

# USE OF CARBON NANOTUBES IN THE RETROFITTING OF REINFORCED CONCRETE BEAMS WITH AN OPENING AND THE EFFECT OF DIRECT FIRE ON THEIR BEHAVIOUR

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**ABSTRACT:** Carbon nanotubes (CNTs) are used to enhance the performance of nano-composites because of their high strength and remarkable physical properties. An experimental study was designed to investigate the use of CNTs in a ferrocement mix as an advanced technique for externally retrofitting for shear zone opening of reinforced concrete beams. The main parameters in this work are opening size, ferrocement techniques (CNTs and wire mesh), and fire exposure. The ferrocement technique is used to retrofit the reduction of open beams strength, whether exposure to fire occurred or not. The burned beams are loaded at 30 kN at room temperature and then subjected to a direct fire, followed by cooling with water before the load was finally increased to failure. In addition, the strength reduction of the test specimens was increased during firing with an increase in the opening size; strengthening with ferrocement decreased this reduction, deflection, and change in crack pattern shape and improved beam ductility. Carbon nanotubes improve the efficiency of retrofitting by ferrocement compared to the use of steel wire mesh in the ferrocement mix.

*Keywords: Reinforced Concrete beams, Openings Retrofitting, Carbon nanotubes, direct fire*

## 1. INTRODUCTION

Many research studies utilize the expressions of small and large openings without consideration of the definitions or providing a clear-cut limit for the opening size as stated by the span-depth ratio.

Circular and square openings in beams have been defined as small openings when opening size is about less than 40% of the overall beam depth [1]. Circular openings have been defined as large when their diameters exceed 1/4 of the beam depth [2]. The moment of inertia decreased at the opened beams, where cracks will start at an earlier stage of loading. Early initiation of cracks has only a minimal effect on the crack widths and deflection [3]. For a beam containing small openings in the shear zone, the mode of failure remains basically the same as that of a solid beam [4]. If the opening is moved away from the support, then a gradual reduction in beam strength occurs until it reaches a constant value. For a beam with a large opening, the top and bottom chord members of the opening behave as a compression strut and a tension tie, respectively; it is essential that the slenderness effect in the compression strut be taken into account [5].

Ferrocement, which provides a significant enhancement in stiffness, strength, and ductility of beams with large openings, is one suitable material for strengthening and retrofitting open beams in developing countries [6]. Some investigations on the shear strength of ferrocement specimens have been recently reported to predict the shear strength of rectangular specimens reinforced by ferrocement

[7]-[9]. When concrete remains exposed to fire for a long period, losses of its mechanical properties occur [10]. In the case of unprotected concrete, the mechanical properties decrease dramatically when the concrete is exposed to a high temperature [11].

A reduction in the fire resistance rating was observed in the reduced cross-section via the good protection layer during elevated temperature exposure tests [11], [12]. Utilization of carbon nanotubes (CNTs) is highlighted amongst the research areas in the field of nanotechnology. CNTs have been used in many different applications. However, very little attention has been paid to nanotechnology applications in the construction industry [13]. In addition to a number of remarkable mechanical, electrical and thermal properties, carbon nanotubes possess a high modulus of elasticity, tensile strength, and yield strain, all of which make CNTs an attractive reinforcing material for concrete. The unique features offered by CNTs provide an excellent opportunity to develop CNT-reinforced structural concrete [14], [15].

This paper describes an experimental study of the effect of retrofitting using traditional ferrocement combined with wire mesh, the effect of retrofitting using an advanced ferrocement combined with carbon nanotubes on open beams and the effect of direct fire on the retrofit.

## 2. RESEARCH SIGNIFICANCE

The reduction in reinforced concrete beam capacity caused by different opening sizes and shapes is considered one of the major problems in

construction, especially when the beams are exposed to direct fire. The addition of ferrocement is one of the retrofitting methods of reinforced concrete beams with openings to provide enhanced beam capacity and resistance shear. The ferrocement technique by adding carbon nanotubes to the cement mixes instead of wire mesh to provide resistance tensile strength is presented as an advanced ferrocement technique that can be used in different conditions or can be used to improve the ferrocement layer efficiency.

### 3. METHODOLOGY

The methodology adopted in this research is based on an experimental program. The experimental work was designed for the use of traditional ferrocement with wire mesh and advanced ferrocement with CNTs fibres to retrofit the reinforced concrete beams with different opening shapes and sizes. The tested RC beams with different opening shapes and sizes (circular openings with diameters of 75 mm and 150 mm, square opening of 150\*150 mm, and rectangular openings of 150\*300 mm) were exposed to fire for one hour at 500°C under a service load of 30 kN. Next, the fire was stopped, the beams were cooled with a water jet, and then the load was increased up to failure. Twenty-one RC beams were tested experimentally to study the effect of opening shape and size using different retrofitting ferrocement techniques.

### 4. EXPERIMENTAL PROGRAM

#### 4.1 Description of Test Specimens

The tested specimens used were 21 reinforced concrete beams with rectangular cross-sections with a size 150 mm (width) × 300 mm (height) × 1650 mm length. The details of the tested specimens are shown in Fig.1. The beams were cast using the same reinforcement: 3 bars with a diameter of 16 mm underwent bottom reinforcement, and 2 bars with a diameter of 12 mm underwent top reinforcement. The shear reinforcement was 8-mm-diameter bars spaced at 8 cm centre to centre. The shear bars in the opening location were neglected, as shown in Fig.2.

Five groups of tested beams were cast; the group G1 consists of five tested beams: one beam without an opening, two beams with circular openings ( $\phi 75$ ,  $\phi 150$  mm) and two beams with opening sizes equal to 150\*150 mm, 150\*300 mm. The centre of all openings location was 375 mm from the beam edge through beam direction and 300 mm from the support system. All groups have the same opening size and location with retrofitting. For all open beams, the top chord was 75 mm. The second group was retrofitted by a ferrocement layer

containing carbon nanotubes to study its effect on the retrofitting of the tested beams.

In the group G3, the tested RC beams were exposed to fire after being loaded by 30 kN and subjected to 500°C for one hour. Next, the fire was stopped, and then the beams were cooled with a water jet for 15 minutes and subsequently left for an hour after water jet cooling. After fire exposure, the tested beams were loaded up to failure.

The fourth group was retrofitted by a ferrocement layer with carbon nanotubes around the opening and left for 30 days before being loaded to failure.

The fifth group was retrofitted by a ferrocement layer with steel wire mesh around the opening and left for 30 days before being loaded to failure. All details of the tested beams with different parameters are shown in table 1.

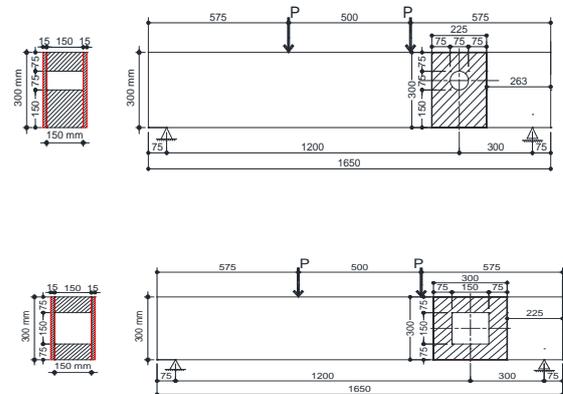


Fig.1. Details of a typical specimen.



Fig.2. Details of the beam reinforcement.

#### 4.2 Material Properties and Mix Preparations

All tested RC beams, have Portland cement equivalent to ASTM Type I, natural aggregates and natural water. Sand, dolomite, and cement were dry mixed. Next, the water was gradually added while mixing to ensure the concrete became homogeneous.

Table 1. Details of the experimental program.

Group	Specimen	Opening size	Retrofitted type (ferrocement)	Fire Temperature (°C)
G1	B1	None	---	None
	B2	Ø 75 mm	---	None
	B3	Ø 150 mm	---	None
	B4	150X150 mm	---	None
	B5	300X150 mm	---	None
	B6	Ø 75 mm	CNTs	None
G2	B7	Ø 150 mm	CNTs	None
	B8	150X150 mm	CNTs	None
	B9	300X150 mm	CNTs	None
G3	B10	Ø 75 mm	---	500
	B11	Ø 150 mm	---	500
	B12	150X150 mm	---	500
	B13	300X150 mm	---	500
G4	B14	Ø 75 mm	CNTs	500
	B15	Ø 150 mm	CNTs	500
	B16	150X150 mm	CNTs	500
	B17	300X150 mm	CNTs	500
G5	B18	Ø 75 mm	wire mesh	500
	B19	Ø 150 mm	wire mesh	500
	B20	150X150 mm	wire mesh	500
	B21	300X150 mm	wire mesh	500

For each mix, three specimens of cubes with dimensions 150\*150\*150 mm and three specimens of cylinders with dimensions of 150\*300 mm were produced. ACI specifications were followed in the casting and curing system. The mix proportions are reported in table 2. The concrete compressive strength was equal to 30 MPa. Mixing was performed using a concrete rotating drum mixer with 0.125 m<sup>3</sup> full capacity. The opening was introduced during casting using wood forms (cylinder, cubes, or cuboids) placed during casting and then removed before testing.

### 4.3 Retrofitting Surface Preparation

During the casting of the tested beams to be retrofitted by ferrocement, the contact area of ferrocement is roughened to improve the bonding between the original concrete layer and the ferrocement layer, as shown in Fig.3. The ferrocement layer thickness was equal to 15 mm. The ferrocement mix consists of cement and sand at a cement-to-sand ratio of 2:3 and a water-cement ratio of 43%. Mixing proceeds until a mortar of uniform colour and consistency is obtained.

Table 2. Concrete mix proportions per m<sup>3</sup>

COMPONENT	Concrete Mix (kg)
Cement	300
Sand	800
Dolomite	1200
Water	150

Fig.4 shows the mortar after being placed through hand plastering, whereby the mortar is forced through the mesh. Each retrofitted beam is left to dry for 30 days before it undergoes testing. Square wire meshes with openings of 14 mm were attached next to the opening with a width of 75 mm. Five shear connectors on each side were used to secure the wire mesh from peeling off during retrofitting process.

CNT fibres were added with water during preparation ferrocement mix at 0.06% of cement weight. Carbon nanotubes are hollow tubular channels; with diameters ranging 4 to 100 nm. The CNT fibres length is not restricted and can reach micrometre or even millimetre sizes. The Young's modulus of CNT fibres varies between 1000 to 5000 GPa, and the density is approximately 2000 kg/m<sup>3</sup>. CNTs exhibit a high aspect ratio (length-to-diameter ratio) ranging from 30 to more than several thousands of fibres. The sizes and shapes of the carbon nanotubes to be used were determined from the representative transmission electron microscope micrograph shown in Fig.5. The XRD of the CNTs used is also shown in Fig.6.



Fig.3. Surface preparation of retrofitted beams.



Fig.4. Ferrocement Layer.

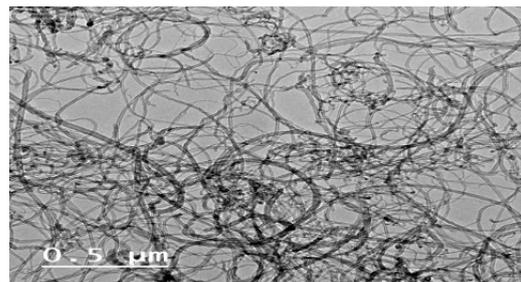


Fig.5. Transmission Electron Microscope Micrograph

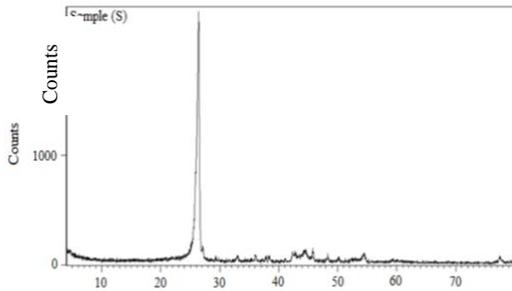


Fig.6. XRD Position [2Theta] (copper (CU))

#### 4.4 Experimental Setup and Testing

A special 3D steel frame set-up for testing the beams was constructed (Mataria Faculty of Engineering, Helwan University). The set-up consisted of I-beams resting on four steel columns to support the beams during firing and loading. The distance between supports for the tested beams is 1.5 m. Loading was undertaken using an additional I-beam acting as a lever. One end of the beam was attached to the strong floor, and the other end of the lever beam was provided with a hanger for supporting weights, as shown in Fig.7. The reaction of lever beam was applied in the centre of the tested beam. A load cell with 0.1 kN accuracy was placed between the lever beam and the tested beam to verify the applied load. Loading was initially performed until the reaction load to the tested beam reached 30 kN. The load remained constant during the measurements and observations.

This system avoided the use of hydraulic jacks during the fire. In the case of fire, the vertical displacement of the tested beams was recorded using a linear variable differential transformer at the middle of the beam, whereas dial gauges were used to measure the vertical displacement at the same location in the case of no fire. Two steel strain gauges were used, one for the main steel bar at mid-span and the other at first stirrups located adjacent to the opening of the tested specimens as shown in Fig.7.

#### 5. TEST RESULTS AND DISCUSSION

The experimental results revealed the following behaviour for tested RC beam retrofitted with ferrocement by carbon nanotubes or wire mesh at room temperature and exposed to 500°C for one hour. The considered elements of the behaviour are cracking patterns, modes of failure, load deflection curves, strain in the stirrups and strain in the main steel.

##### 5.1. Effect of the Retrofitting Technique on the Crack Patterns and the Modes of Failure

The crack pattern and mode of failure of the control solid tested RC beam (B1) were bending

cracks and shear, respectively, which appeared during loading. The first crack of the control beam appeared as a bending crack at 103.8 kN. As the load increased, the bending crack extended vertically in the flexural region, and then the first diagonal shear cracks appeared at 122 kN. The shear cracks extended to the beam edge by angles of approximately 45°, and as the load increased, a progression of flexural cracks appeared in the shear region. These cracks rotated to form flexural-shear cracks between supporting and the loading points. Additional shear cracks appeared during the subsequent loading stages to 277.5 kN failure load, as shown in Fig.8.



Fig.7. Experimental Setup and measuring devices

For the tested RC beams with openings of circular (75mm, and 150 mm diameter) the first crack appeared at 52.50 kN, 50.10 kN. And for tested RC beams with square (150mm\*150 mm), and rectangular (150mm\*300 mm), the first cracking load were equal to 26.30 kN, and 24.80 kN. the beam type failure and frame type failure appeared for circular, and square and rectangular opening respectively, at the bottom in the form of a diagonal crack, as shown in Fig.8,9,10 and 11. Next, a series of shear cracks appeared with increasing loading at the top and bottom of the opening. Flexural cracks appeared in the flexural region, starting at 110 kN as vertical cracks and then stopped at 140 kN with a rotation angle of less than 45° for B2. For B3, B4 and B5, no flexural cracks were observed because of the reduction in shear stiffness in the case of a large opening.

Retrofitting tested beams by CNT ferrocement layer with different openings (B6, B7, B8, and B9) resulted in a significant improvement for the first crack load to 107%, 40%, 53%, and 38% respectively. In addition, a slight change in the crack width in the retrofitted beams decreased the number of cracks compared with the control open beams, and no crushing failure appeared in the retrofitting layer. Major effect more than 30% was observed in the first crack after exposure to direct fire for the open beams, whereas the failure mode

was observed early at 0.73, 0.81, 0.7 and 0.89 of the failure load of the open tested beam without fire exposure.

Ferrocement with wire mesh and CNT improved the failure load to 11.5% and 35%, respectively, for the beam with a 75-mm opening and to 14.5% and 26%, respectively, for the beam with a 150-mm opening after exposure to direct fire. Ferrocement with wire mesh and carbon nanotube improved the maximum load of the tested RC beam with a square opening (150\*150 mm) to 22.5% and 32%, respectively, whereas the beam with a rectangular opening (150\* 300 mm) did not improve more than 6% in failure load.

The ferrocement with wire mesh was stable and fixed in the beam better than ferrocement with CNT at failure because of the method of fixed wire (riveted steel was used). After exposure to fire, the specimens retrofit using CNT ferrocement were found to have enhanced overall behaviour compared to the specimens retrofit using ferrocement with wire mesh.

### 5.2. Effect of Opening Size on the load deflection curve

In general, the load deflection curves show that the energy absorption decreased because of the introduced opening and with an increase in its dimensions.

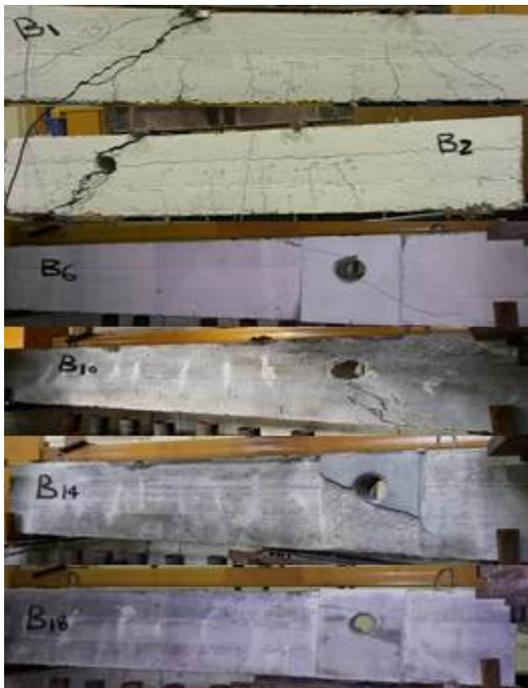


Fig.8. The crack patterns for 75 mm opening.



Fig.9. The crack patterns for 150 mm opening.



Fig.10. The crack patterns for 150 mm square opening.

The change in slope for all tested beams at the linear stage is very small relative to that of the other stages from the start of loading until the cracking stage. An abrupt change in the deflection value is observed at the point of cracking load. The post cracking stage begins earlier with increasing opening size.



Fig.11. The crack patterns for 150\*300 mm opening.

The maximum load decreased to 65%, 32%, 27% and 21% of the control beam failure load for openings of 75 mm in diameter, 150 mm in diameter, 150\*150 mm, and 300\*150 mm, respectively, as reported in Fig.12. Increasing the opening sizes has a dramatic effect on the load capacity of the tested beams because of the reduced beam stiffness (which does not comply with the code limitation) in the shear region caused by the large openings

The deflection at ultimate load reduced to 94%, 57%, 57% and 36% for beams with openings of 75, 150, 150\*150, and 300\*150 mm, respectively, when the opening location was in the critical shear zone. The deflection reduction was first observed with a high reduction in the energy absorption area for a large 150-mm-diameter opening. The 150\*300 mm opening reduces the beam ultimate ductility to 60%, as shown in Fig.13.

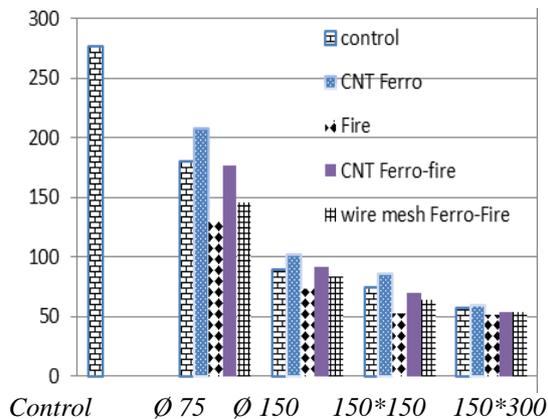


Fig.12. Failure load of retrofitted open beams with and without fire exposure.

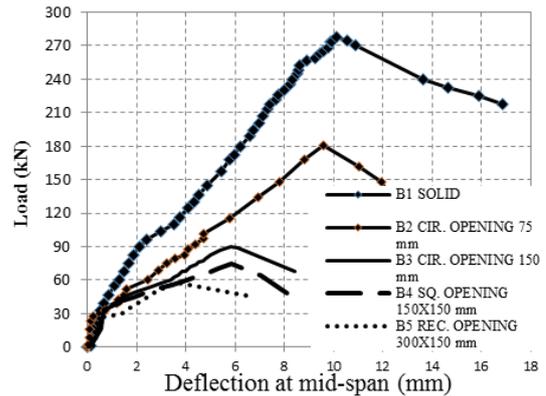


Fig.13. Load-deflection for control and different open beams.

### 5.3. Effect of Ferrocement Retrofitting on the Beam Behaviour before and after Fire Exposure

The use of a CNT ferrocement layer at room temperature improved the performance for the retrofitted beam with a 75-mm opening, increasing the failure load, decreasing the deflection, and improving the ductility (by approximately 47%) compared with the open beam. A significant reduction in failure load and ductility was reported after exposing the open beam to fire at 500°C. Use of the ferrocement retrofitting technique improved the shear resistance for open beams after exposure to fire. The beams with small openings exhibited better improvement compared to the beams with large openings. The deflection response is only slightly affected at the pre-cracking stage; however, this behaviour is dramatically changed at the cracking stage. The retrofitted beam with ferrocement has a lower value of deflection compared to the beam without retrofitting at the same value of load, as shown in Figs.14, 15, 16 and 17. Once the crack point has been reached, the gradient decreases until it reaches the ultimate load. The ferrocement layer increased the beam stiffness and relatively decreased the deflection in comparison to the control specimen. The number of cracks increased with the decrease in crack width for the retrofitted beams. The efficiency of increasing the beam stiffness via retrofitting by ferrocement reduced with increasing opening size.

The use of ferrocement with carbon nanotubes enhances the beam behaviour and ductility compared to the use of the wire mesh in the ferrocement layer. It is known that cementitious composites, such as concrete, are held together by a complex network of nanoparticles known as calcium silicate hydrate (CSH). Because of their Nano-scale characteristic, CNTs will interact most intimately with CSH.

The large surface energy and a large number of atoms present at the nanotube surface will promote the formation of an interface with C-S-H that is

most suitable for carrying the load Carbon nanotubes are highly flexible and capable of bending in circles and forming bridges that cross the micro- and nano-cracks developed in the cement composites; these CNTs interact with the C-S-H, generating bridges that enable the CNTs to increase the strength of the cement composites and improve the retrofitted beam ductility [15],[16] (Colleparidi et al., 2004; Makar et al., 2005). Such interfaces will act as crack blunting mechanisms at the very nascent stage crack growth. CNTs can be widely distributed in the concrete paste; in addition, interaction of CNTs with the paste will be more intense than that of the larger fibres (Sobolev and Gutierrez 2005).

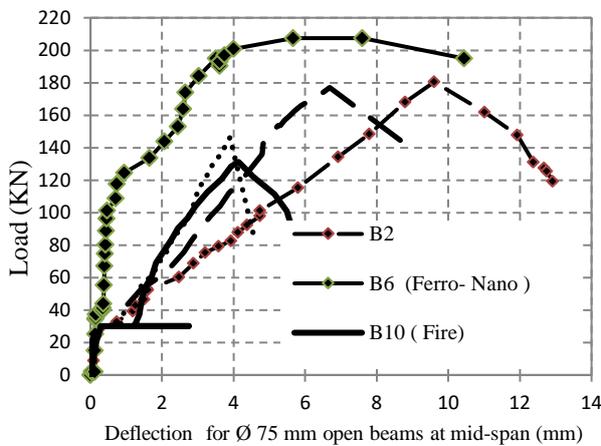


Fig.14. Load-deflection for retrofitted beams with Ø 75 mm open beams under different conditions

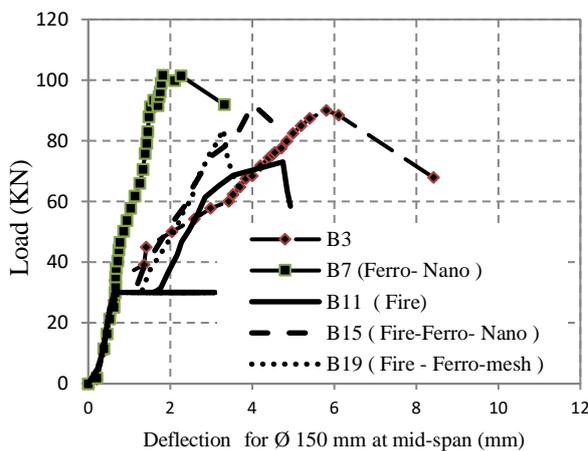


Fig.15. Load-deflection for retrofitted beams with Ø 150 mm open beams under different conditions

#### 5.4. Stirrup Strains for control, opened and retrofitted beams

The strains were measured at the first stirrup located beside the opening location for all specimens, except for the fire-exposed beams, for which a steel strain gauge cannot be used. The strain

in the stirrup was in a linear regime in the first stage of loading. After the first crack, the stress in the shear zone on stirrups increased. For a beam with a 75-mm opening, the stirrup stress increased less than that of the control beams, in which case an increase in stirrup strain occurred under early load.

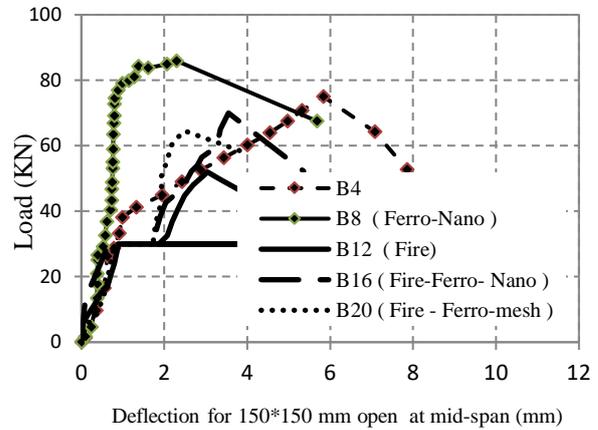


Fig.16. Load-deflection for 150\*150mm open beams under different conditions

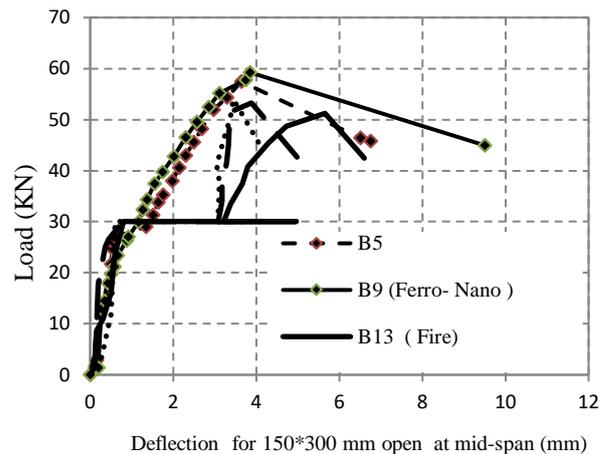


Fig.17. Load-deflection for 150\*300mm open beams under different conditions

For all opened beams, the shear stress increased with increasing opening size, and the first crack appeared early, which reduced the beam shear resistance; as a result, the stirrup strain increased rapidly and appeared early under lower load, as shown in Fig.18. CNT ferrocement improved the beam behaviour and delayed the stirrup stresses for a small opening, whereas for a beam with a large opening, the stirrup strain remained approximately constant after retrofitting at the linear stage (before cracking), and the change in strain was small relative to the load increasing, as shown in Figs 19 and 20.

The retrofitting enhanced the stirrup behaviour at the maximum point of loading for B2 and B3 comparing with B6 and B7. In the rectangular-opening beam, the CNT ferrocement enhanced the concrete behaviour, but the strains in stirrups were the approximately the same as that of the open beams without retrofitting, as shown in Fig.21 and 22. For the beam with the 150 mm × 150 mm opening, the stirrups acted in the retrofitted beam more than those in the open beam; otherwise, there was no noticeable difference in the strain in the stirrups for the beam with an opening of 300 mm × 150 mm.

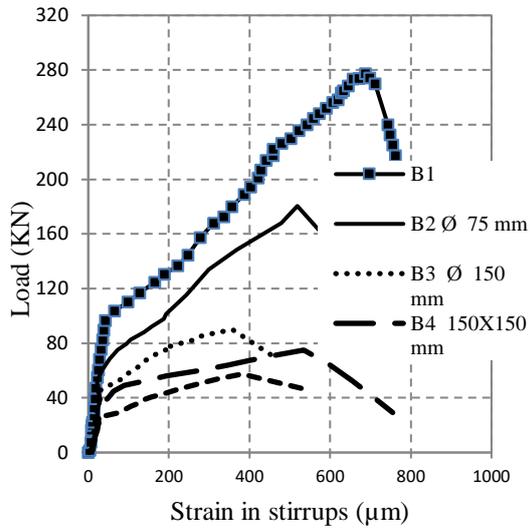


Fig.18. Load-stirrup strain for control and opened beams.

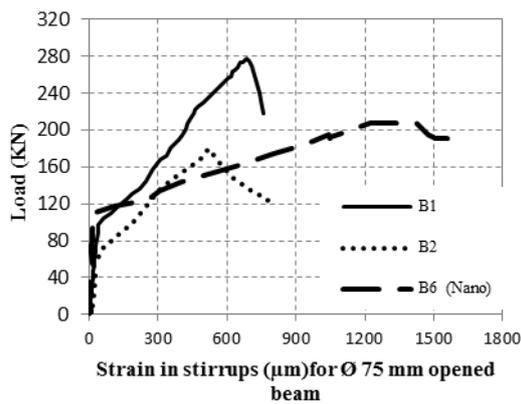


Fig.19. Load-stirrup strain for control and 75 mm opened beam

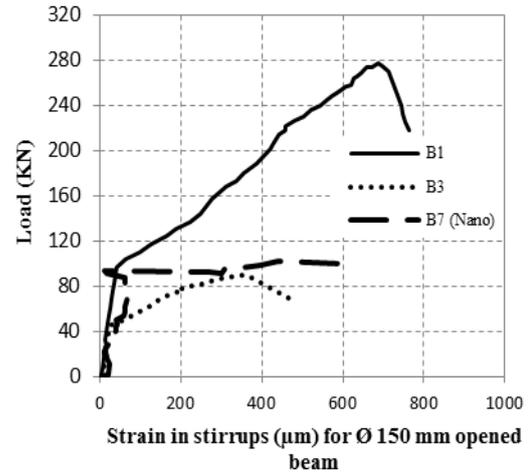


Fig.20. Load-stirrup strain for control and 150 mm opened beam

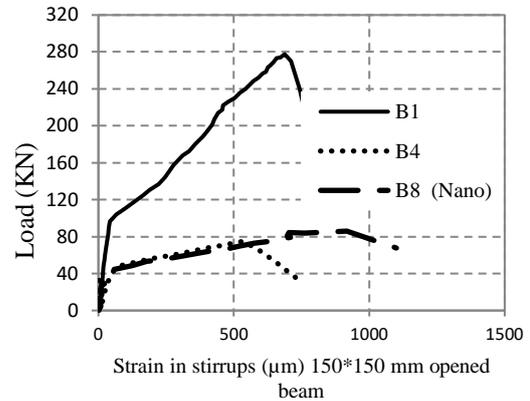


Fig.21. Load-stirrup strain for control and 150 mm × 150 mm opened beam.

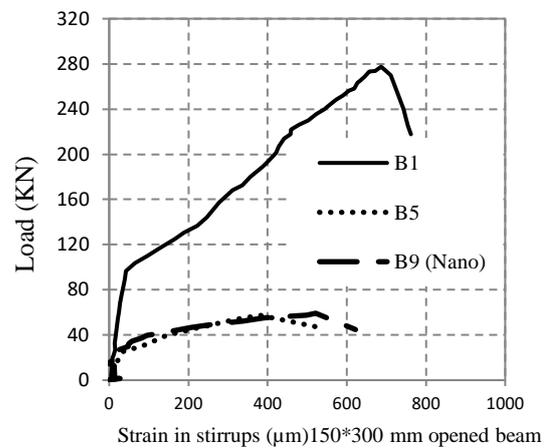


Fig.22. Load- stirrup strain for control and 150 mm × 300 mm opened beam.

### 5.5. Effect of Retrofitting with CNT Ferrocement on Main Steel Strain

The strain was measured at mid-span of the beam in the main steel. The steel strains for B1 and B2 were approximately the same value as the cracking load. For the tested beams with an opening of 75 mm, no improvement was observed, whereas for beams retrofitted by CNT ferrocement, the main steel strain improved clearly via an increased ultimate load. The retrofitting enhanced the main steel behaviour at the maximum point of loading. For beams with an opening of 150 mm, the strain was increased for B3, and the retrofitting did not significantly enhance the bar strain at the maximum point of loading. The retrofitting of rectangular-opening beams resulted in an enhancement relative to the concrete behaviour at the opening. Fig. 23, 24, 25, 26 and 27 shows the effect of opening and retrofitting on the main steel strain.

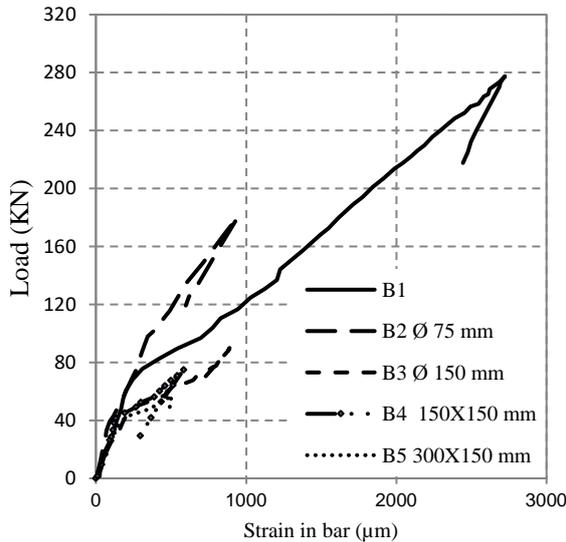


Fig. 23. Load-main steel strain for opened beams.

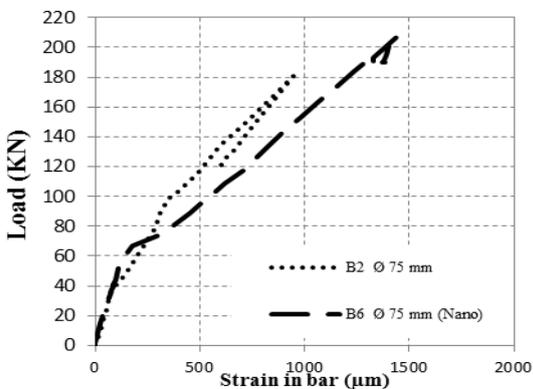


Fig. 24. Load-strain of bars for 75 mm opened beam.

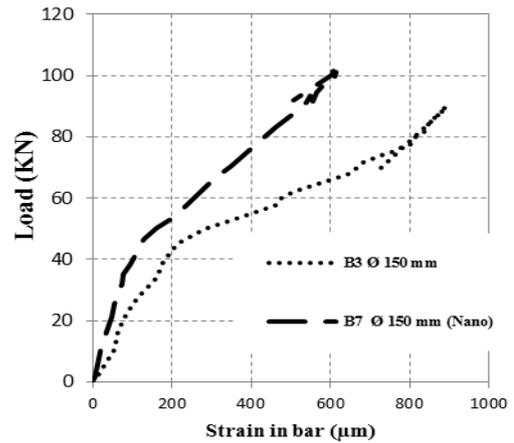


Fig. 25. Load-strain of bars for 150 mm opened beam.

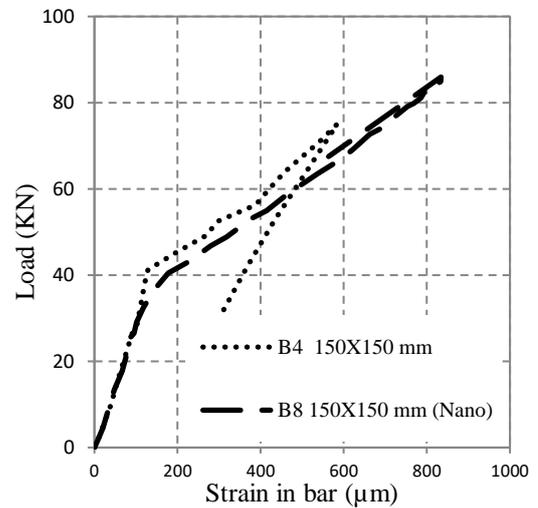


Fig. 26. Load-strain of bars for B4, and B8.

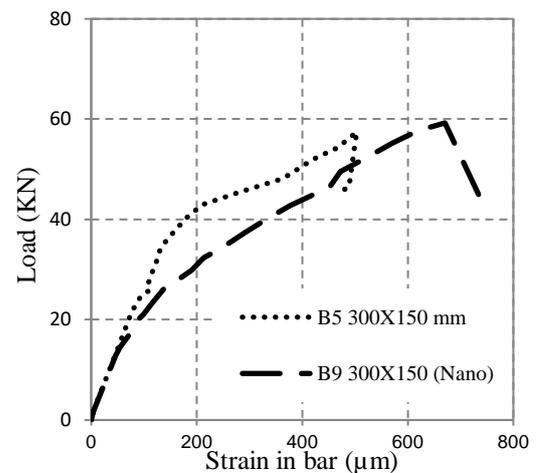


Fig. 27. Load-strain of bars for B5, and B9

## 6. CONCLUSION

The following conclusions can be drawn:

1-The retrofitting using CNT ferrocement enhanced the overall behaviour of the beams with small openings by increasing the ultimate load to 17%, increasing the ductility by approximately 45%, and reducing the crack width and deflections.

2-CNT ferrocement improved the first crack by 200% for a small opening and by approximately 35% for a medium-sized opening; however, it did not have a significant effect on a large opening.

3-The ferrocement technique does not have a significant effect on large opening behaviour.

4-Fire has a dramatic effect on large opening behaviour: the ultimate load for an opening of size 15\*30 cm reduced to approximately 22% of that of the control beam, and the retrofitting by ferrocement does not have any benefits for this opening.

5-Carbon nanotubes have a good effect compared to wire mesh when mixed in the ferrocement used for retrofitting the opened beams, regardless of whether the beam was subjected to fire or not, by an average of approximately 15% for different openings.

6-CNT ferrocement improves the ductility of opened beams by approximately 50%, whereas wire mesh does not have a major effect on the ductility.

## 7. ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Beni Suef University, for this research work

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