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Flexural Investigation of Concrete Beams Reinforced with Welded Wire Reinforcement

Sami W. Tabsh[1], Abdelaziz Younes[2]
[1]American University of Sharjah
Department of Civil Engineering, P.O. Box 26666, Sharjah, UAE
stabsh@aus.edu
[2]American University of Sharjah
Material Science and Engineering PhD Program, P.O. Box 26666, Sharjah, UAE
b00077508@alumni.aus.edu

Abstract – This research investigates the flexural behaviour of reinforced concrete (RC) beams that are transversely reinforced with cold-formed welded wire reinforcement (WWR) sheets in the shape of a closed steel cage. The experimental program comprises the laboratory testing of twelve 2000 mm long beams with 200 mm x 300 mm cross-section. The beams are tested under four-point load configuration with consideration of different wire diameters (4, 6, and 8 mm), grid openings (25, 50, and 100 mm), and concrete compressive strengths (30 and 35 MPa). The specimens are instrumented with linear variable differential transformers and strain gauges and tested inside a universal test machine. Results of the study showed that WWR reinforced beams have about 2% higher elastic stiffness, 18% surplus bending moment capacity, 19% lower ductility, and 4% extra residual capacity than corresponding conventionally reinforced beams with stirrups having the same transverse steel volumetric ratio. However, the impact of the grid size of the WWR on concrete confinement within the core was found to be minimal.

Keywords: Concrete, Beam, Confinement, Ductility, Flexure, Stiffness, Welded Wire Fabric, Welded Wire Mesh.

1. Introduction

In general, there are various modes of failure for RC beams, including flexural, shear, torsional, and bond. Flexural failure occurs when a beam is subjected to bending moment, causing one side of the beam to undergo compression and the other side tension. It is characterized by vertical cracks on the tension side of the beam and eventual crushing of the concrete at the extreme compressive fibres, within the maximum bending moment region. Concrete can resist large compression forces, but it has limited tensile strength; therefore, the tension side is usually reinforced with longitudinal steel bars that increase the flexural capacity and ductility of the beam. Concrete beams must also be transversely reinforced against flexural-shear and diagonal-tension cracks to avoid shear failure. In that case, steel stirrups are used to arrest these diagonal shear cracks since concrete alone is often incapable of resisting high shear forces.

Previous experience has shown that the use of rectilinear stirrups to resist shear forces in concrete beams has proved their effectiveness. However, stirrups are also associated with some deficiencies, including intensive labour, time consumption, high material cost, and lack of proper quality control on the final product. Such shortcomings have prompted researchers to find alternative ways to reinforce concrete beams against shear.

Welded wire reinforcement (WWR) consists of a series of parallel longitudinal steel wires at relatively small spacing that are connected at an orthogonal direction with another series of parallel wires to form a sheet of grids. The WWR sheet is produced in a precise fashion using an automated process that utilizes tack welding at the joints and is available in the market in different wire sizes and grid spacing. The manufacturing process of WWR is called the cold-drawn process, which involves reducing the cross-sectional area and/or the shape of a bar by pulling it through a die at room temperature [1]. This procedure affects the mechanical properties of the steel material by increasing the tensile strength but at the expense of reducing the ductility. Such a reinforcement can be used as a replacement for shear stirrups in concrete beams.

Traditionally, WWR has been extensively used in slabs-on-grades and pavements, but not in beams. Using WWR as shear reinforcement in beams has the potential of enhancing the structural performance not only in shear but also possibly in flexure if such reinforcement is formed in the shape of a closed steel cage, as shown in Figure 1. It is expected that the proposed method of reinforcement can increase the concrete confinement in the core; thus, delaying the formation of cracks and making them more uniform and controlled along the structure. The use of WWR to replace stirrups in beams can also reduce labour and cost and increase the productivity and quality of construction [2]. A literature review revealed limited research on the subject of using closed cage WWR as an alternative to the traditional form of reinforcement in concrete beams. Some studies investigated the effect of using WWR in form of flat sheets or U-shaped steel cages but not as a closed cage, resulting in lower confinement of the core of concrete. Others did not consider a wide range of parameters such as grid openings, concrete compressive strength, and wire diameter when investigating the effect of WWR on the structural behaviour.

(a) (b) (c)

Fig. 1: Proposed use of WWR in concrete beams, (a) WWR setup for bending, (b) bending of the sheet, and (c) final product.

2. Objectives and Scope

This research addresses the flexural performance of concrete beams transversely reinforced with WWR, as an alternative to conventional stirrups. The main objectives of this research are to: (1) Study the flexural performance of concrete beams transversely reinforced with WWR at the service and ultimate load levels, and (2) Compare the flexural response of concrete beams laterally reinforced with WWF with corresponding beams laterally reinforced with stirrups. To achieve the objectives, twelve half-scale beams are tested in flexure in the structural laboratory inside a UTM under displacement-controlled conditions. The beams are instrumented with strain gauges and linear variable differential transformers (LVDTs) and the measurements are recorded using a data acquisition system. The experimental program considers different wire diameters, grid openings, concrete compressive strengths, and longitudinal steel reinforcement ratios. All WWR reinforced beams are paired with corresponding beams that are laterally reinforced with stirrups. The stiffness at service load condition, crack pattern, onset of steel yielding, ultimate flexural capacity, strain in concrete at ultimate, ductility, and residual strength are monitored during the tests. All beams are adequately reinforced for shear to ensure that they fail in flexure, which is the subject of this study.

3. Previous Studies

In 2019, Rajha et al. [4] conducted a study on the cost-effectiveness of using WWR instead of ordinary rebars as a reinforcement of a 6 m by 6 m concrete slab. In this research, two types of WWR are considered and compared with conventional rebars, "WWR Standard Mesh" and "Tailor-Made Welded Mesh". The results demonstrated that the waste produced from preparing WWR standard Mesh and Tailor-Made Welded Mesh is 0.5% and 0.8% respectively, which is much lower than the 2% waste produced from preparing the conventional rebars. The labour cost of both types of WWR is lower by 94.8% than that of the conventional rebars. The overall savings in cost is 6.5% for WWR Standard Mesh and 4.7% for Tailor-Made Welded Mesh when compared with the cost of preparing the conventional rebars.

Xuan et al. [5] investigated the shear performance of prestressed concrete beams reinforced with WWR. Tests were performed on six single T-beams with similar span-to-depth ratio and flexural reinforcement. The study featured five beams beams containing different types of shear reinforcement and one beam without shear reinforcement. Three types of shear reinforcement were used, including conventional double-legged stirrups, single-legged stirrups, and WWR. Smoothed and and deformed WWR were considered with different shear reinforcement ratios. The results show that both WWR and conventional reinforced beams can attain the same shear strength capacity. Moreover, the crack widths are almost the same same in all specimens up to the initiation of the major diagonal crack. However, at higher loads, smooth WWR and double-legged stirrups beams showed smaller crack widths due to their larger amount of shear reinforcement. Therefore, the crack widths of the beams mainly depend on the amount of shear reinforcement rather than its type.

Pincheira et al. [6] also investigated the shear performance of prestressed T-beams reinforced with WWR and compared their performance with that of beams that are reinforced with traditional stirrups. The aim of the research was to compare the results with the provisions of the ACI 318 building code [3] and the recommendations of the ACI committee 215. Results of the study indicated that under cyclic loading deformed WWR is not as effective in resisting shear as conventional stirrups. The authors concluded that the provisions of the ACI 318 code overestimate the shear cracking load under cyclic loading, and ACI Committee 215 recommendations provide conservative predictions for the beam ultimate shear strength.

Nithin and Saravana [7] published a study on the flexural behaviour of beams reinforced with WWR and stirrups as shear reinforcement. They conducted experiments on six beams made with self-compacting concrete. Out of the six beams, five are reinforced with stirrups along with WWR, and one beam is reinforced with stirrups only. Different volumetric ratios of stirrups and WWR were considered with the aim of the study to investigate the effects of using small grid WWF along with conventional stirrups, and how the increase of WWF layers will affect the behaviour of the beams in flexure. The results showed that the beam containing one layer of WWR did not exhibit an appreciable increase in ultimate load over the control beam, although there is a noticeable increase in deflection. The authors observed that when the spacing of the stirrups increased, the ultimate load decreased; thus, concluding that adding WWR layer will not increase the beam strength when the spacing between stirrups is increased.

Ayyub et al. [8] tested 15 slabs up to their ultimate flexural capacity to investigate the viability of using WWR as reinforcement in concrete bridge deck slabs. This study considered the effects of the reinforcement ratio and transverse wire orientation on the flexural behaviour of the concrete slabs. The results demonstrated that failure mode of the specimens reinforced with relatively low reinforcement is steel fracture, even though their reinforcement ratios are larger than the minimum amount specified by ACI 318 code [3]. On the other hand, specimens with reinforcement ratios about twice more than what required by ACI code did not fail by steel fracture. The authors concluded that the minimum reinforcement ratio stated by ACI code for conventional steel is deficient for WWR. As expected, the increase in the reinforcement ratio increases the flexural capacity while reduces the deflection due to increased stiffness. The authors also noted that placing the transverse wires on the bottom increases the slab ductility because of the better distribution of stresses in the steel caused by the uniform crack distribution instead of one larger crack.

Gilbert and Sakka [9] tested two-span continuous one-way slabs reinforced with WWR. One of the slabs was a control sample and was laid on rigid supports, while the other was subjected to a 13.5 mm settlement at the interior support. The experimental results showed that the strain in the WWR steel wires at peak stress has a significant effect on the strength and ductility of the reinforced concrete slabs. At any value of support settlement, the ultimate load value that the slab can resist is lowered as the value of the strain and the ratio of the peak-to-yield stress of the wire reinforcement is reduced. In a follow-up study by the authors [10], eleven 2-way slabs were tested to compare the behaviour of slabs reinforced with low-ductility WWR with that reinforced with conventional deformed bars. The results of the study demonstrated that slabs reinforced with WWR failed in a brittle mode because of the rupture of WWR wires with insignificant plastic deformation beyond the ultimate load. The authors concluded that the behaviour of the slabs that showed low ductility justifies the decision made by the Australian standard to reduce the strength reduction factor for all members containing low-ductility steel.

In 2016, Radhakrishnan [11] completed an MS thesis at the University of Alaska Fairbanks by performing a numerical analysis using the finite element "ABAQUS" to evaluate the structural behaviour of simply supported concrete beams reinforced with welded wires and compare it with the behaviour of concrete beams reinforced with conventional steel. Based on the results obtained when the beams are subjected to four-point load, the beams that are reinforced with welded wire show 5.5%-22.2% lower bending moment capacity than the beam reinforced with conventional steel. Also, welded wire reinforced beams have 25% lower flexural reinforcement than the conventional steel reinforced beam. However, the welded wire reinforced beams exhibit a 7.58%-16.55% higher ductility than the equivalent conventionally reinforced steel beams.

4. Experimental Program

The experimental program of this study consists of twelve beams of 2000 mm length with 200 mm by 300 mm rectangular cross-section. The beams are longitudinally reinforced at the bottom with two No. 16 bars and tested inside a 2500 kN capacity Universal Test Machine. All beams are simply supported at 1800 mm span with 100 mm overhangs beyond the supports. Two concentrated loads are applied at 200 mm from the midspan, causing a 400 mm central region that has a constant bending moment and zero shear force. The clear concrete cover on the lateral reinforcement is 25 mm, resulting in a concrete core equal to 150 mm by 250 mm. All the beams are adequately strengthened in shear within the regions near the supports to ensure flexural failure. The effects of using different concrete compressive strengths, WWR grid spacing, and wire diameter are investigated. The WWR is based on the available specifications in the local market of the UAE. The considered wire diameters are 4mm, 6mm, and 8mm, and the grid spacing is 25mm, 50mm, and 100mm. Details of the beam specimens in the experimental program are summarized in Table 1.

Table 1: Summary of reinforcement details and nomenclature.

Serial No.	Beam ID	f'_c (MPa)	Type of Lateral Reinforcement	Reinforcement Diameter (mm)	Spacing of Lateral Reinforcement (mm)
1	W-16-4-25-35	35	WWR	4	25
2	W-16-6-50-35		WWR	6	50
3	W-16-8-100-35		WWR	8	100
4	W-16-4-50-35		WWR	4	50
5	S-16-8-91.5-35		Stirrups	8	91.5
6	S-16-6-103.5-35		Stirrups	6	103.5
7	W-16-4-25-30	30	WWR	4	25
8	W-16-6-50-30		WWR	6	50
9	W-16-8-100-30		WWR	8	100
10	W-16-4-50-30		WWR	4	50
11	S-16-8-91.5-30		Stirrups	8	91.5
12	S-16-6-103.5-30		Stirrups	6	103.5

In this study, a special specimen designation that consists of 5 variables is developed to describe each beam characteristic. It starts with a letter that refers to the type of vertical reinforcement, the letter (W) for WWR, and the letter (S) for stirrups. The second variable is a number that specifies the diameter of the longitudinal rebars, if present, and for the case of beams with no rebars the letter (N) is used instead. The third variable specifies the diameter (mm) of either the wire or the stirrup. The fourth variable is a number that represents the transverse reinforcement spacings (mm). The concrete compressive strength (MPa) is specified by the last variable within the specimen designation.

The considered beams were designed to achieve two different compressive strengths based on 150mmx300mm cylinders at the time testing; f'_c = 35 MPa (average obtained 37.2 MPa) and f'_c = 30 MPa (average obtained 30.4 MPa). The yield strength of the WWR with 4, 6 and 8 mm diameter wires was 590 MPa, 509 MPa and 574 MPa, respectively. The corresponding yield strength for the stirrups having 6, 8 and 10 mm diameter bars was 556, 557 and 577 MPa, respectively. The yield strength for the No. 16 longitudinal rebars used in the beams was 550 MPa. Figure 2 shows material testing procedures, steel cage assembly, placement of strain gauges and concreting work.

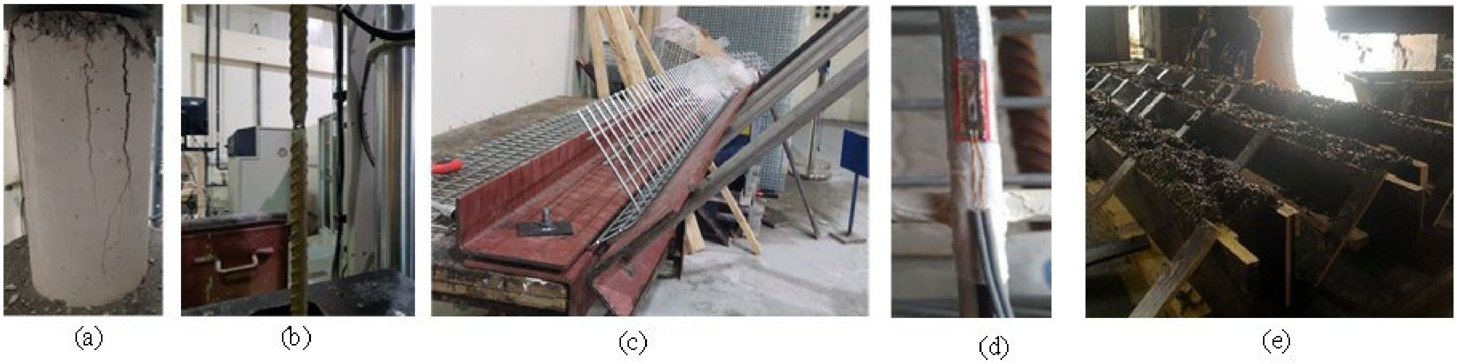

Fig. 2: Laboratory work, (a) concrete cylinder test, (b) steel bar test, (c) steel cage fabrication, (d) strain gauge, and (e) concreting.

5. Results

The flexural behaviour of the 12 beams is studied using a 4-point test setup by a UTM. Figure 3 shows the testing framework and cracking patterns of the beams just before collapse. Strain gauge reading captured the strain in the steel wires and rebars at different stages of the loads. The LVDT that was placed within the compression zone of the concrete at the location of maximum moment recorded the strain in the concrete.

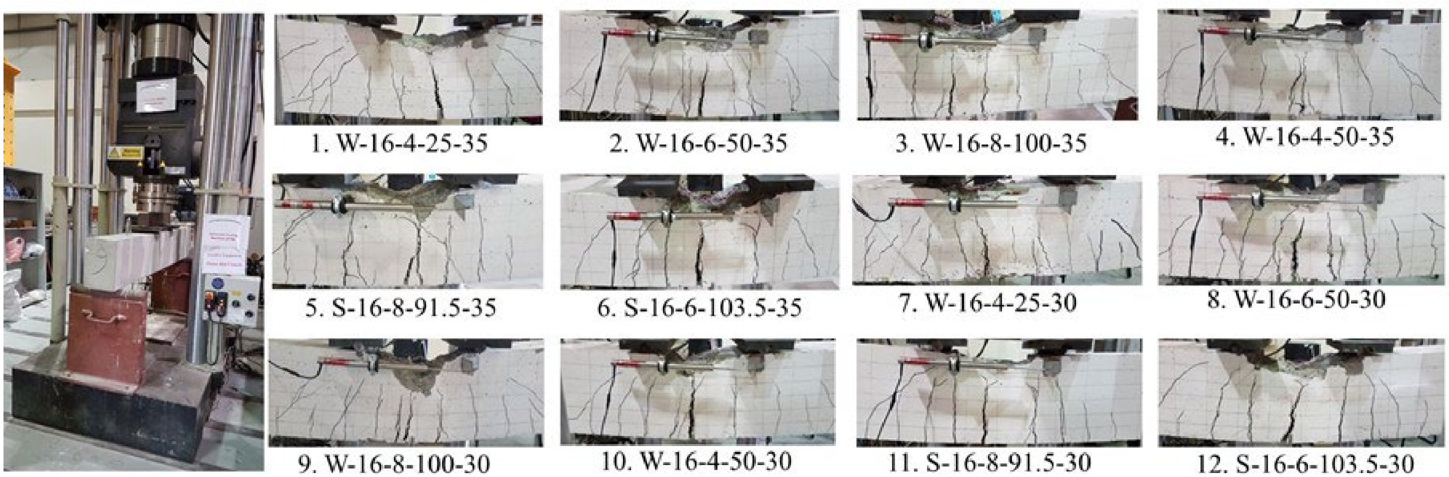

Fig. 3: Test setup and cracking pattern for all 12 tested concrete beams.

To compare the performance of WWD reinforced beams with that of stirrups, the related graphs of the moment-deflection relationship are combined and presented in Figure 4. In general, all the bending moment versus deflection relationships of the tested beams in this study consist of three parts, an ascending part that represents the behaviour prior to steel yielding, a somewhat horizontal part which is the region where the ultimate load is located, and a descending part that represents the residual capacity of the beams following the extensive damage. Within the ascending part, the slope of the curve starts steep until the occurrence of the first crack due to the beam reaching the modulus of rupture on the bottom tension side within the location of maximum bending moment between the two applied loads from the UTM. Thereafter, the slope of the ascending part of the moment-deflection curve reduces a little bit due to the formation and extension of cracks, and the moment of inertia of the beam changes from gross, to cracked, and then to effective. The horizontal part of the curve starts from the point of initiation longitudinal steel yielding and carries on until the beam reaches the ultimate flexural capacity, often characterized by crushing of concrete at the top of the beam when attaining an extreme compressive strain

0.0025-0.005. The final stage of the flexural behaviour of the beam as depicted by the moment-deflection relationship in this study is related to how much the beam can still carry part of the applied load with extensive deformations before collapse. This near-failure stage is possible to capture by the experimental tests because the load is applied in displacement-controlled conditions.

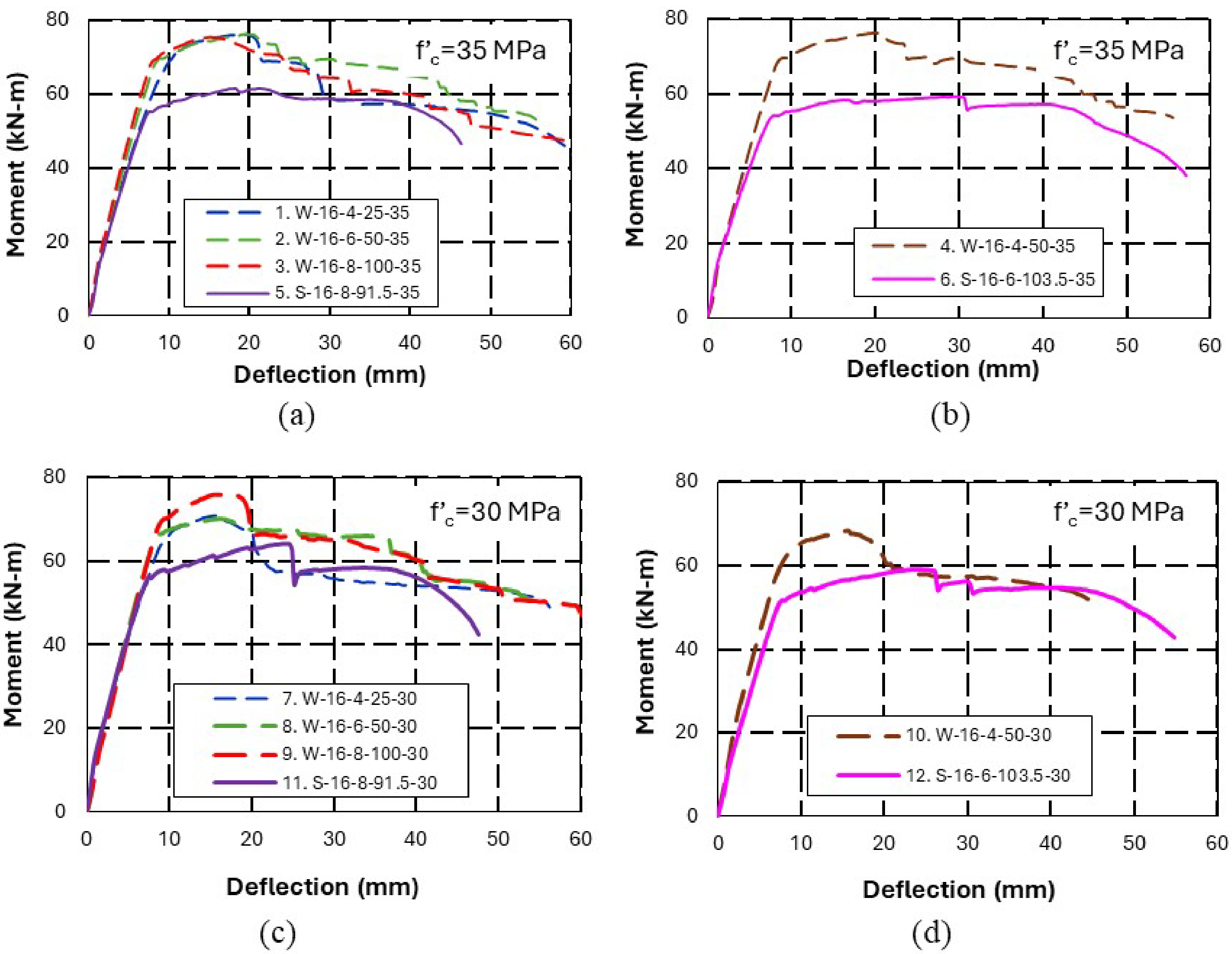

Fig. 4: Moment-deflection relationships, (a) Beams 1,2,3 & 5, (b) Beam 4 & 6, (c) Beams 7,8, 9 and 11, and (d) Beams 10 & 12.

6. Analysis of Results

In this section, a detailed analysis of the obtained experimental data from the tests is presented and a comparison of the flexural behaviour of the WWR reinforced beams with their corresponding stirrups reinforced beams is discussed. The effects of the grid size, wire diameter and concrete compressive strength on the flexural performance of the considered beams are also discussed. The parameters that are investigated are the beam stiffness at service, flexural strength, ductility, and post-peak residual strength. Practical implementation of the obtained results and recommendations concerning structural design are included. Table 2 shows a summary of the results of analysis.

Table 2: Summary of the analysis of the experimental results.

Serial No.	Beam ID	Equivalent Stiffness E_cI (kN-m^2)	Flexural Strength (kN-m)	Ductility Index	Residual Capacity Ratio

1	W-16-4-25-35	2540	76.12	2.14	0.749
2	W-16-6-50-35	2910	76.15	2.55	0.875
3	W-16-8-100-35	3000	75.34	2.11	0.854
4	W-16-4-50-35	2890	76.30	2.55	0.851
5	S-16-8-91.5-35	2670	61.75	2.67	0.947
6	S-16-6-103.5-35	2790	59.55	4.33	0.563
7	W-16-4-25-30	2760	70.91	1.91	0.781
8	W-16-6-50-30	2760	70.21	2.25	0.940
9	W-16-8-100-30	2760	76.00	2.09	0.834
10	W-16-4-50-30	2720	68.26	2.18	0.835
11	S-16-8-91.5-30	2750	64.12	3.42	0.661
12	S-16-6-103.5-30	2380	59.03	3.31	0.870

A close look at the slope of the ascending part of the moment-deflection relationships of the tested beams provides an idea about the stiffness within the service-level loading stage. For the beams with f'_c = 35 MPa, the average value of equivalent stiffness for the 3 beams that contains WWF with wires diameter of 4 mm at a spacing of 25 mm (Beam 1), wires diameter of 6 mm at a spacing of 50 mm (Beam 2) and wires diameter of 8 mm at 100 mm spacing (Beam 3), is 6.0% greater than the stiffness of the corresponding beam reinforced with No. 8 stirrups 91.5 mm (Beam 5). The other two beams that have less transverse steel reinforcement (Beams 4 and 6), the WWR reinforced beam has 4.7% higher stiffness than the corresponding stirrups reinforced beam (Beam 6). Note that the higher stiffness of the WWR reinforced beams is mainly due to the superior confinement provided by the grid of wires compared with stirrups. With regard to the beams with f'_c = 30 MPa, the average value of equivalent stiffness of Beams 7, 8, and 9 which contain WWR is almost the same as that of Beam 11 which contains stirrups. Also, WWF reinforced Beam 10 has 14.3% greater stiffness compared with stirrups reinforced Beam 12.

The results in Table 2 show that the flexural strength of the beams containing WWR is 9.5-28.1% higher than that of corresponding beams containing stirrups, depending on grid size, concrete compressive strength, and transverse steel reinforcement ratio. The increase in the flexural capacity of the beams containing WWR is mainly due to the presence of the longitudinal skin reinforcement around the parameter of the entire section and the small size of the WWR grid which provides more confinement to the beam's concrete core.

The effect of the grid opening size and the corresponding wires diameter on the flexural strength of the WWF reinforced beams is investigated by comparing the results of the beams having three different grid sizes of 25, 50 and 100mm with corresponding wire diameters of 4, 6 and 8mm. Based on the results, the wire spacing of the WWF has an insignificant effect on the flexural strength of the beams, although the beams that are reinforced with 6 mm and 8 mm wires show slightly higher flexural capacity than the beams reinforced with 4 mm wires. This finding indicates that the diameter of the wires has somewhat more impact on bending moment capacity than the wire spacing.

The effect of different grid openings with the same wire diameter on the flexural strength of the beams can be observed by comparing the experimental results obtained from testing Beams 1 and 7 with Beams 4 and 10. These beams are reinforced with WWF having 4 mm wires diameter but with two different grid openings of 25 mm and 50 mm. Note that using various grid spacing while keeping the same wire size results in different shear strengths provided by the related beams. The study outcome indicates that using smaller mesh spacing of WWF with the same wire size slightly increases the flexural strength of the specimens. A benefit of this finding is that larger grid openings results in less steel cage congestion and allows for utilizing larger coarse aggregate in the concrete mix.

The effect of the concrete compressive strength (30 versus 35 MPa) on the flexural capacity of the beams is investigated by analysing the results of Beams 1-6 to Beam 7-12. The flexural reinforcement ratio and the shear reinforcement ratio are the same among the compared beams. Based on the experimental results, four WWF reinforced beams having 30 MPa concrete strength are compared with their four beams having 35 MPa concrete strength, and two stirrups reinforced beams having 30 MPa concrete strength are compared with their two beams having 35 MPa concrete strength. For the WWF reinforced beams, the ratio of the flexural capacity of the beams with higher concrete compressive strength to that of the corresponding beams with lower concrete compressive strength ranged between 0.99 and 1.12. Conversely, the ratio of the flexural capacity of the two stirrups reinforced beams with higher concrete compressive strength to that of the corresponding two beams with lower concrete compressive strength ranged between 0.96 and 1.01. These findings reflect the effectiveness of welded wire fabric over stirrups with regard to the flexural capacity of beams made with higher strength concrete.

In this study, the ductility of the tested beams is quantified by considering the ratio of deflection of the beam at ultimate to the corresponding deflection at the onset of the flexural steel yielding, approximated by the beam deflection corresponding to 85% of the flexural strength on the ascending part of the moment-deflection relationship. With regard to the beams with f'_c=35 MPa, the ductility indices of Beams 1-3 are on an average 15% lower than that of the corresponding stirrup reinforced Beam 5, and the WWF reinforced Beam 4 has a ductility index that is 41.1% lower than the corresponding stirrups reinforced Beam 6. Concerning the beams with f'_c=35 MPa, the ductility indices of WWR reinforced Beams 7-9 are on average 39.2% lower than the corresponding stirrup reinforced Beam 11, and the WWF reinforced Beam 10 has a ductility index that is 34.1% lower than the corresponding stirrups reinforced Beam 12.

The residual strength of the beams is quantified in this study by the residual capacity ratio, defined as the ratio of the moment capacity on the descending branch that corresponds to twice the deformation at peak moment capacity to the peak moment capacity. Table 2 shows that the average residual strength of the WWR reinforced beams that contain a low transverse reinforcement ratio (Beams 1, 2, and 3) is lower by 14.7% than that of the stirrups reinforced beam (Beam 5). However, for the beams with a higher transverse reinforcement ratio, the WWR reinforced beam (Beam 4) shows 51.2% higher residual strength than the stirrups reinforced beam (Beam 6). Also, the WWR reinforced beams with a low transverse reinforcement ratio (Beams 7, 8, and 9) show 29.0% higher average residual strength than the stirrups reinforced beam (Beam 11). The other two beams that have less transverse steel reinforcement ratio, the stirrups reinforced beam (Beam 12) shows a slight increase of 4.2% in the residual capacity over the WWR reinforced beam (Beam 10).

7. Conclusion

Based on the obtained results from the conducted research in this study, the following conclusions are drawn:

1. The flexural performance of WWR reinforced concrete beams compared with that of corresponding beams having stirrups and containing the same amount of longitudinal rebars is superior.
2. The cracked beam stiffness prior to steel yielding in the WWR reinforced beams is just about the same as that of the corresponding stirrups reinforced beams.
3. The ultimate bending moment capacity of the WWR reinforced beams is moderately higher on average than that of the corresponding stirrups reinforced beams. The flexural strength of the WWF and stirrups reinforced beams that have a concrete compressive strength equal to 35 MPa is slightly higher than the corresponding strength of the beams that have a compressive strength equal to 30 MPa.
4. The flexural ductility index of the WWR reinforced beams is slightly lower on average than that of the corresponding stirrups reinforced beams due to the brittle nature of the steel used in the WWR wires.
5. The residual flexural strength beyond the peak capacity of the WWR reinforced beams can be either lower or higher than the corresponding stirrups reinforced beams, depends on the concrete compressive strength transverse steel reinforcement ratio.

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