Lap splices in steel fiber-reinforced reactive powder concrete beams under dynamic loading

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Abstract. Reactive powder concrete is a new cement-based composite with ultra-high strength and performance that has been recently used in many structural elements. This study is focused on studying the effect of lap splices in reinforcing bars on the behavior, strength and deflection of steel fiber-reinforced reactive powder concrete beams under dynamic-harmonic loading. The models were simulated using finite elements approach by ANSYS software with different parameters such as compressive strength of concrete, lap splice length of reinforcing bars, steel fiber percentage and the presence of stirrups in the lap splices zone. Data from experimental test by others were adopted as input data such as loading and mechanical properties of concrete and reinforcements. Total eight beam models were analyzed and two of them were compared with the experimental tests. The analysis results indicate that the criteria based on the ACI code for lap splices is enough in the case of splices in reinforced concrete beam under the effects of harmonic loadings under low and medium frequency ranges, and showed that the increase in lap splice length under the effect of harmonic loading resulted in a decrease in the deflection of beams, especially in case of medium frequency.

1. Introduction
Numerous researches investigated the advantages of using Reactive Powder Concrete (RPC), which is a high-performance concrete as compared to the normal concrete because of attainment of better compressive and tensile strength with lower permeability by removing coarse aggregate so that there is no weakest link in the concrete. Reactive powder concrete is composite materials consisting of cement, fine sand, powder and silica fume with or without steel fiber [1, 2]. The bonding mechanism between the reinforcing bars and surrounding concrete involves shear frictional force due to the slip between the two different materials and bearing force that enhanced the flexural resistance of members. The lap splices in reinforcing bars were discussed in many codes, and all codes recommended providing a minimum lap splice length to produce the design yield strength of the reinforcing bar. Chan and Chu [3] investigated the effects of silica fume on steel fiber bond specifications of RPC and adopted pull-out test including various conditions to evaluate the bond of RPC with different silica fume percentages in the range (0-40%). It was found that the optimal silica fume in range (20-30%) gave high bond. Ogura et al [4] studied analytically the influence of lateral reinforcement, concrete strength and the positioning of the main reinforcing bars on the development of bond splitting failure in reinforced concrete. The results showed, along with radial opening displacement of the concrete due to slippage of the main reinforcing bars, compressive stress is transferred from the steel to the concrete. Kadum [5] analyzed the behavior of steel fiber reinforced concrete beams with lap splices by finite elements method. The studied parameters included steel fiber content and lap splice length. It was observed that increasing of the steel fiber content lead to an
increase in the load capacity and decreasing the stresses generated in the rebars and increasing the length of lapped spliced bar enhanced the strength. Ali and Hussein [6] performed an experimental and numerical investigation on the behavior of reinforced concrete beams with lap splices in tensile reinforcement strengthened by CFRP laminates. They found that the finite elements analysis through ANSYS computer program gave good agreement when compared with the experimental results, which include; ultimate load, cracking load, maximum deflection and mode of failure. And they performed a parametric study included the effect of wrapping shape of CFRP sheet and diameter of reinforcing spliced bar parameters on beams containing tensile reinforcement with lap splices. Jun-Ki Lee [7] investigated the bond behavior and strength of lap splice reinforcing steel bars embedded in high strength concrete beams containing steel fiber. The steel fiber content ranged with (0-2%) and the adopted lap splices was ten bar diameters. It was found that beams with lap-spliced rebar revealed equivalent flexural responses to those specimens without a lap splice. Ali et al [8] performed a nonlinear analysis of spliced continuous reinforced concrete girders strengthened with (CFRP) laminates using ANSYS with a total of five spliced continuous girders and one non-spliced continuous girder. It was found that the predicted results by the numerical model were generally in acceptable degree with the experiment. Al-Hassani et al [9] investigated the effects of lap splice rebars used in high strength concrete under the effects of repeated loading and concluded that the lap splice length of twenty times bar diameter was sufficient for full bond strength. Mabrouk and Mounir [10] studied experimentally and numerically by finite element software-ABAQUS the effect of the diameter of transverse reinforcement on the behavior of simply supported beams using three types of concrete with different tension lap splices shapes. It was found that the adding transverse reinforcement along the splice zone improved the beam behavior by eliminating the formation of cracks in tension splice zone and had an important role in improving beam ductility and mode of failure.

In the present paper, the effects of lap splice reinforcement on the behavior, strength and deflection of steel fiber-reinforced RPC beams under dynamic-harmonic loading are presented and discussed with that under static loading. The finite element analysis was performed considering the main parameters as compressive strength of concrete, lap splice reinforced bars, steel fiber ratio and the presence of stirrups in the lap splice reinforced zone.

2. Mechanical Properties of Materials

The mechanical properties of materials were adopted from previous experimental tests carried out by others, for more detail see ref. [9]. The concrete compressive strength of (129 MPa) with flow (95%) and (2%) of steel fiber volumetric ratio was adopted in the analysis. The weight of water to the weight of binder, which consists of cement and silica fume was equal to (0.16). The compressive strength represented the average of three cylinders of 100 mm in diameter and 200 mm height. Besides, three more cylinders of dimension of (150×300 mm) were cast and tested at age 28 days to obtain the concrete modulus of elasticity. In addition, three prisms of (100x100x400 mm) were cast and tested to obtain the modulus of rupture for concrete. The modulus of elasticity is (43797 MPa) and the modulus of rupture is (22.6 MPa). The reinforced concrete beam specimen was designed based on ACI-318-2014 Code [11] as plastic design to estimate the full capacity of the beam.

2.1. Steel Fiber

The common straight short brass coated gold colored steel fibers with aspect ratio equal to (75) was used. The physical properties are listed in table (1). The steel fibers were well distributed through concrete mix by stirring the total mix many times until all components become as unity.

| Table 1. Physical Properties of Steel fibers. |
|-----------------|---------|---------|---------|
| Ultimate tensile strength (MPa) | Length (mm) | Diameter (mm) | Density (kg/m3) |


Specifications > 2850 15 0.2 7850

2.2. Silica Fume
Grey densities silica fume was used as extremely fine powder, its particles are hundreds of times smaller than cement particles. Test results of silica fume conformed to the chemical ASTM C1240-04 [12].

2.3. Steel Reinforcing Bars
The deformed steel bars of diameter (10 and 12 mm) were used as main reinforcing bars; also, the 10 mm diameter deformed steel bars were used as stirrups. The mechanical properties are listed in table (2), where all of the shown values were the average of three specimens for each bar diameter. The result of testing for these bars matched with ASTM A615-16 [13] requirements.

| Nominal Diameter (mm) | Actual Diameter (mm) | Yield Stress (MPa) | Ultimate Strength (MPa) | Total elongation (%) |
|-----------------------|----------------------|--------------------|------------------------|---------------------|
| 10                    | 10.03                | 769                | 887                    | 10.63               |
| 12                    | 11.98                | 655                | 739                    | 11.0                |

The lap splices reinforcements at the tension and compression zone of the reinforced concrete beams were not designed based on ACI-318-2014 Code [11] under the effects of dynamic loadings. Considering that the induced stresses in dynamic loadings may be reversal in sign so that at such locations needs to provide more reinforcements. The lap splices don’t need to consider a reduction factor due to the strength reduction, which was already existing in the expression of splice lengths. The lap splice length increases as the compressive strength of concrete less than $f_{c}^{0.5}$ so that this value is limited to 8.30 MPa [11]. According to ACI Code, the splice length of reinforced bars in tension is classified as a class A and a class B based on the maximum percent of area that spliced within required length and greater than of $l_d$ and 300 mm or 1.3 $l_d$ and 300 mm for class A and B, respectively. Compression lap splice greater of $(0.13f_y-24) d_b$ and 300 mm, in which $l_d$ is the development length, $d_b$ is the bar diameter.

3. Finite Element Modeling for The Studied Beam
The reinforced concrete beam specimen was designed based on ACI-318-2014 [11] with beam dimensions (180x180x2100 mm) with simple span of (1800 mm) and the beam cover from top and bottom of (30 mm), as shown in figure (1). Three-dimensional linear numerical analysis as finite element models were built using the finite element approach by ANSYS software [14] for beams that were subjected to harmonic loading (load-deflection). The type of element that was selected for concrete to simulate the actual behavior of the concrete was SOLID65 with eight nodes because of this type of element has capability for cracking and crushing. The element is defined by eight nodes having three degrees of freedom at each node. The supports and the plates underneath the applied load were simulated by using SOLID185 element. This element is defined with eight nodes having three degrees of freedom at each node and eight translations in the nodal directions. The main longitudinal and secondary transverse reinforcement as stirrups were simulated by LINK180 because this type of element is used in three dimensional analyses and has three degree of freedom in each node. The interface between concrete and steel plates such as plate under applied loading and supports has merged; also the concrete nodes at the locations of steel reinforcements were the same only at the spliced zone. COMBIN7 is a 3-Dimension pinned joint, which is used to connect the nodes between concrete beam and steel reinforcements at the interface (common point). Properties of this element are
stiffness, friction, and damping. An important feature of this element is a large deflection capability in which a local coordinate system is fixed to and moves with the joint. Figure (2) shows the three-dimensional reinforced concrete beam model.

The harmonic loading was applied as load-deflection at the point's location shown in figure (1). The full structural analysis was performed to predict the load-deflection of beams modeling under the effects of harmonic loading. The criteria for convergence was based on the displacement control tolerance of (5%), so that the loads were applied incrementally up to convergence in small steps. Concentrated loads were applied at distance (550 mm) from left and right supports so that the loading is four points loads. The load step increments with total sub-steps were (300). The rotational degrees of freedom were released to allow a rotation at each support where one was pin and the other was roller to satisfy the simply supported boundary conditions at each end. The cases adopted here are classified as low and medium level of frequency with the range of (0-40) and (40-400), respectively in addition to static loading. All harmonic loading was applied at each (4 Hz) as sub steps and the type of applied loading was stepped not ramped to ensure that the same amplitude of loading for each of the frequencies was developed. The applied static loading was adopted from the ultimate value that was developed through the experimental test.

Figure 1. Reinforced concrete beam layout with and without lap splices of rebars at bottom face.

Figure 2. Three-dimensional reinforced concrete beam model

3.1. Reinforced Concrete Simulation
Compressive strength and modulus of elasticity for the first type of analysis was (129 MPa) and (43800 MPa) and for the second type was (118.4 MPa) and (38200 MPa) for (2%) and (1.5%) of steel fiber, respectively. Poission’s ratio for concrete and steel were (0.15) and (0.30), respectively. The (two) main reinforcement bar diameter was (12 mm) and for the (two) top reinforcement bar diameter was (10 mm). Mass of concrete and reinforcement was needed in the dynamic analysis that is based on geometry dimensions of the concrete beam and diameter of reinforcement with a density of (25 kN/m³) and (78.5 kN/m³), respectively. In ANSYS, solid65 element, which represents the concrete has real constant that contains the steel distributions in three dimensions as x, y and z; a matter that coincides the reactive powder concrete with well distributed steel fibers in all directions as uniform percentages. In case of normal concrete, the percentages become zero. Table (3) lists the studied parameters and the mechanical properties for all simulated model cases.

Table 3. Load cases for all simulated models.

| Cases | Loading  | Steel fiber % | Overlap splice (mm) | Stirrups                      | Compressive Strength (MPa) | Modulus of elasticity (MPa) |
|-------|----------|---------------|---------------------|-------------------------------|---------------------------|----------------------------|
| 1     | Static   | 2             | 240                 | No stirrups at the zone of lap splice | 129                       | 43800                      |
| 2     | Harmonic Low | 2       | 240                 | No stirrups at the zone of lap splice | 129                       | 43800                      |
| 3     | Harmonic Medium | 2   | 240                 | No stirrups at the zone of lap splice | 129                       | 43800                      |
| 4     | Harmonic Low | 2       | 240                 | stirrups at the zone of lap splice | 129                       | 43800                      |
| 5     | Harmonic Medium | 2   | 240                 | stirrups at the zone of lap splice | 129                       | 43800                      |
| 6     | Static   | 2             | 240                 | No stirrups at the zone of lap splice | 129                       | 43800                      |
| 7     | Harmonic Low | 1.5  | 180                 | No stirrups at the zone of lap splice | 118.4                     | 38200                      |
| 8     | Harmonic Medium | 1.5 | 180                 | No stirrups at the zone of lap splice | 118.4                     | 38200                      |
| 9     | Harmonic Low | 1.5  | 180                 | stirrups at the zone of lap splice | 118.4                     | 38200                      |
| 10    | Harmonic Medium | 1.5 | 180                 | stirrups at the zone of lap splice | 118.4                     | 38200                      |

4. Analysis Results

The static load analysis results for models as deflection are presented in figures (3) and (4) in which figure (3) depicts the beam deflection performance and figure (4) represents the deflection vector distribution due to applied static loading through the beam at ultimate stage in case of (2%) steel fiber. Figure (5) shows the cracks and crushing propagations at ultimate loading stage. Figure (6) represents the deflection performance due to applied static load at ultimate stage in case of (1.5%) steel fiber. Figures (7) and (8) represent the deflection performance of the beam under static loading in case of (2%) and (1.5%) steel fiber, respectively, while figure (9) depicts a comparison between the two cases. Consequently, the finite elements analysis results gave a reasonable agreement when compared to the available experimental results detailed in ref. [9], where experimentally the maximum deflection value was (23.40 mm) and that obtained numerically by finite elements approach was (19.5 mm).
In case of dynamic – harmonic loading, figures (10) to (21) depict the effects of the studied parameters as steel fiber percentage, lap splices length and the presence of stirrups at the lap splices zone under low and medium loading conditions.

5. Discussions
The load cases for all simulated models were adopted according to the loading type, steel fiber percentage, lap splice and the presence of stirrups in the splice zone, see Table (3).

In general, under static loading, the deflection in case of the presence of (2%) steel fiber was lower than the deflection in case of (1.5%) as (18.058 mm) and (19.085 mm), respectively, because the increase in steel fiber up to specific limit enhanced the tensile strength of concrete, which in turn reduced the cracks and deflection.

Figure (5) shows the cracks propagation and crushing at ultimate stage load. The cracks were developed at tension zone but were limited, and a crushing at compression zone but it was still less than the compressive strength because there was no crushed point's intensity at that zone.

Figures (7) and (8) show the performance of incremental applied loading versus central deflections. The performance up to (22%) from ultimate loading behaved as linear and there is an inflection point. The deflection of (5 mm) in the two cases if compared with the service loading indicated the onset of beam failure. Besides that, figure (9) depicts a comparison between the two cases.

The models also checked for under the effect of dynamic harmonic loading as low and medium frequency levels. Figures (10) and (11) show the performance of the beam under low frequency of harmonic loading and the maximum deflections occur at frequency (4 Hz). The maximum deflections were as (4.89 mm) and (5.83 mm) in case of (2%) and (1.5%) steel fiber, respectively, but they occur at the same frequency and still less than the service deflection static loading. Figures (12) and (13) represent the performance of the beam model under the effect of medium frequency of harmonic loading in case of (2%) steel fiber, where the deflection was (0.445 mm) which occurred at frequency of (168 Hz). But in case of (1.5%) steel fiber, the deflection was (0.299 mm) at (208 Hz) frequency, that means there was an enhancement in the tensile resistance of concrete and the deflection was reduced because the number of cycles per unit time increased to reach this value of deflection. Figures (14) and (15) show the comparison between different percentages of steel fiber content in case of low and medium frequencies.

Figures (16) and (17) represent the deflections due to applied harmonic loading at low and medium frequencies with (1.5%) and (2%) of steel fiber and different lap splice lengths of reinforcing bar. No effects on the beam performance was depicted in this type of loadings for the different lap splices.

Figures (18) to (21) represent the deflections due to applied harmonic loading at low and medium frequencies in the presence of (1.5%) and (2%) steel fiber with the existence of transverse reinforcement (stirrups) in the lap spliced zone. So, in case of low frequency there was a little effect compared to that case of medium frequency. Hence, in case of (1.5%) steel fiber, the central deflection became smaller than that without stirrups in the splice zone. But in case of (2%) steel fiber the deflection increased as the frequency increased, that means the presence of stirrups at the lap splice revealed an effect on the deflection value and the frequency that cause maximum deflection because of the steel fiber made the concrete more ductile and the stirrups offered more confinements to the main reinforcements so that the deflection became less.
**Figure 3.** Deflection due to applied monotonic load at ultimate stage 2% of steel fiber

**Figure 4.** Deflection vector distributions due to applied static load at ultimate stage 2% of steel fiber

**Figure 5.** Cracks distribution due to applied static load at ultimate stage of 2% steel fiber

**Figure 6.** Deflection due to applied monotonic load at ultimate stage 1.5% of steel fiber

**Figure 7.** Deflection due to applied monotonic load at ultimate stage in case of (2%) of steel fiber

**Figure 8.** Deflection due to applied monotonic load at ultimate stage 1.5% of steel fiber
Figure 9. Deflection comparison due to applied load between (1.5%) and (2%) of steel fiber

Figure 10. Deflection due to applied harmonic loading – Low frequency and (2%) of steel fiber

Figure 11. Deflection due to applied harmonic loading–Low frequency and (1.5%) of steel fiber

Figure 12. Deflection due to applied harmonic loading–Medium frequency and (2%) of steel fiber

Figure 13. Deflection due to applied harmonic loading–Medium frequency and (1.5%) of steel fiber

Figure 14. Deflection comparison due to applied harmonic loading – Low frequency
Figure 15. Deflection comparison due to applied harmonic loading – Medium frequency

Figure 16. Deflection due to applied harmonic loading–Low frequency for 2% steel fiber and different splices

Figure 17. Deflection due to applied harmonic loading – Medium frequency and (1.5%) of steel fiber and different lap splice

Figure 18. Deflection due to applied harmonic loading – Low frequency and (1.5%) of steel fiber with and without stirrups at middle

Figure 19. Deflection due to applied harmonic loading – Medium frequency and (1.5%) of steel fiber with and without stirrups at middle

Figure 20. Deflection due to applied harmonic loading – Low frequency and (2%) of steel fiber with and without stirrups at middle
6. Conclusions

Based on the analysis results, the following points are concluded:

- Strength capacity of reinforced concrete beams increases in case of the presence of steel fibers because of the increase in compressive strength that leads to an increase in modulus of elasticity and moment strength capacity.
- Deflection decreases in case of an increase in steel fiber content because of the increase in compressive strength and in modulus of elasticity of concrete.
- The increase in lap splice length of reinforcing bars under the effect of harmonic loading leads to a decrease in deflection. This decrease was noted especially in case of medium frequency as the required time in this case was less.
- The presence of transverse reinforcement (stirrups) in the lap spliced zone offered more confinements to the main reinforcement and reduce the deflection. Also in case of harmonic loading the lap splices in reinforcements reduce the deflection at the same frequency.
- No effects on the beam performance is depicted for different lap splices lengths with the same steel fiber content under the same type of loading.
- The criteria based on the ACI code for lap splices is enough in case of splices in reinforced concrete beam under the effects of harmonic loadings under low and medium frequency ranges.

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