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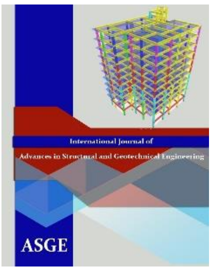

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ABSTRACT

Shear failure in RC beams is brittle sudden one characterized by increased major crack width approaching failure. Thus, in order to improve the shear resistance of RC beams, special configuration of web reinforcement has to be provided in order to limit the crack width as well as to increase its shear capacity. In the current paper, a pre-prepared steel trusses have been configured and assembled using steel strips of 2 mm thickness and then used to enhance both the cracking characteristics and ultimate load capacity. Thus, an experimental program consists of five RC beams have been prepared and tested up to complete shear failure. Test specimens included un-reinforced control beam as well as another beam reinforced for shear by equivalent truss composed of smooth bars of 8 mm diameter simulating the trussed strips. Besides, three beams were reinforced by inclined steel strips, vertical steel strips and trussed steel strips. All steel strips have constant cross-section of 2 mm thickness and 25 mm width. It was found that the beam reinforced by trussed strips showed the outermost shear performance. It showed the highest ultimate capacity as well as the lowest major shear crack width among all specimens. The increases in the ultimate capacity were 79%, 107%, 141% and 129% for beams provided by vertical strips, inclined strips, trussed strips and equivalent trussed bars, respectively, compared to that of control un-strengthened beam. On the other hand, the measured crack width for the major shear crack near failure were about 0.9, 0.8, 0.5 and 0.6 mm, respectively, for beams provided by vertical strips, inclined strips, trussed strips and equivalent trussed bars.

Keywords: Shear Behavior, Steel Strips, Steel Plate Truss, Experimental Test, Crack Width, RC Beams.

INTRODUCTION

Reinforced concrete (RC) beams entail shear reinforcement in the shape of vertical stirrups, inclined stirrups, or bent up bars in order to resist the shear stresses when the concrete shear strength is exceeded [1, 2]. Shear failure of RC beam is brittle and sudden after formation of the diagonal cracks, which makes it more critical and un-safer than the flexural failure for the same beam. It is important to improve the shear performance and ultimate shear strength of RC beams for civil engineering structures, and also to keep the crack width within the acceptable level. Therefore, different techniques were developed to enhance the shear capacity of RC beams including internal and external systems. Internal techniques include spiral stirrups [3], internal plates [4], and while, external techniques include the applications of fiber-reinforced polymer (FRP) composites, steel strips or textile reinforced mortar sheets. However, the shear strength of reinforced concrete members using these techniques is limited due to debonding/detachment between the applied strengthening material and the substrate concrete surface. Besides, these strengthening techniques need special precautions in their implementation and specific adhesive materials.

Ammash [5], presented a study to compare experimental results with the ABAQUS numerical results. The main goal of his study was to investigate the effect of using steel strips as shear reinforcement instead of steel bar stirrups. It was found that, the use of that type of reinforcement decreased the crack width, the number of cracks, and crack spacing. Therefore, it led to maintain the confinement of the concrete core of the section and increased the ultimate strength of RC beam.

Zakaria [6], investigated the effect of various parameters such as beam size, shear span to depth ratio, side concrete cover to stirrup, stirrup spacing, stirrup configuration, longitudinal reinforcement ratio, and loading paths on the spacing between shear cracks and the relationship between shear crack width and stirrup strain at the intersection with shear cracks. The results showed that shear cracks width increased proportionally with both the strain of shear reinforcement and the spacing between shear cracks.

In the current paper, different internal shear reinforcement assemblies were proposed and implemented. These assemblies include inclined steel strips, vertical steel strips, and trussed steel strips. For comparison purpose, equivalent trussed bars was configured and prepared to simulate the trussed strips and its results were compared with these of trussed steel strips. The ultimate capacity gains as well as the decrease in the major shear crack width compared with un-reinforced control beam were the main comparison criteria.

EXPERIMENTAL PROGRAM

Test specimens

In the current research, an experimental program was mainly designed in order to study the effect of using different configurations of internal steel strips as shear reinforcements in RC beams in shear span zone instead of regular steel bar stirrups. A total of five RC beams were constructed with the same concrete material and longitudinal reinforcing steel bars. The total length of the beams was 2200 mmm while the center-to-center span was 2000 mm. the cross-section dimensions were 200 mm width by 400 mm total depth. The test specimens were divided into one reference un-strengthened beam in shear, there beams reinforced with different configurations of steel strips and one specimen reinforced with equivalent trussed bras as an equivalent to the beam reinforced with trussed steel strips as summarized in Table 1. Figure 1 shows the typical concrete dimensions for all beams as well as the longitudinal and the web reinforcement for the right side part of the control un-strengthened beam along with the remaining strengthened beams. It is worth mentioning that all beams were cast, cured for 28 days under field conditions, and tested at the same day.

Table 1 Test matrix

Specimen	Characteristics	Objectives
BC	Control un-reinforced beam	Reference beam
BS-V-25-200	Beam reinforced by vertical strips of 25 mm width and 200 mm spacing	Studying the effect of strips configuration
BS-I-25-200	Beam reinforced by inclined strips of 25 mm width and 200 mm spacing	
BS-T-25-200	Beam reinforced by trussed strips of 25 mm width and 200 mm spacing	
BB-T-D8-200	Beam reinforced by equivalent trussed bars of 8 mm diameter and 200 mm spacing	Equivalent bar diameter for strip cross section (25*2) mm

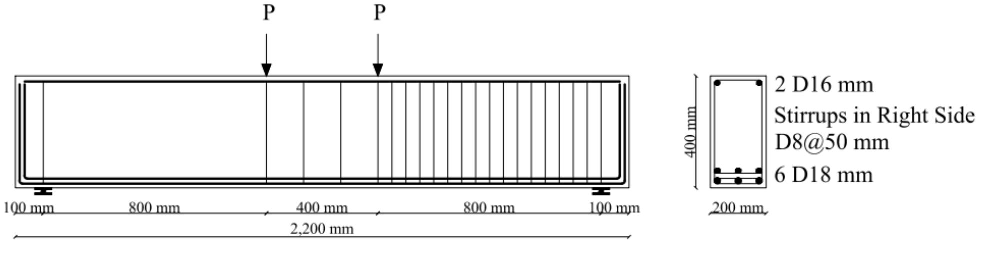


Fig. 1 Typical concrete dimensions and reinforcement.

Material properties

Concrete

Ready mix concrete was used, According to the data sheet of the producer, Portland cement (Type V), crushed limestone with (5-19) mm size and specific gravity of 2.60 was used as coarse aggregate according to the Egyptian code of practice (ECP 203-2018) standards specifications [7]. Volumetric mixing ratio of (1:2:4) with water/cement ratio (w/c) = 0.478 was used. The average compressive strength of the concrete mix after 28- days was about 25.4 MPa based on the results of 6 standard cubes of 150 mm side length.

Steel reinforcement (bars and plates)

All beams were reinforced with high tensile steel bars of 6Ø18 mm and 2Ø16 mm as longitudinal reinforcement in tension and compression side, respectively. Standard tension tests were performed on three typical specimens of each bar type as well as the steel strips. The mechanical properties of all bar diameters and steel strips are summarized in Table 2. The experimental stress-strain relationship for the steel plate tested by universal testing machine (UTM) is shown in Fig. 2. The used shear reinforcement for the reference beam BC was a regular ties (Ø 8 @ 50 mm) in right side, while the left side was un-strengthened as depicted in Fig. 1. Three beams were reinforced in the left side by vertical strips, inclined strips and trussed strips as illustrated in Fig. 3. For the these beams, the vertical spacing was 200 mm and the cross-section of the used strips was 2 mm thickness by 250 mm width. It is worth mentioning that the dimension of the steel strip was chosen to be equivalent to steel bar of 8 mm diameter. Thus, the last specimen was reinforced with trussed steel bars equivalent to the beam reinforced with trussed steel strips as depicted in Fig. 3. Figure 4 shows the assembled steel cage for all beam before inserting then into the pre-prepared plywood formwork.

Table 2 Mechanical properties of bars and plates

Dimensions of steel bar or plate	Type	Average yield strength, MPa	Average tensile strength, MPa	Average modulus of elasticity, GPa
Ø8 bar	Smooth mild steel	270	392	201
Ø16 bar	Deformed high-tensile	420	576	203
Ø18 bar	Deformed high-tensile	446	583	203
Plate (t=2 mm)	Smooth mild steel	350	385	202

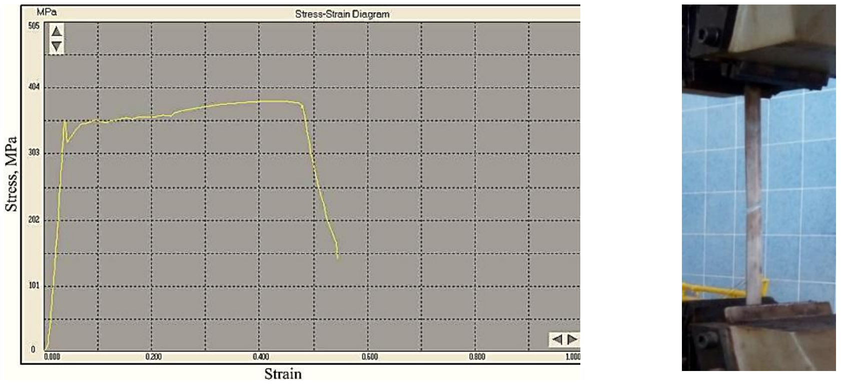


Fig. 2 Experimental stress-strain relationship of steel plate.

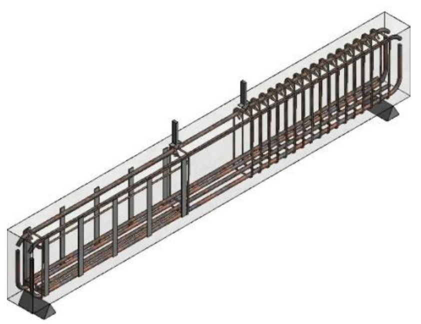
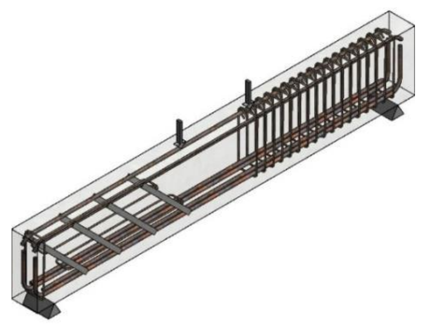
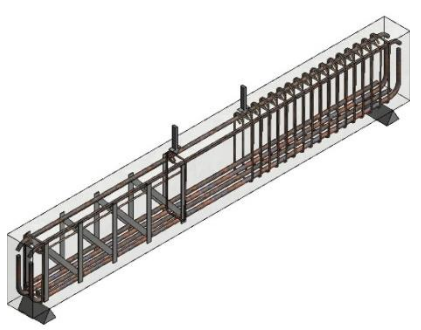
	
BS-V-25-200	BS-I-25-200
	
BS-T-25-200	BB-T-D8-200

Fig. 3 Configuration of internal shear reinforcement for reinforced beams.

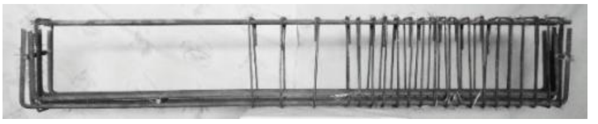
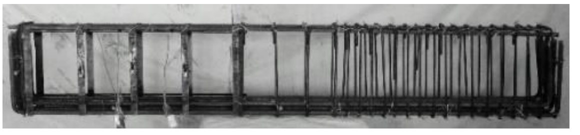
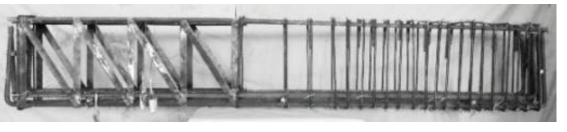
BC	
BS-V-25-200	
BS-I-25-200	
BS-T-25-200	
BB-T-D8-200	

Fig. 4 Steel cages for all beams.

Test setup and procedures

All beams were tested under four point loading scheme with a loading rate of 0.05 mm/sec where the shear-to-span ratio was 2.3 in order to ensure the occurrence of shear failure. At the strengthened shear span side, two Linear Variable Differential Transformers (LVDTs) of 100 measuring length were arranged at right angle in order to obtain the developed shear strain. In addition, one LVDT of 50 mm measuring length was used in order to measure the developed mid-span deflection as shown in Fig. 5. The developed tensile normal strain on the main tensile steel bars was measured by 6 mm gauge length strain gauge, while two Pi gauges of 100 mm gauge length were used to measure the developed deformations on the concrete surface at both tension and compression sides. All beams were incrementally loaded up to failure where the acting load was measured by a load cell of 600 kN capacity. After each loading step, the vertical mid-span deflection, the Pi-gauge readings and the developed normal strains in the longitudinal steel bars were recoded and stored using an automatic data logger unit (TDS-150).

Fig. 5 Test setup and instrumentation

TEST RESULTS AND DISCUSSION

Table 3 summarizes the characteristic loads such as the first cracking loads for both flexure and shear as well as the failure loads along with the corresponding mid-span deflections and developed normal strains on the main reinforcing steel bars.

Table 3 Experimental results

Specimen	$P_{cr,f}$ (kN)	$P_{cr,sh}$ (kN)		P_u (kN)	δ_{max} *** (mm)	$\varepsilon_{s\,max}$ (micro-strain)	W_{cr} (mm)	θ_{cr}
		Left side*	Right side**					
BC	103	153	--	177	4.2	792	1.2	36
BS-V-25-200	106	165	203	317	7.3	1726	0.9	44
BS-I-25-200	113	212	212	366	8.2	1808	0.8	38
BS-T-25-200	114	222	207	427	7.5	2210	0.5	37
BB-T-D8-200	105	203	209	407	7.8	2350	0.6	44

$P_{cr,f}$ = First flexural cracking load, $P_{cr,sh}$= First shear cracking load, P_u= Failure load, δ_{max} = Maximum mid-span deflection corresponding to ultimate load, $\varepsilon_{s\,max}$ = Maximum tensile normal strain on the main tensile steel, W_{cr}= Crack width for major shear crack at failure, θ_{cr} = Crack angle at failure, * Left side reinforced with steel strips, ** Right side reinforced with closely spaced stirrups.

Failure Modes and Cracks Characteristics

Figure 6 shows the developed crack patterns for all beams after the occurrence of complete shear failure. For control beam (BC), cracks appeared at the mid-span zone at a vertical load of about 103 kN. With further loading, more flexural cracks appeared till a vertical load of about 153. And then shear crack appeared at left side at a vertical load of about 153 kN. Soon later, sudden shear failure controlled the failure at the same side at a vertical load of about 177 kN. For beams provided with steel strips, flexural cracks appeared at the mid-span zone at vertical loads of about 106, 113, and 114 kN for beams BS-V-25-200, BS-I-25-200, and BS-T-25-200, respectively, while the first shear cracks started at the left side at vertical loads of about 165, 212, and 222 kN respectively. In the sequel, shear cracks started at right side at vertical loads of about 203, 212, and 207 kN, respectively. Proceeding with loading triggered the shear sudden failure at the left side at vertical loads of about 317, 366, and 427 kN, respectively, for beams BS-V-25-200, BS-I-25-200, and BS-T-25-200.

For beam BB-T-D8-200, provided with equivalent trussed bars, flexural crack appeared at the mid-span zone at a vertical load of about 105 kN, which is lower than the relevant value for beam BS-T-25-200 (114 kN). In addition, the developed shear cracks at both sides appeared at lower loads compared to those for BB-T-D8-200. Furthermore, the failure load was about 407 kN, which was lower than the failure load of beam BS-T-25-200 by about 4.7%.

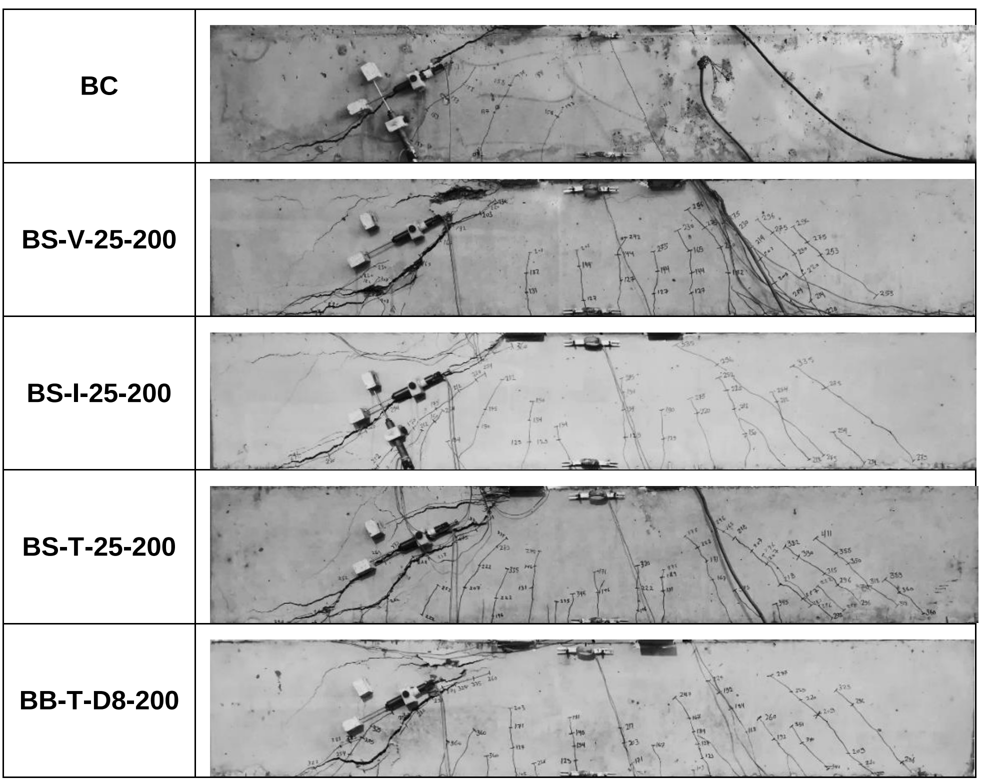
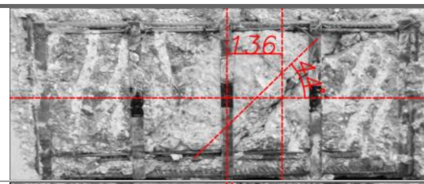
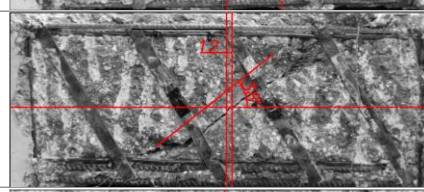
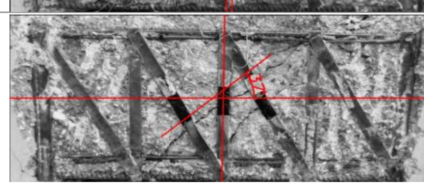
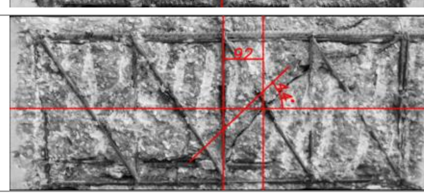


Fig. 6 Crack patterns of all beams after complete failure.

After complete of all beams, the concrete cover at the failed shear span for all strengthened beams was removed in order to expose the steel assemblies as shown in Fig. 7. It was noticed that the shear failure was characterized by the formation of major shear cracks located at somewhere inside the shear span zone and inclined with dissimilar angles. Thus, the locations of the major crack with along with its inclination angle were measured for each beam. The center on the major shear cracks was found to be at distances of 136, 12, 0 and 92 mm for beams BS-V-25-200, BS-I-25-200, BS-T-25-200 and BB-T-D8-200, respectively, from the center of the shear span zone. That means the trussed strips triggered the major shear crack to be developed at the center of the shear span zone. In addition, the inclination angle for the major shear cracks were 44°, 38°,37°, and 44°, respectively, for beams BS-V-25-200, BS-I-25-200, BS-T-25-200 and BB-T-D8-200.

Specimen	Crack angle	X, mm	Exposed failed side after complete failure
BS-V-25-200	44°	136	
BS-I-25-200	38°	12	
BS-T-25-200	37°	0	
BB-T-D8-200	44°	92	

X distance between center of major shear crack and center of shear span

Fig. 7 Internal view on the steel assembly and developed shear crack after complete failure.

Figure 8 shows the relationships between the jacking load and the major shear crack width for all beams before the occurrence of complete shear failure in the left side. During testing, the developed major shear cracks were measured at different load level using optical microscope of 0.01 mm accuracy. It can be observed that during the loading history the wider cracks were developed in the reinforced by vertical strips, while the narrower cracks were exhibited by the beam reinforced by trussed strips. Based on the relationship depicted in Fig. 8, at the same loading level, the beam BS-V-25-200 showed the highest crack width which approximately twice the crack width developed by beam BS-I-25-200.

As for beam BB-T-D8-200, the developed crack width at any load level was narrower than that developed by either beams reached at some load level more than 4 times that developed by beam BS-V-25-200 or beam BS-I-25-200. On the other hand, the developed crack with by beam BB-T-D8-200, at any loading level, was higher than that developed by beam BS-T-25-200.

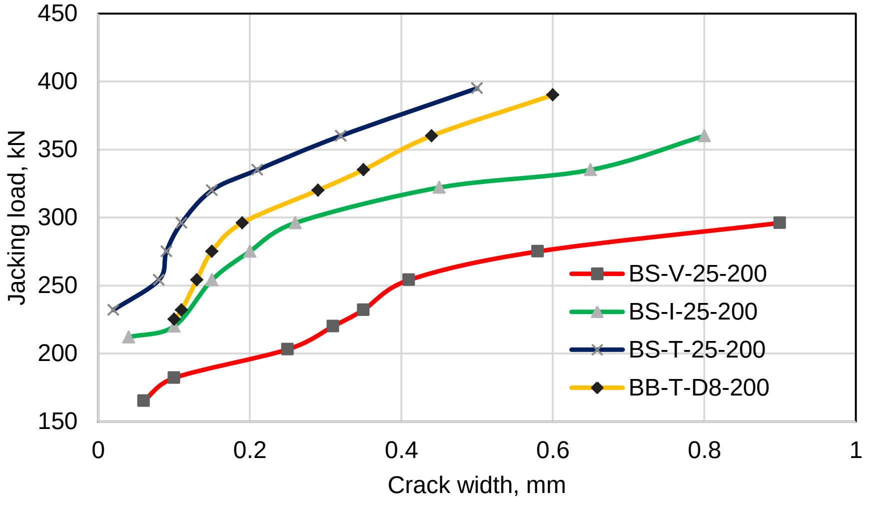


Fig. 8 Experimental results of load versus major shear crack width for all beams.

Load deflection

Figure 9 shows the relationships between the jacking load and the developed mid-span deflection for all beams. It can be observed that the beams BC, BS-V-25-200, BS-I-25-200 and BB-T-D8-200 showed approximately the same trend from the beginning of loading up to approaching the failure of each beam. On the other hand, beam BS-T-25-200 showed more stiffer behavior ant any loading level than that exhibited by other beams.

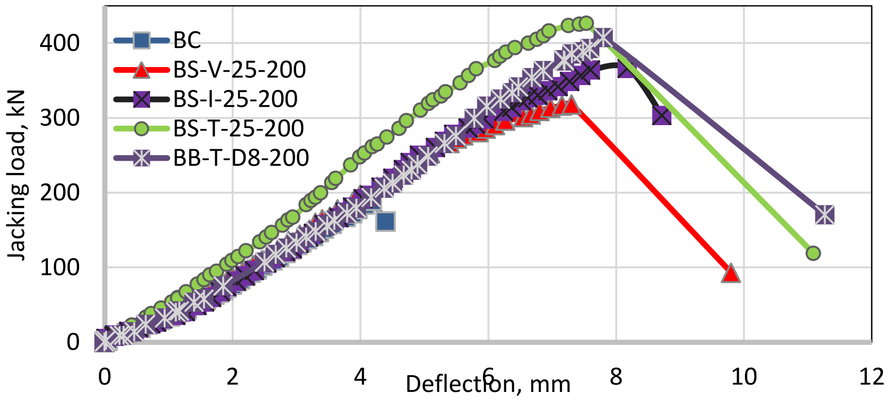


Fig. 9 Jacking load versus mid-span deflection for five beams.

Tensile strain

Figure 10 shows the relationships between the jacking load and the tensile normal strain on the main steel reinforcing bar at the mid-span section for all beams. Based on the mechanical properties of the used longitudinal steel bars, the yielding strain is about 2197 micro-strain. It can be observed that the developed normal strain on the main tensile steel did not reach the yielding strain at failure for beam BC, BS-V-25-200 and BS-I-25-200, as expected. On the other hand, the developed tensile strains for beams BS-T-25-200 and BB-T-D8-200 slightly exceeded the yielding strain, which were 2308 and 2210 micro-strain, respectively.

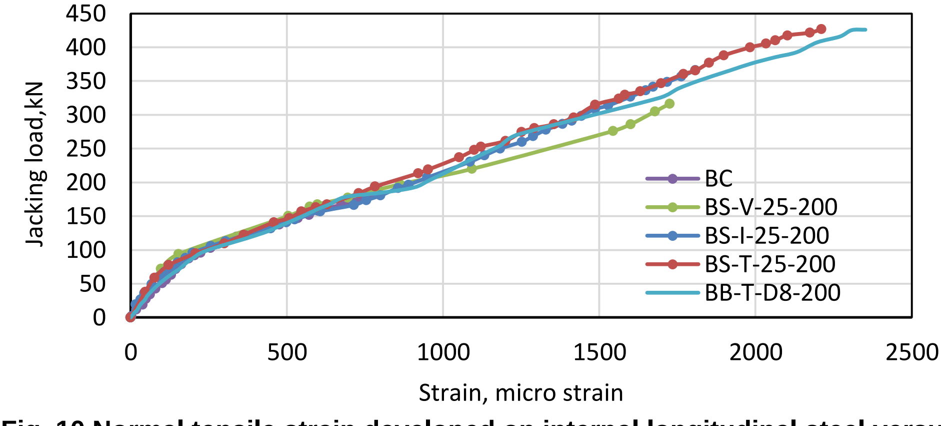


Fig. 10 Normal tensile strain developed on internal longitudinal steel versus jacking load for all beams.

Comparisons between calculated shear capacity and test results

Based on the mechanical properties of the used steel bars and steel strips listed in Table 2, the ultimate shear capacity of reinforced concrete beams with embedded steel trusses, V_{st}, can be calculated by Eq. (1) [8].

$$V_{st} = \frac{A_v f_v d_v}{s \tan\theta_{st}} + \frac{A_m f_m d_m}{s_m}\left(\frac{1}{\tan\theta_{st}} + \frac{1}{\tan\alpha}\right)\sin\alpha$$

As for the un-reinforced control specimen, the shear capacity was calculated based on the ECP 203-2018 equations. Table 4 shows the results of both experimental test and the analytical estimation. It can be observed that the analytical results are in the conservative side for all specimens; however, safety margin was reduced for both specimens reinforced by trussed strips and trussed equivalent bars.

Table 4 Comparisons between calculated ultimate shear load and test results

Specimen	Test results Q_u^T,KN	Analytical results Q_u^C,KN	Q_u^T / Q_u^C
BC	88.5	64.5	1.37
BS-V-25-200	158.5	115.8	1.37
BS-I-25-200	183.0	123.0	1.49
BS-T-25-200	213.5	197.1	1.08
BB-T-D8-200	203.5	197.1	1.03

CONCLUSION

Special configuration of web reinforcement has been provided in order to limit the major shear crack width as well as to increase the shear capacity of RC beams. Based on the adopted concrete dimensions, material properties and the configurations of the used steel assemblies, the following conclusions could be drawn:

1. Using internal steel assemblies in order to enhance the shear performance of RC beams showed increases in the ultimate capacity by about 79%, 107%, 141% and 129% for beams provided by vertical strips, inclined strips, trussed strips and equivalent trussed bars, respectively, compared to that of control un-strengthened beam.
2. The application of internal steel assemblies restrained the propagation of the major shear crack. Thus they reduced exhibited shear crack width near failure. The major shear cracks widths near failure were about 0.9, 0.8, 0.5

and 0.6 mm, respectively, for beams provided by vertical strips, inclined strips, trussed strips and equivalent trussed bars.

3. Based on the results of the experimental program it can be concluded that the beam reinforced with trussed steel strips showed the most enhanced shear performance from the viewpoint of both the ultimate capacity and the developed major shear crack width.

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