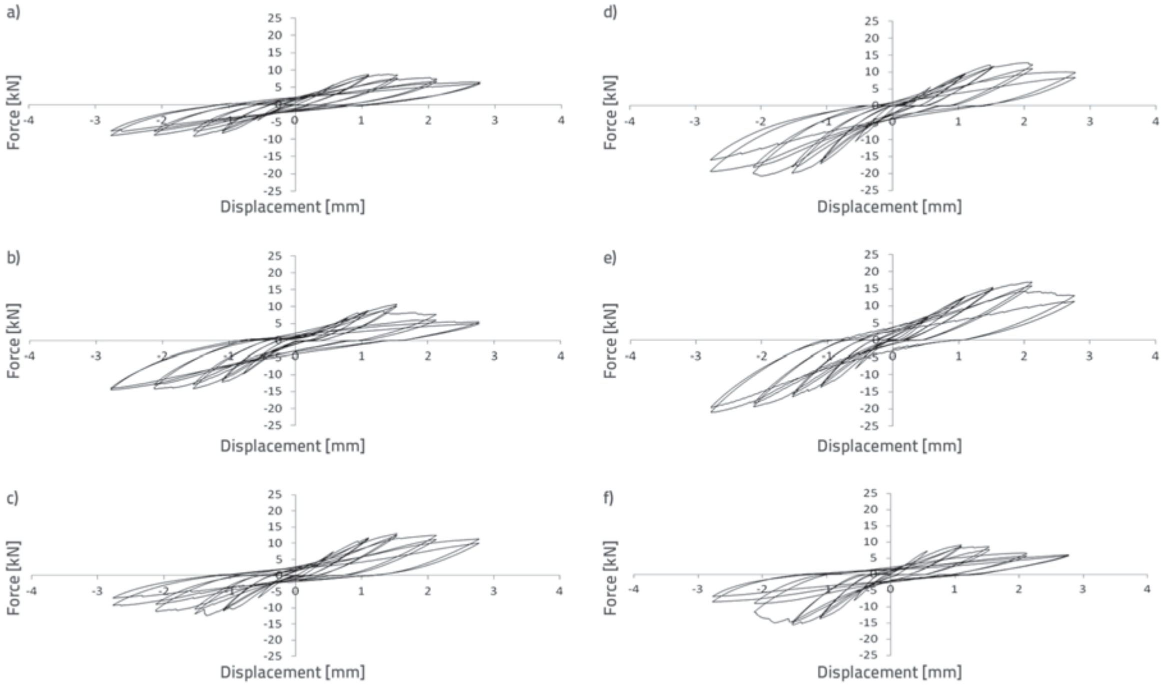

Figure 11. Load-displacement hysteretic responses of beams under reverse cyclic loading: a) ST0.5; b) ST1; c) ST1.3; d) ST1.5; e) ST2; f) FGRCST

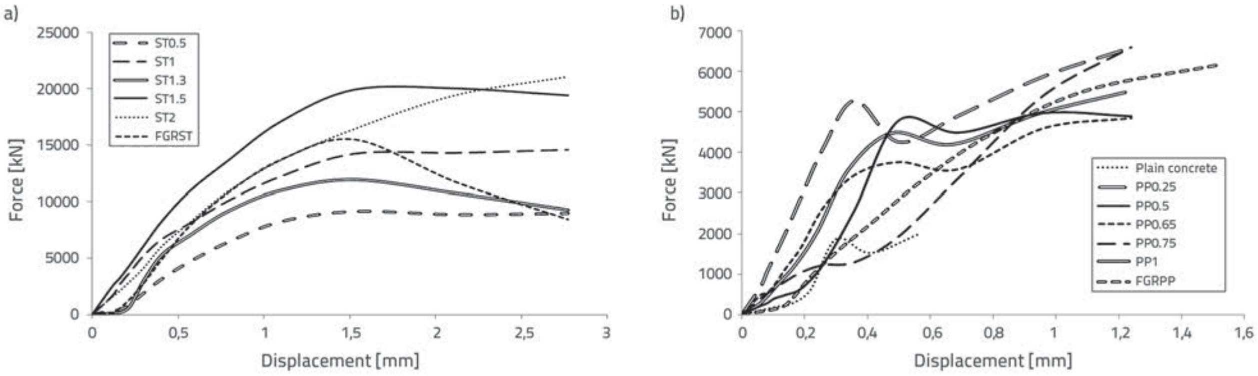

Figure 12. Load-displacement envelope for reinforced concrete beams with: a) steel fibres; b) PP fibres

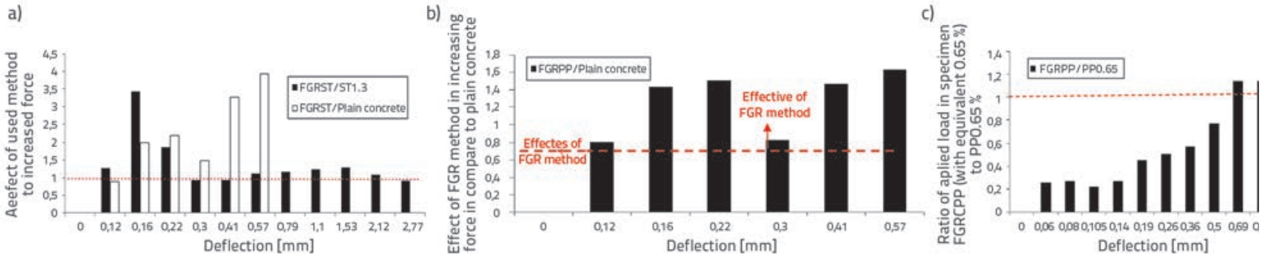

Figure 13. Effects of using functionally graded reinforced concrete beams (FGR) with steel and PP fibres on the load carrying capacity compared to: a) plain concrete and entirely reinforced cross-section with steel fibres; b) plain concrete; c) entirely reinforced cross-section with PP fibres

obtained at the 2 % (158 kg/m^3) steel fibre volume fraction, while the best reverse cyclic performance was observed in the entirely reinforced cross-section with the 1.5 % (118.5 kg/m^3) steel fibre volume fraction. This fact was also validated for the entirely reinforced concrete beams with PP fibres in which an increase in PP fibres not only led to improvement in the cyclic performance of beams, but also sometimes debilitated the beam performance.

According to the achieved results, the cyclic performance of functionally graded beam with the equivalent 1.3 % (102.7 kg/m^3) steel fibre is better than that of the entirely reinforced cross-section with the 1.3 % (102.7 kg/m^3) steel fibre volume fraction. On the other hand, the use of reinforcement as the functionally graded method increased the load carrying capacity of the beam reinforced with the same equivalent steel fibre in the reinforced beam with the entirely reinforced cross-section.

The use of the functionally graded method for reinforcement of plain concrete with PP fibres would be more efficient for increasing the load carrying capacity of beams under reverse cyclic loading, compared to the entirely reinforced cross-section, for displacement values higher than 0.69 mm. Therefore, for displacement values lower than 0.69 mm, the entirely reinforced cross-section becomes more efficient with regard to the load carrying capacity.

The maximum and minimum forces needed to form the first crack in the reinforced concrete beams with steel fibres amount to approximately 17.1 kN and 5.3 kN in specimens ST1.5 and ST1.3, respectively. It is interesting to note that the 0.2 % variation in the steel fibre volume fraction is sufficient for achieving the minimum force to form the first crack, and the maximum force to form the first crack. This is due to the fact that the maximum and minimum forces to form the first crack in the reinforced concrete beams with PP fibres amount to approximately 5.28 kN and 1.22 kN in specimens PP0.25 and PP0.75, respectively.

The use of the functionally graded reinforced concrete beams with steel fibres led to the 47.7 % increment as compared to the beams with the entirely reinforced cross-section. The use of the functionally graded method for the reinforcement of concrete beams with PP fibres not only did not increase the force needed to form the first crack in comparison with the entirely reinforced cross-section, but rather it decreased it by 4.7 %.

In order to gain a better insight into the effects of reinforcement as functionally graded method on increasing load carrying capacity under the reverse cyclic load, the load applied on FGRC specimens to plain concrete and entirely reinforced cross-section (ST1.3 and PP0.65) ratios are shown in Figure 13 and then evaluated.

According to the results shown in Figure 13.a, the use of the functionally graded method for steel fibre reinforcement increases the load carrying capacity significantly, as compared to the entirely reinforced cross-section up to 0.22 mm. Nevertheless, this increment is slightly smaller for further displacement. In addition, the use of the functionally graded reinforced concrete leads to a significant increment in the load carrying capacity as compared to plain concrete at the displacement between 0.16 mm and 0.57 mm. However, the plain concrete beam collapses at further displacement. In Figure 13.b, the fluctuating behaviour can be observed in the applied load measured in the functionally graded reinforced concrete beams with PP fibres and plain concrete due to various displacements and, consequently, no clear result can be extracted. In Figure 13.c, by increasing displacement, the effect of

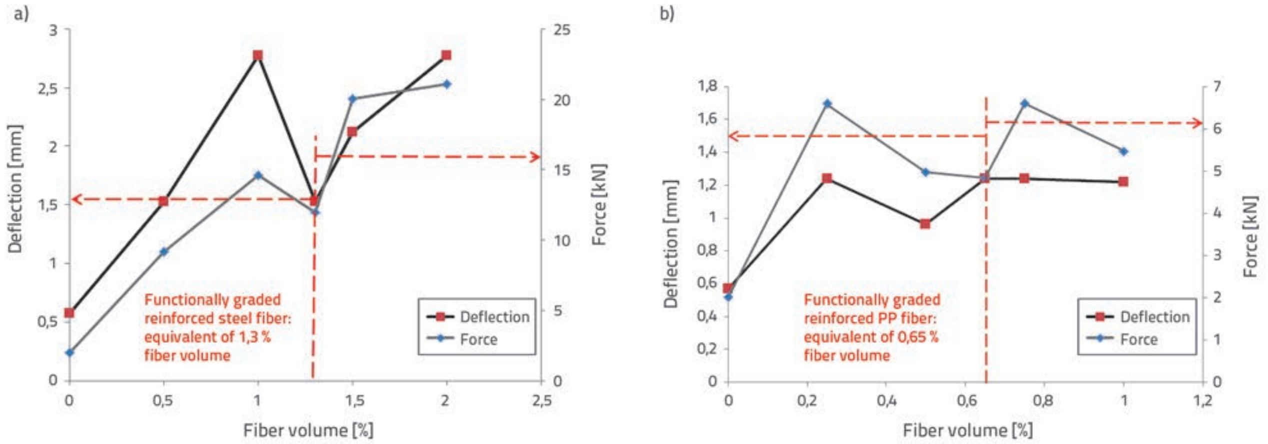

Figure 14. Maximum measured load and displacement for reinforced concrete beams with: a) steel fibres; b) PP fibres

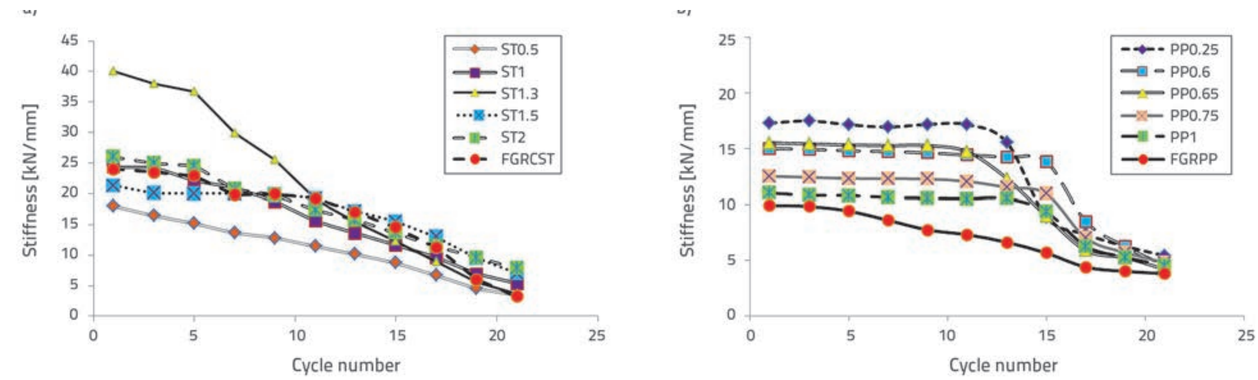

Figure 15. Stiffness variations for beams reinforced with: a) steel fibres; b) PP fibres

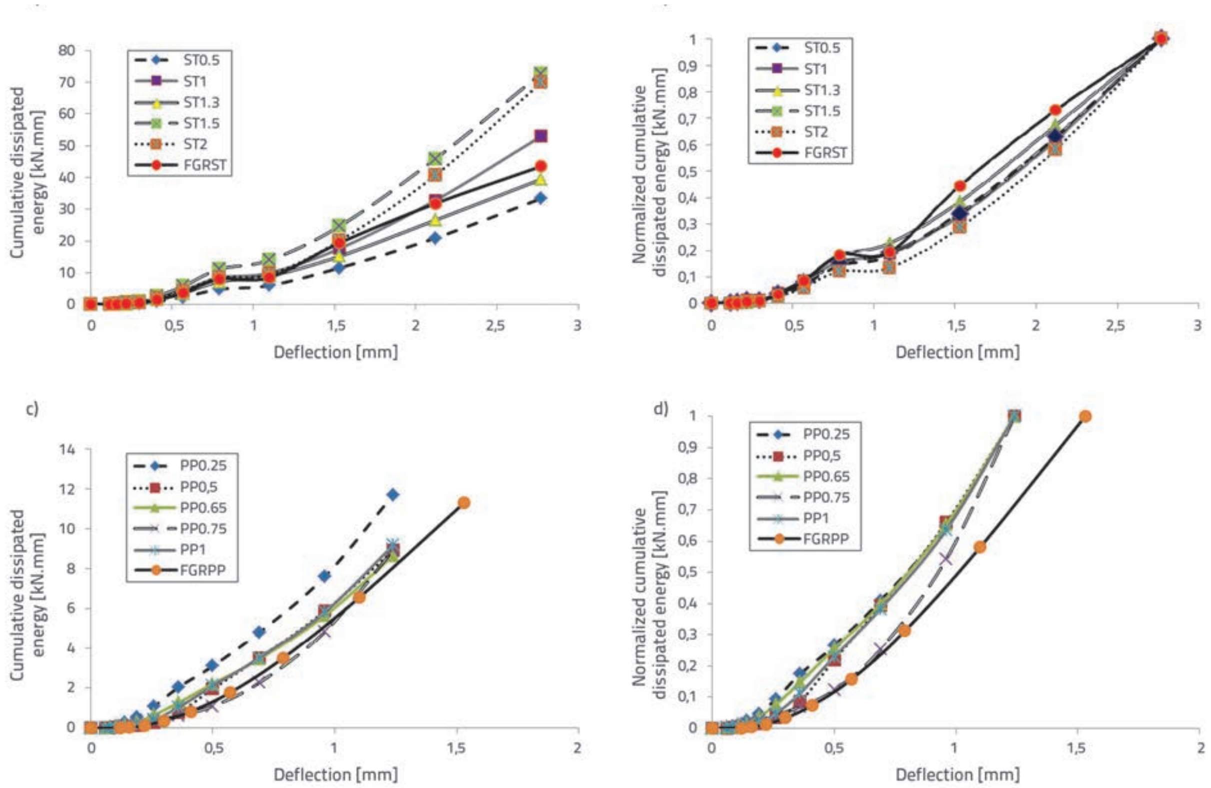

Figure 16. a) Energy-dissipation capacity for reinforced concrete beams with steel fibres; b) Normalized energy-dissipation capacity for reinforced concrete beams with steel fibres; c) Energy-dissipation capacity for reinforced concrete beams with PP fibres; d) Normalized energy-dissipation capacity for reinforced concrete beams with steel fibres.

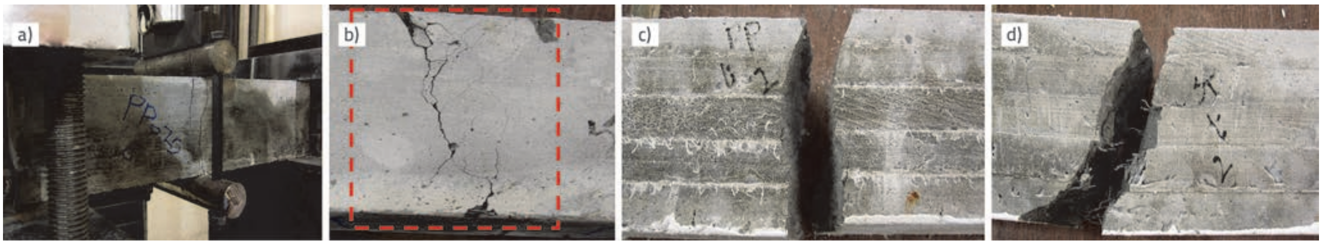

Figure 17. a) Damaged specimen PP0.25 under cyclic loading; b) Multiple cracks formed in reinforced concrete with steel fibres; c) Specimen FGRPP after failure; d) Specimen FGRST after failure

the functionally graded reinforced concrete beams is increased as compared to the entirely reinforced cross-section, and the highest effect was observed at the displacement of 1.24 mm.

The maximum measured load and displacement of beams under the reverse cyclic load is shown in Figure 14. With respect to Figure 14.a, the use of the functionally graded method for the concrete beam reinforcement with the equivalent 1.3 % (102.7 kg/m^3) steel fibre volume fraction increases the maximum load by 29.77 % as compared to the entirely reinforced cross-section. The use of the PP fibres in the reinforcement of plain concrete as the functionally graded method increased both the maximum load and displacement as compared to the entirely reinforced cross-section utilization with the 0.65 % (5.98 kg/m^3) PP fibre volume fraction. These increments for both the maximum load and displacement amounted to 27.49 % and 23.38 %.

The stiffness degradation shown in Figure 15 was assessed by computing the secant stiffness which provides a measure of stiffness degradation in specimens. Figure 15 shows the stiffness degradation trends for reinforced beams. It may be noted that the ST1.5 specimen has the lowest initial stiffness for the reinforced concrete beams with steel fibres. Also, it shows a quick reduction in secant stiffness values. The stiffness degradation trends of other specimens are quite similar. Steel fibres contributed significantly to the initial secant stiffness values of reinforced specimens, and provided a stable reduction in stiffness up to the failure point. This contribution may be related to the bond behaviour between the steel fibres and the surrounding matrix. Moreover, this contribution can control cracks at both micro and macro levels. The use of PP fibres in the matrix reinforcement leads to a sudden drop in stiffness value. This comes from the hard bond between PP fibres and the surrounding matrix in which PP fibres rupture, and the stiffness of reinforced beams suddenly drops.

The use of the functionally graded method for steel fibre reinforcement decreased the stiffness value as compared to the entirely reinforced cross-section, but the stiffness degradation slightly decreased under reverse cyclic loads in the specimen FGRCST as compared to ST1.3. Furthermore, the use of the functionally graded method in the PP fibre reinforcement led to the lowest stiffness value, but the stiffness value slightly decreased with a low gradient. The cumulative energy dissipation of specimens during each cycle is shown in Figure 16. The energy-dissipation capacity can be used as an important indicator for defining seismic properties of a structure. Structures can withstand strong ground earthquake motions provided that their components possess sufficient ability to dissipate the seismic energy. Most of this energy dissipation is provided by inelastic deformations in critical regions of the structural system, which requires adequate ductility from the elements and their connections [18]. The energy-dissipation capacity can be estimated from the area within the load–displacement hysteretic loop for each load cycle. The cumulative energy dissipated in the specimens was calculated by summing up the energy dissipated in consecutive load displacement loops throughout the test. According to Figure 16, the highest capacity for absorbing energy in the reinforced concrete beams with steel fibres can be seen in specimen ST1.5. However, the specimen ST1 with the 1 % (79 kg/m^3) steel fibre volume fraction can achieve a higher load carrying capacity compared to FGRST and ST1.3 with a higher volume fraction. To achieve a better interpretation of the energy absorbed in each cycle, the normalized dissipated energy is also shown for each cycle in Figure 16. According to the results obtained for each cycle, the use of the functionally graded reinforced method with steel fibres enabled achievement of the highest normalized absorbed energy for more than 1.1 mm deflection. Regarding this finding, it was discovered that the functionally graded reinforced concrete beams have a high potential for use instead of the entirely reinforced cross-section beams with steel fibres as a structural element for seismic applications.

The cumulative energy dissipation of reinforced concrete beams with PP fibres as the functionally graded method decreased in comparison with the entirely reinforced cross-section beams. Furthermore, the normalized dissipated energy for each cycle confirmed that the use of the functionally graded reinforced method with PP fibres did not result in better performance of beams subjected to the reverse cyclic loading.

3.4. Failure modes

Differences in fibre content, fibre type, and reinforced concrete layers, can form various failure modes. Subsequently, different failure modes were observed for specimens. Some of the specimens that failed due to the reverse cyclic loading are shown in Figure 17. It is worth mentioning that the layers in the functionally graded reinforced concrete beams exhibited a uniform action, and that no sliding was observed during the test. Uniform behaviour of all layers up to the Ultimate Limit State (ULS) demonstrates that a good bond was formed between composite layers in all specimens. In fact, flexural cracks propagated in the slabs without any change in their angle at the intermediate layer [11, 13]. Note that the observation was conducted by visual monitoring.

4. Conclusion

Previous studies pointed to a high potential of the functionally graded reinforced concretes. These findings were validated for behaviour of the functionally graded reinforced concretes under the monotonic shear loading. Regarding this point, our study was conducted to investigate efficiency of the functionally graded reinforced concrete beams under reverse cyclic loads. In this respect, the following results were obtained:

1. The best performance of reinforced concrete beams with steel and PP fibres was achieved by the 1.5 % (118.5 kg/m^3) and the 0.25 % (2.3 kg/m^3) fibre volume fraction and the entirely reinforced cross-section beams, respectively.
2. The use of the functionally graded reinforced concrete with the equivalent 1.3 % (102.7 kg/m^3) steel fibre volume fraction improved behaviour of reinforced concrete beams under cyclic loading, as compared to the entirely reinforced concrete beam with 1.3 % (102.7 kg/m^3). The use of the functionally graded reinforced concrete with the equivalent 0.65 % (5.98 kg/m^3) PP fibre volume fraction not only did not improve the behaviour of reinforced beams under cyclic loading, but it also undermined behaviour of reinforced beams under cyclic loading.
3. This study confirmed previous findings related to the effects of fibre content, fibre type, and reinforced concrete layer positions, on the responses obtained from the functionally graded reinforced concrete [9-13].
4. Steel fibres significantly contributed to the initial secant stiffness values of the reinforced specimens, and provided a stable reduction in stiffness up to the failure point. The use of PP fibres in matrix reinforcement led to a sudden drop in stiffness value. The reason for this phenomenon lies in the hard bond between PP fibres and the surrounding matrix, in which PP fibres rupture and cause the explained drop.
5. According to the obtained results, the use of the functionally graded method to reinforce concrete increases the dissipated energy due to the applied cyclic loading as compared to the entirely reinforced cross-section. So, the use of this method for reinforcement of concrete elements with steel fibres can increase the capacity of structural elements in seismic applications.

REFERENCES

[1] Pye, A.M.: A Review of asbestos substitute materials industrial applications, Journal of Hazard Material, Vol. 3, pp. 125-147, 1979., http://dx.doi.org/10.1016/0304-3894(79)80001-1

[2] Bentur, A., Mindess, S.: Fibre reinforced cementitious composites, 2nd edn. UK: Taylor and Francis, 2006.

[3] Coutts, R.S.P.: A review of Australian research into natural fibre cement composites, Journal of Cement and Concrete Composites, Vol. 27, pp. 518-526, 2005., http://dx.doi.org/10.1016/j.cemconcomp.2004.09.003

[4] Bezerra, E.M., Joaquim. A.P., Savastano, Jr H.: Some properties of fibre cement composites with selected fibres, Habitacoes Infra-Estrutura de Interesse Social, Brazil, October 29 to November 3, 2004.

[5] Brandt, A.M.: Fiber reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering, Journal of Composite Structures, Vol. 86, pp. 3-9, 2012., http://dx.doi.org/10.1016/j.compstruct.2008.03.006

[6] Zollo, R.F.: Fibre-reinforced concrete: An overview after 30 years of development. Journal of Cement and Concrete Composites, Vol. 19, pp. 107-122, 1997., http://dx.doi.org/10.1016/S0958-9465(96)00046-7

[7] Reinhardt, H.W., Naaman, A.E.: High performance fibre reinforced cement composites, France: RILEM Publications, 1999.

[8] Shen, B., Hubler, M., Paulino, H.G., Struble, J.L.: Functionally-graded fiber-reinforced cement composite: Processing, microstructure, and properties, Journal of Cement and Concrete Composites, Vol. 30, pp. 663-673, 2008., http://dx.doi.org/10.1016/j.cemconcomp.2008.02.002

[9] Ishkahov, I., Ribakov, Y., Holschemacher, K., Mueller, T.: High performance repairing of reinforced concrete structures, Journal of Materials and Design, Vol. 44, pp. 216-222, 2013., http://dx.doi.org/10.1016/j.matdes.2012.07.041

[10] Holschemacher, K., Mueller, T., Ribakov, Y.: Effects of steel fibers on mechanical properties of high-strength concrete, Journal of Materials and Design, Vol. 31, pp. 2604-2615, 2010., http://dx.doi.org/10.1016/j.matdes.2009.11.025

[11] Iskhakov, I., Ribakov, Y.: A design method for two-layer beams consisting of normal fibered high strength concrete, Journal of Materials and Design, Vol. 28, pp. 1672-1677, 2007., http://dx.doi.org/10.1016/j.matdes.2006.03.017

[12] Ghasemi, N.M., Sharbatdar, M.K., Mastali, M.: Repairing reinforced concrete slabs using composite layers, Journal of Materials and Design, Vol. 58, pp. 136-144, 2014., http://dx.doi.org/10.1016/j.matdes.2014.02.015

[13] Ghasemi, N.M., Mastali, M., Sharbatdar, M.K., Ghasemi, N.M.: Flexural performance of functionally graded RC cross section with steel and PP fibers, Magazine of Concrete Research, Vol. 66, pp. 219-233, 2014., http://dx.doi.org/10.1680/macr.13.00248

[14] Holschemacher, K., Iskhakov, I., Ribakov, Y., Mueller, T.: Laboratory Tests of Two-Layer Beams Consisting of Normal and Fibered High Strength Concrete: Ductility and Technological Aspects, Mechanics of Advanced Materials and Structures, Vol. 19, pp. 513-522, 2014., http://dx.doi.org/10.1080/15376494.2011.556840

[15] ASTM C496 / C496M, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

[16] FEMA 461, Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components, Quasi-Static Cyclic Testing, 2007

[17] ASTM C1018: Standard test method for flexural toughness and first-crack strength of fiber-reinforced concrete. ASTM International, West Conshohocken, PA, USA. 1998

[18] Ganesan, N., Indira, P.V., Sabeena, M.V.: Behavior of hybrid fiber reinforced concrete beam-column joints under reverse cyclic loads, Journal of Materials and Design, Vol. 54, pp. 686-693, 2014., http://dx.doi.org/10.1016/j.matdes.2013.08.076