Flexural Behavior of Polypropylene Fiber Reinforced Concrete Beams with Super elastic Wire Under Repeated Loading

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Abstract. This paper investigates the effect of polypropylene fiber (PPM-12) and nitinol (NiTi) superelastic Shape Memory Alloy (SMA) wires in concrete beams under flexural repeated loading. For this purpose, nine of simply supported beams with dimensions of (1000 mm length, 80 mm width and 125 mm depth) were considered. Test specimens were divided into three groups (G1, G2 and G3). Specimens in group G2 and G3 were reinforced with different ratios of PPM-12 fiber (0.5% and 0.75%) by volume of concrete and threaded (NiTi) superelastic SMA wires. Group G1 was reinforced with traditional steel rebar and SMA wires without PPM-12 fiber. The results revealed that the addition of PPM-12 fiber to concrete have a negative effect on the mechanical properties of concrete with respect to load carrying capacity in the other side the addition of fiber led to a controlled crack propagation in concrete and increased the fatigue life of concrete. The (NiTi) superelastic threaded wires were active in some specimens in which some displacement recovery was noticed. The importance of study is how to enhance concrete life and reducing crack propagation in concrete by using polypropylene fiber and NiTi wire as reinforcement in concrete.

Keywords: flexural repeated loading, fatigue, NiTi superelastic wire, polypropylene fiber, Shape Memory Alloy (SMA).

1. Introduction

Structures such as airport runways, bridges, railway tracks are often subjected to repeated loads which cause a steady decrease in stiffness then the damage happened at a micro-mechanical level. This process may eventually lead to a fatigue failure. Conventional concrete has brittle behavior and weak resistance to abrasion, cracking, impact, fatigue and other degradation; therefore, this behavior remains a real handicap for structures subjected to repeated loads. Polypropylene fibers are one of the cheapest types and can be utilized to enhance concrete tensile strength in a cost-effective way [1-3]. The addition of polypropylene fibers to concrete enhance ductility and improve the fatigue life [4]. Repairing damaged of RC structures might not be feasible and they may need to be demolished and replaced [5]. So, the trend of designing structures with minimal maintenance cost during its life is increasing. To achieve structures with minimal maintenance cost, smart materials can be implemented. Superelastic Shape Memory Alloy (SMA) wires are a good example of smart materials which can be used in RC structures as an alternative to the conventional reinforcement in critical regions. Post-
yielding behavior under severe earthquakes causes high residual deformations and these deformations can significantly be reduced by using (SMA) due to its self-centering behavior [6]. SMA have been used in various fields since 1932, such as mechanical and electrical engineering, medical and other fields. In the last two decades, SMA materials are used in structural applications due to their unique behavior [7]. The usage of hybrid reinforcement, nitinol (NiTi) wires and steel rebar can substantially mitigate earthquake consequences [8]. The effect of polypropylene fibers and (SMA) wires on concrete has been investigated by numerous research works.

Rifat Sezer et al. (2016) investigated the performance of concrete beams reinforced with polypropylene fibers. Test specimens consisted of five reinforced concrete beams (two of them were without fibers as a reference and the others were strengthened with 0.60 kg/m3). Mono filaments polypropylene fibers with a length of (12 mm) were used. The results revealed that the energy absorption capacity of reference beams is higher than that of polypropylene fibers reinforced beams and the ductility of reference beams is lower than the ductility of beams reinforced with polypropylene fiber [9]. Ashish Kumar Yadav et al. (2017) studied the structural behavior of fiber reinforced concrete beams. Beams with dimensions (1500 mm length x 150 mm width x 200 mm depth) with different proportion of polypropylene fiber (0, 0.12, 0.16 and 0.2) % were experimentally investigated. Mono filaments polypropylene fibers with length 36 mm were used. The experimental results showed that the addition of polypropylene fiber to reinforced concrete lead to satisfactory increased in the ultimate load carrying capacity where the load increased up to 12 % with the addition of 5 kg/m3 of polypropylene fiber [1].

N. Vimal et al. (2018) investigated the flexural behavior of polypropylene fiber reinforced concrete beam by using fiber length of 12 mm. The experimental program included tests on beams with size of (1200 mm length x 120 mm width x 150 mm depth) containing polypropylene fiber up to 0.5% by volume of concrete. The results indicated that the addition of polypropylene fibers increases the flexural strength of concrete, controlled the cracks and increased the beam resistance [10].

E. Khakimova et al. (2015) studied the shape memory alloy (SMA) as randomly distributed fibers in concrete. Five reinforced concrete beams were considered and prepared for flexural tests. One specimen was a plain concrete beam that served as a reference beam while a second beam was reinforced with steel fiber by 0.6 % by volume of concrete. For other beams, 25 %, 50 % and 100 % of steel fibers were replaced with the NiTi (SMA) fibers respectively. Three-point bending tests were carried out on all beams under cycling load with increments of 0.51 mm for a total of 8 cycles (about 4 mm of total displacement). The experimental test results indicated that (SMA) fibers reduce the development of crack propagation and crack width. However, there was no significant improvement in deformation recovery for beams reinforced with the NiTi (SMA) fibers [11].

Benito Mas et al. (2016) studied the shear resistance of RC beams with Ni-Ti (SMA) continuous rectangular spiral reinforcement. Experiments were carried out on eight reinforced concrete beams. The test variables were: 1) amount of shear reinforcement and type of shear reinforcement, 2) load applied (semi-cyclic and monotonic load). As predicted, the shear ductility of specimens reinforced with NiTi rectangular spiral showed high improvement, with large crack width and deflections at failure. The beams reinforced with NiTi (SMA) rectangular spiral were able to sustain a considerable load after the critical shear crack reached full development. Other resisting mechanism at failure, such as shear transferred by shear reinforcement, dowel effect, and the arch effect were also improved [12].

Nubailah Abd Hamid et al. (2018) investigated the behavior of reinforced concrete beams with superelastic NiTi rebar. The experimental program included tests on small-scale concrete beams, with dimensions of (1000 mm length x 125 mm width x 270 mm depth) reinforced with NiTi rebar of 12.7 mm diameter used as a replacement for steel bars at the critical zone of the beam. Flexural test results indicated that the (SMA) bars contribution along with steel reinforcement improve the flexural behavior in terms of a better crack and deformation recovery [8].
2. Aim of study
The study aim is how to reduce the cracks that occurs in reinforced concrete by using polypropylene fiber and NiTi wire as reinforcement in concrete where these wires return to its normal position after load release thereby working on closing cracks in concrete that lead to enhance concrete life.

3. Experimental work
3.1 Description of tested specimens
The exploratory study conducted on nine different specimens of reinforced concrete to study the effect of test parameters. The specimens were divided into three groups (G1, G2 and G3) as mentioned, each group have three specimens of dimensions (1000) mm length, width of (80) mm and depth of (125) mm. Longitudinal reinforcement consists of (steel rebars of 8 mm diameter and (SMA) superelastic wires). Shear reinforcement used was (Ø4 mm @ 100 mm c/c), the specimens containing a different percentage of polypropylene fiber (0%, 0.5%, and 0.75%) by volume of concrete. Additional test specimens were casted with plain concrete without superelastic wires and polypropylene fiber that serve as reference specimens and to obtained load history. The specimens have been designed to fail in flexural and testing under flexural repeated loading. The geometry of test specimens for all groups are shown in Figure 1, while the reinforcement details of the specimens are shown in Figure 2. The properties of the tested specimens and their details are presented in Table 1.

![Figure 1. Geometry and dimensions of specimens (All dimensions are in mm).](image-url)
Figure 2. Specimen dimensions and reinforcement details (All dimensions are in mm).

Table 1. Properties and reinforcement details of test specimens.

| Specimen designation | Longitudinal Reinforcement                      | PPF% Vf |
|-----------------------|-------------------------------------------------|---------|
| G1B1                  | (Control) 3 steel rebars                        | 0.0%    |
| G1B2                  | 3 strands (5 wires)                             | 0.0%    |
| G1B3                  | 3 strands (7 wires)                             | 0.0%    |
| G2B1                  | 3 steel rebars                                  | 0.50%   |
| G2B2                  | 1 steel rebar + 2 strand (5 wires)              | 0.50%   |
| G2B3                  | 1 steel rebar + 2 strand (7 wires)              | 0.50%   |
| G3B1                  | 3 steel rebars                                  | 0.75%   |
| G3B2                  | 2 steel rebar + 1 strand (5 wires)              | 0.75%   |
| G3B3                  | 2 steel rebar + 1 strand (7 wires)              | 0.75%   |

3.2 Materials

The materials used in this study are illustrated in Table 2. (Sika ViscoCrete-5930) [13] which is a high-performance superplasticizer (SP) was used to achieve good workability and ASTM requirements of C494 / C494M-16 for Type F admixture [14]. One type of sikafiber PPM-12 [15] (monofilament polypropylene fibers of 12 mm length (± 1 mm) and One type of NiTi wire (Nickel titanium), [16] also known as Nitinol, part of shape memory alloy is a metal alloy of nickel and titanium with diameter (0.75) mm was used in this study. NiTi wire and PPM-12 fiber are shown in Figure 3. The physical properties of (SMA) and (PPM-12 fiber) provided by the manufacturer are given in Table 3. While the properties of reinforcing steel bars are given in Table 4.
Table 2. Materials description

| Material          | Description                                    |
|-------------------|------------------------------------------------|
| Cement            | O.P.C (type I)                                 |
| Sand              | river sand passing through 4.75 (mm) sieves    |
| coarse aggregate  | Max. size 12 (mm)                              |
| Water             | Ordinary tap water (mixing and curing)         |

Table 3. Physical properties of shape memory alloy and polypropylene fiber.

| Property of SMA         | Specifications | Property of PPM-12 | Specifications |
|-------------------------|----------------|--------------------|----------------|
| Type                    | Nickel titanium | Class              | I.A.           |
| Elongation              | Min 10%         | Elongation         | 20-25%         |
| Density                 | 6500 kg/m³      | Density            | 910 kg/m³      |
| Ultimate Tensile strength | Min 1100 MPa   | Tensile strength fy | (600-700) MPa |
| Modulus of Elasticity   | (41000-75000) MPa | Modulus of Elasticity | (3 – 3.5) MPa |
| average length (lf)     | Not specified   | average length (lf) | 12 mm          |

Table 4. Tensile properties for steel bars.

| Bar diameter (mm) | Average yield tensile strength (MPa) | ultimate tensile strength (MPa) | modulus of elasticity (MPa) (assumed) | Elongation (%) |
|-------------------|---------------------------------------|----------------------------------|---------------------------------------|----------------|
| 8mm deformed      | 520                                   | 630                              | 200000                                 | 4.00           |
| 4mm deformed      | 580                                   | 822                              | 200000                                 | 4.00           |

3.3 Mixture design and proportions

Concrete mixture used in this study was designed as normal weight according to BS 5328: Part 2: [1997] (British Mix Design Method) [17]. The concrete mixture proportions are illustrated in Table 5. First, and for conventional concrete mixture (reference mixture) the materials (cement, sand, gravel and water with SP) were well mixed for about two minutes to achieve homogenous of the ingredients in the drum. Concrete mixture with PPM-12 fiber was the same to reference mixture but PPM-12 fiber was added gradually to mixture and the total mixing time was increased in the range of 5 to 7 minutes to insure homogeneous distribution in the concrete mixture.

Table 5. Concrete mixture proportions.

| Mixture type        | Quantity of material | S.P % by wt. of cement | W/C |
|---------------------|----------------------|------------------------|-----|
|                     | Cement Kg/m³ | Sand Kg/m³ | Gravel Kg/m³ |                     |
| Reference Mixture   | 400           | 850         | 1010         | 0.35               | 0.43          |
| With 0.5 % PPM-12   | 400           | 850         | 1010         | 0.35               | 0.43          |
| With 0.75 % PPM-12  | 400           | 850         | 1010         | 0.35               | 0.43          |

3.4 Specimens preparation and concrete casting

Nine molds made of strong thin wooden board (plywood) were used for casting concrete specimens. The inside dimensions of each mold were 1000 mm length, 80 mm width and 125 mm depth. The smooth surface of superelastic wire and to achieve bond between concrete and wire, the wire was cut at length (900) mm and every group of wires were fixed at one end and threaded manually together as one wire (like strand). Figure 4 show the process of plexus. Mechanical vibrator using to compact the concrete in the molds. Figure 5 show the plywood molds, specimens’ preparation and test specimens after casting.
Figure 3. (a) NiTi superelastic (SMA) wire, (b) polypropylene fibers

Figure 4. The possessing of plexus.

Figure 5. Test specimens (a). Ready for casting (b). ready for testing.
4. Results and discussion

4.1 Compressive strength

A compression testing machine type (ELE) with 2000 kN capacity was used to test concrete cubes of size (150×150×150) mm with a loading rate equal to 0.3 MPa/sec according to BS 1881: part 116:1989 [18]. Drop in strength was observed from test results by increasing the dosage of PPM-12 fiber where it was noticed that the polypropylene fibers caused decrease in weight of cube lead to decrease in density and compressive strength of cube, in other side the crack propagation was diminished from the face of concrete cube with increase in polypropylene fiber ratio.

4.2 Splitting tensile strength

The same testing machine was used to test cube specimens used to test cylindrical specimens, the dimensions of cylindrical specimens were 150 mm diameter and 300 mm length, the loading rate of the testing machine was set at 0.028 MPa/sec accordance with ASTM C496/C496M-05 [19]. As in compressive strength, the results obtained from the splitting tensile strength was decreased with increase in polypropylene fiber percentage while the crack propagation was diminished and decreased from the concrete cylinder face, the reason behind this related to the crack propagation resisted by PPM-12 fiber.

4.3 Flexural strength

A flexural machine for plain concrete and prism with a capacity of 150 kN type (MATEST) was used to test prisms with dimensions of (100×100×400) mm under two-point load accordance with ASTM C-78, 2002 [20]. The results show that the flexural strength decreases with the addition of PPM-12 fiber ratio. The test results of mechanical properties of concrete with different percentage of polypropylene fibers are presented in Table 6.

| Specimen type     | Compressive strength (N/mm²) | Splitting tensile strength (N/mm²) | Flexural strength (N/mm²) |
|-------------------|------------------------------|-----------------------------------|---------------------------|
| reference         | 42.09                        | 3.00                              | 4.50                      |
| With 0.5% PPM-12  | 40.78                        | 2.15                              | 3.37                      |
| With 0.75% PPM-12 | 37.94                        | 1.79                              | 3.39                      |

4.4 Results of tested beam specimens

Cracking patterns, first crack, mid-span deflection and ultimate flexural load were adopted. Better results obtained from group G3 with respect number of cycles to failure and energy absorption. (NiTi) wire and polypropylene fiber show better effect when it used with steel rebar where the polypropylene fiber enhanced the ductility of concrete and the (NiTi) wire try to closed the cracks by return to original position after load release and not subjected to permanently deformation while steel rebar work as support to them. The cracking pattern at failure for test specimens are shown in Figure 6 while the loading history illustrated in Figure 7, load-deflection behavior for test specimens illustrated in Figure 8, values of load-deflection and energy absorption for specimens of groups G1, G2, and G3 are given in Table 7.
Figure 6. Cracking patterns at failure for test specimens.
Figure 7. Loading History of specimens.
5. Conclusions

Based on the results of the experimental program, the following conclusions can be drawn:

1. The exploratory results illustrated drop in the mechanical properties (compressive strength, splitting tensile strength and flexural strength) with addition of PPM-12 fiber.

2. The ratio of polypropylene fibers (0.5% and 0.75%) by volume of concrete gives better effect when it used in concrete specimens, i.e (combined effect between the steel rebar & PPM-12 fiber), as adopted in specimens G2B1 & G3B1.

3. Specimens (G2B1 and G3B1) with (0.5% and 0.75%) PPM-12 fiber by volume of concrete respectively and without (NiTi) superelastic wire give better behavior with respect to load carrying capacity, that is because of the PPM-12 fiber control and diminished the crack propagation in the specimen and provide strengthen for the small weak regions in three dimensions that’s lead to increase in concrete service life.
4. The energy absorption capacity of specimen (G2B1) reinforced with 0.5% of PPM-12 fiber were higher than the other specimens while other specimens showed slightly decrease in energy absorption capacity compare with reference specimen.

5. Noticed from experimental result there was inverse relationship between PPM-12 fiber and crack propagation, where the increase in PPM-12 fiber ratio lead to decrease in crack propagation that’s obvious in mechanical properties of concrete and concrete specimen under ultimate load.

6. Specimen (G1B3) without PPM-12 fiber show better behavior of NiTi superelastic wire, where it can observe from load-deflection response the wire tries to return to its original position.

7. The behavior of NiTi superelastic wire for remain specimens have no significant effect with respect to the load carrying capacity and energy absorption.

8. Specimens (G1B2 and G1B3) with NiTi superelastic wire failed due to concrete crash and the wire not exposed to permanently deformation inside the specimen, while the other specimens the steel bar exposed to permanently deformation.

9. Crack width of specimens reinforced with NiTi superelastic wire was larger than the crack width of specimens without wires under failure load.

10. Specimens reinforced with steel rebar and NiTi superelastic wire gives improve in load-carrying capacity compare with specimens reinforced with NiTi superelastic wire only. So, the NiTi superelastic threaded wire can be used as supported element besides steel rebars.

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