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Experimental Study of the Structural Behavior of RC Box Girder with Steel Plates Strengthening and Different Shapes of Cells

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ABSTRACT

The aim of this research is to study the effect of corrugated steel plate strengthening on the structural behavior of reinforced concrete box girder using corrugated steel plates with vertical and horizontal corrugation and studying the effect of the shape of cells using rectangular and circular shape with the same web width and strengthening the circular cell with flat plate. Five simply supported reinforced concrete box girders are casted using Self-compacting concrete and experimentally tested under four-point load. The box girder specimens are divided into two groups according to the steel strengthening and the shape of cells. The experimental results showed that in the first group, the using of the vertical and horizontal corrugated steel plates strengthening increased the ultimate load by (7.14% and 11.03%) respectively compared with the control box girder, and decreased the crack width, the results also showed that in the second group, the using of circular cell and circular strengthened cell increased the ultimate load by (17.85% and 29.22%) respectively compared with the control box girder with rectangular cell and decreased the crack width. All the box girders in the first and second group failed with diagonal shear.

1. Introduction

The box girder is a very commonly used structural member, it consists of two or more webs that either vertical or inclined, connected with top and bottom flanges to produce the single-cell or multi-cell box girder with rectangular or trapezoidal cross-section [1]. The un necessary materials are removed out of the section in order to reduce the dead load, which result the shape of the box girder or the cellular structure. The formed closed cell has a very greater torsional stiffness and strength compared with the open section which is the usual reason for choosing the box girder [2]. The geometry of the box girder is characterized by its strength to the positive and negative bending moments [3]. The web of box girder can be relatively thin in order to reduce the deadweight [4].

The span range for the box girder bridge is more compared with the T-beam girder bridge, hence, less requirement for support points which results to make the box girder more economical [2]. The box girder bridges are chosen for the span range from (20m to 40m) for reinforced concrete bridges and (40m to 100m) for the prestressed concrete bridges [5].

The objective of this work is studying the effect of using corrugated steel plate strengthening on the structural behavior of reinforced concrete box girder using corrugated steel plates with vertical and horizontal corrugation, and studying the effect of the shape of cells using rectangular and circular shape and strengthening the circular cell with flat plate.

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2. Previous studies

There are many previous studies that related to this work, Abeer, et al. (2013) [6] predicted a new analytical method to surmise the behavior and the torsional capacity of the reinforced concrete multi-cell box girder with CFRP sheets strengthening, the study modified the softened truss model with the proposed method. Ezeokpube, et al. (2015) [7] presented a numerical and experimental modelling for the static response of simply supported thin-walled reinforced concrete box girder bridges. The study included six reinforced concrete box girder bridges with the same dimensions of (3220mm) length, (322mm) height and (500mm) bottom flange width with different top flange width, this work was carried out in order to verify the validity of the software for the finite element, and also to study the effect on the flange width on the response of the box girder bridge. The results showed a very good agreement between the experimental and software results, the results also showed that the effect of the shear deformation increase with the increase of the flange width. Waryosh, et al. (2015) [8] presented an experimental study of the torsional behavior of reinforced concrete hollow cores, the study included eight rectangular beams with the same dimensions of (2000mm) length, (170mm) width and (240mm) height. The beams are with solid and hollow sections that varied in the shape and the percentage (circular18%, rectangular 18% and circular 27%) of the total cross section area of the beam. Chen, et al. (2019) [9] studied the shear lag effect in details of the composite box girder bridge with a corrugated steel webs and trusses, the study contained two specimens with span length of (8744mm) for each, the study results showed that the most important parameter of the shear lag-effect is the width-to-span ratio of the studied structure, a small width-to-span ratio should be taken to avoid the severe shear-lag effect, the shear-lag effect magnitude of this structure increase with the suspension ratio. Ali Laftah Abbas and Qassim Yehya Hamood (2018) [10] Presented a finite element study of modelling existed composite bridge in Iraq, the bridge was simulated by using a real dimension in order to examine the connectors performance and strengths performance of the composite girder under the worst static load condition. Hadeer Ahmed and Ali Laftah (2020) [11] studied the effect of replacing the traditional stirrups by shear steel plates with vertical and inclined rectangular holes under repeated and Monotonic Loadings.

3. Experimental program

3.1. Testing specimens

The experimental program consists of casting and testing five simply supported reinforced concrete box girders using Self-compacting concrete. The specimens are divided into two groups according to the shape of cells (rectangular and circular) and the strengthening type (vertical and horizonal corrugated steel plates), all the specimens are with the dimensions presented in Table.1 and with solid ends with thickness of (150mm).

Table 1. The dimensions of the box girder specimens

Top flange width (mm)	420
Bottom flange width (mm)	270
Web width (mm)	60
Flange thickness (mm)	60
Total height (mm)	320
Total span length (mm)	1500

All the box girders are reinforced with main reinforcement of 3Ø12 and shear reinforcement of Ø8@170mm, all the dimensions and reinforcement details are shown in Fig.1 to Fig.6 The first box girder (BRVS) is the control specimen for both of the two groups, which is a conventional box girder with rectangular cell without strengthening, the first group contains two box girder specimens, the box girder (BSPSVC) which contains vertical corrugated steel plate strengthening and the box girder (BSPSHC) which contains horizontal corrugated steel plate strengthening, the second group contains the box girder (BCC) which is with circular cell and the box girder (BCCSPS) with circular cell strengthened with flat steel plate. The details of all the specimens are presented in Table2.

Table 2. Details of the specimens

Specimen designation	Designation	Strengthening type	Shape of cell
BRVS	**B**ox girder with **R**ebar **V**ertical **S**tirrups	No strengthening	Rectangular
BSPSVC	**B**ox girder with **S**teel **P**late **S**trengthening with **V**ertical **C**orrugation	Vertical corrugated steel plate	Rectangular
BSPSHC	**B**ox girder with **S**teel **P**late **S**trengthening with **H**orizontal **C**orrugation	Horizontal corrugated steel plate	Corrugated
BCC	**B**ox girder with **C**ircular **C**ell	No strengthening	Circular
BCCSPS	**B**ox girder with **C**ircular **C**ell and **S**teel **P**late **S**trengthening	Flat Steel plate	Circular

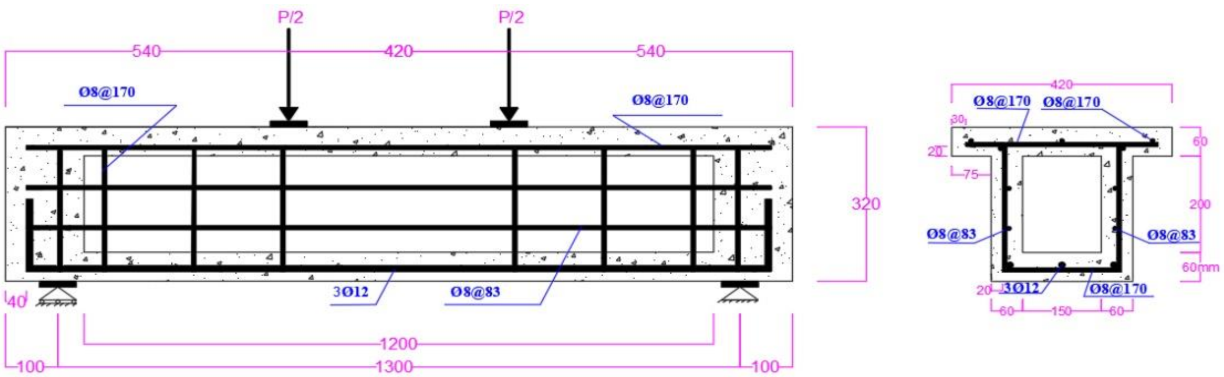


Figure 1. Dimensions and reinforcement detailes of (BRVS) (all units are in mm)

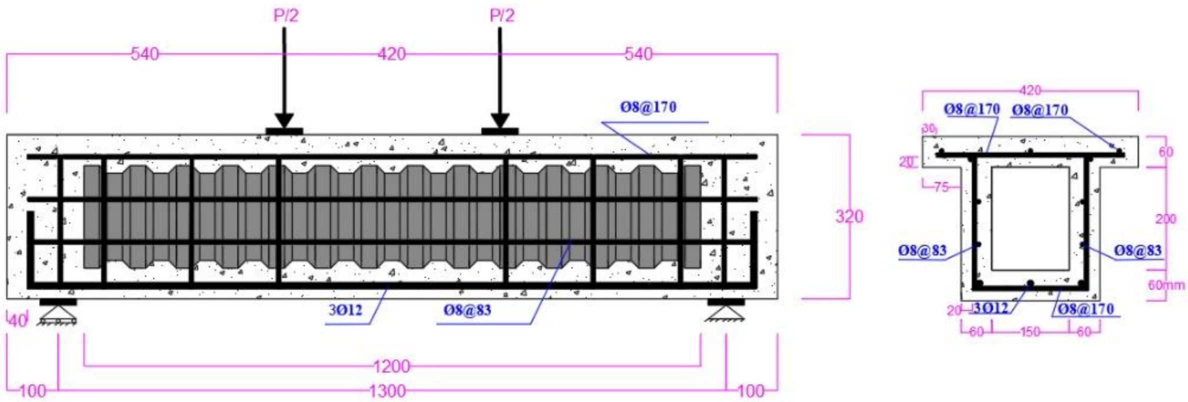


Figure 2. Dimensions and reinforcement detailes of (BSPSVC) (all units are in mm)

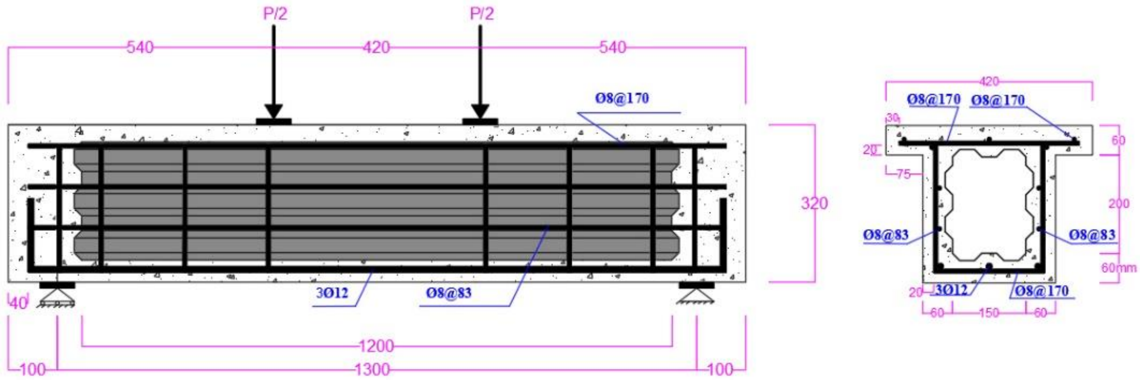


Figure 3. Dimensions and reinforcement detailes of (BSPSHC) (all units are in mm)

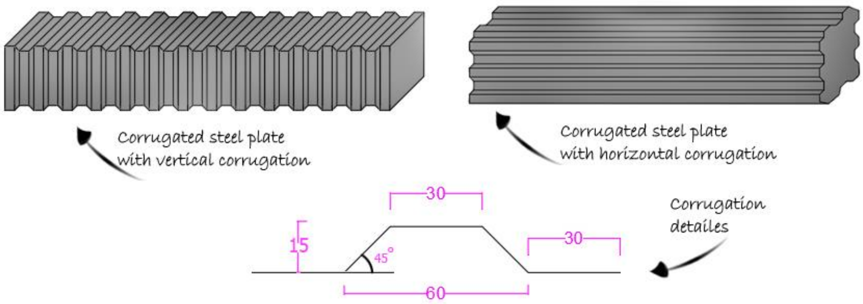


Figure 4. The details of vertical and horizontal corrugated steel plates (all units are in mm)

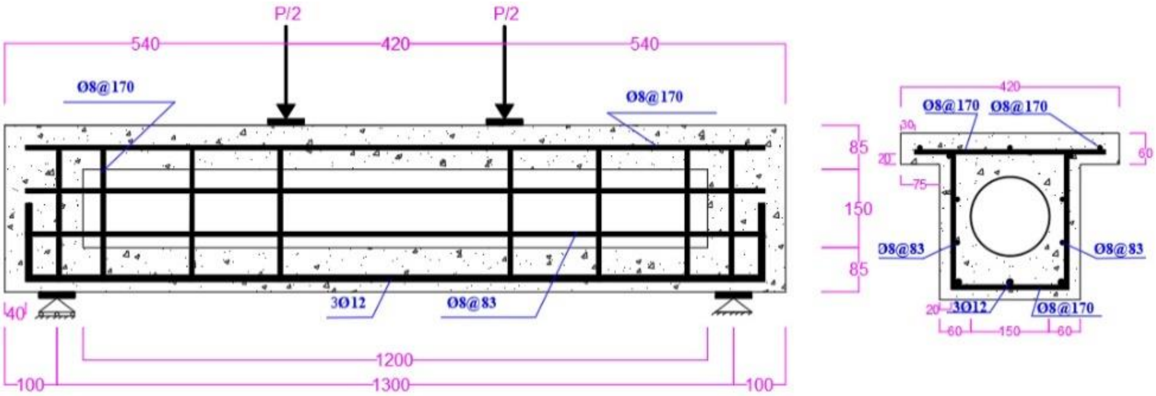


Figure 5. Dimensions and reinforcement detailes of (BCC) (all units are in mm)

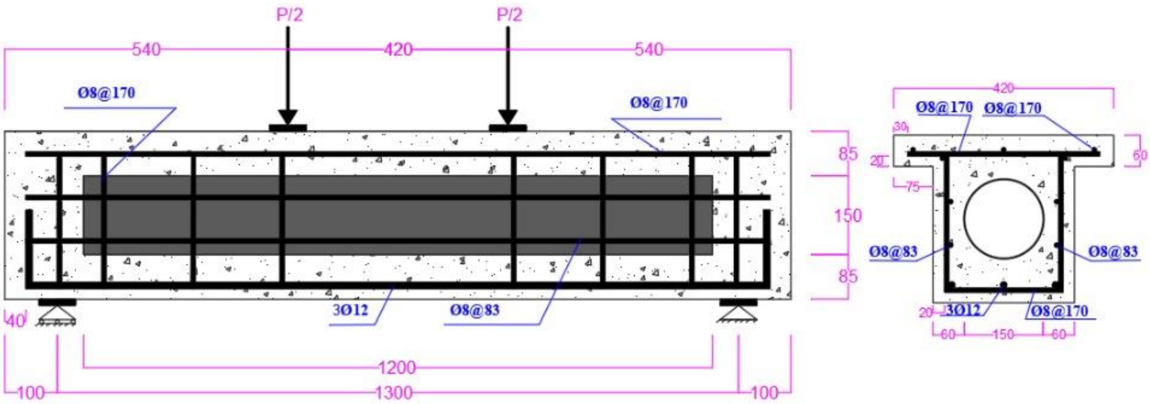


Figure 6. Dimensions and reinforcement detailes of (BCCSPS) (all units are in mm)

3.2. Materials

In this work, SCC with compressive strength of f_c'=(25Mpa) is used to cast all the testing box girder specimens, ordinary Portland cement, fine aggregate, coarse aggregate with 10mm maximum size of particles, limestone powder, tap water and High-Performance Superplasticizer Concrete Admixture (HPSCA) that known commercially as “Sika Viscocrete 5930” are used in the concrete mix, Table3. presents the mixing proportions of the concrete. The deformed steel bars that used to reinforce the specimens are steel bar with diameter of (12mm) and yield stress of (566MPa), steel bar with diameter of (8mm) and yield stress of (541MPa). The steel plates that used are corrugated steel plates with thickness of (0.8mm) and yield stress of (290MPa) and flat steel plate with thickness of (2.7mm) and yield stress of (279MPa).

Table 3. The mix proportions of the concrete

Cement (Kg/m^3)	**Sand (Kg/m^3)**	**Gravel (Kg/m^3)**	**Limestone (Kg/m^3)**	**Water (Kg/m^3)**	**Superplasticizer (L/m^3)**
430	760	700	200	218	3.6

3.3. Testing procedure

The testing process are carried out after 28 days from the casting of specimens, the specimens are painted with white in order to make it easier to observe the crack development during the test. The specimens are place on the testing machine and simply supported at the ends over span of (1300mm) center-to-center of the supports, all the specimens are subjected to four-point load. LVDT is attached in the center of the bottom of the specimens to measure the vertical deflection at one central point. Ultimate loads, crack patterns, load-deflection, tensile strain and concrete compressive strain will be studied in this study. All the specimens are tested by using laboratory testing machine of structural laboratory of engineering college of Diyala University.

4. Results and discussions

The results of five simply supported reinforced concrete box girder specimens with SCC with the same dimensions divided into two groups are presented and discuessed.

4.1 Ultimate load capacity

The results of the tested box girder specimens of this group are listed in Table4. For the first group, the results show that there is increment in the ultimate load of the specimens (BSPSVC and BSPSHC) by (7.14% and 11.03%) respectively compared with the specimen (BRVS), This increment is due to the use of steel plates strengthening. It can be noticed that horizontal corrugated steel plate enhanced the ultimate more than the vertical corrugated steel plate by (3.63%).

For the second group, the results show that there is increment in the ultimate load of the specimens (BCC and BCCSPS) by (17.85% and 29.22%) respectively compared with the specimen (BRVS), This increment is due to the use of circular cell because the stress in the circular shape cell is equally distributed and acts as uniform while the stress distribution in the rectangular shape cell is more concentrated in the corners, also, the volume of concrete increased in the specimens with circular cell which lead to increase the stiffness due to the increase in the moment of inertia, finally, it is also due to the using of steel plate strengthening in the specimen (BCCSPS). The using of the steel plate strengthening lead to increase the ultimate load of the specimen (BCCSPS) by (9.64%) compared with the specimen (BCC).

Table 4. The experimental results of the tested box girders

Name of specimen	P_y[a] (kN)	% diff. in P_y	Δ_y [b] (mm)	% diff. in Δ_y	P_u [c] (kN)	% diff. in P_u	Δ_u [d] (mm)	% diff. in Δ_u	Ductility	% diff. in ductility	Mode of failure
BRVS	240	---	5.298	---	308	---	8.977	---	1.694	---	Diagonal shear
First group											
BSPSVC	268	11.66	7.857	48.3	330	7.14	9.957	10.91	1.267	-25.2	Diagonal shear
BSPSHC	318	32.5	8.399	58.5	342	11.03	9.211	2.60	1.096	-35.3	Diagonal shear
Second group											
BCC	272	13.33	7.194	35.78	363	17.85	14.678	63.5	2.040	20.42	Diagonal shear
BCCSPS	371	54.58	9.622	81.61	398	29.22	12.007	33.75	1.247	-26.38	Diagonal shear

where: [a]Py: Yield load
[b]Δy: The displacement at yield load
[c]Pu: Ultimate load
[d]Δu: The displacement at ultimate load

4.2. Crack pattern and mode of failure

In the first group, the first visible flexural crack appeared at the mid span of the box girder at (17.2%, 18.18 and 11.69%) from the ultimate load of (BRVS, BSPSVC and BSPSHC) respectively, the crack width which measured by using optical micro-meter decreased compared with (BRVS) as presented in Fig.7(a), this decrement in the crack width is the due to the using of corrugated steel plates strengthening.

In the second group, the first visible flexural crack appeared at the mid span of the box girder at (17.2%, 19.3 and 20.1%) from the ultimate load of (BRVS, BCC and BCCSPS) respectively. In the specimens (BCC and BCCSPS), the crack width decreased for the same load compared with (BRVS) as presented in Fig.7(b), this decrement is due to the use of circular cell which led to distribute the stresses uniformly, and the increase in the stiffness, also due to the use of steel plate in the specimen (BCCSPS). All the specimens in the first and second group failed with diagonal shear as shown in Fig.8 to Fig.12.

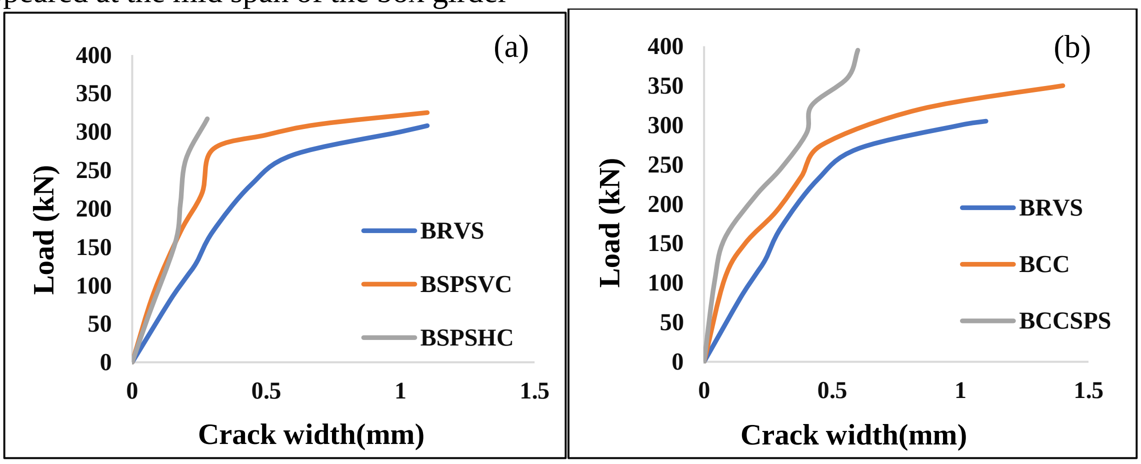


Figure 7. Crack width-load relationship (a) Group one (b) Group two

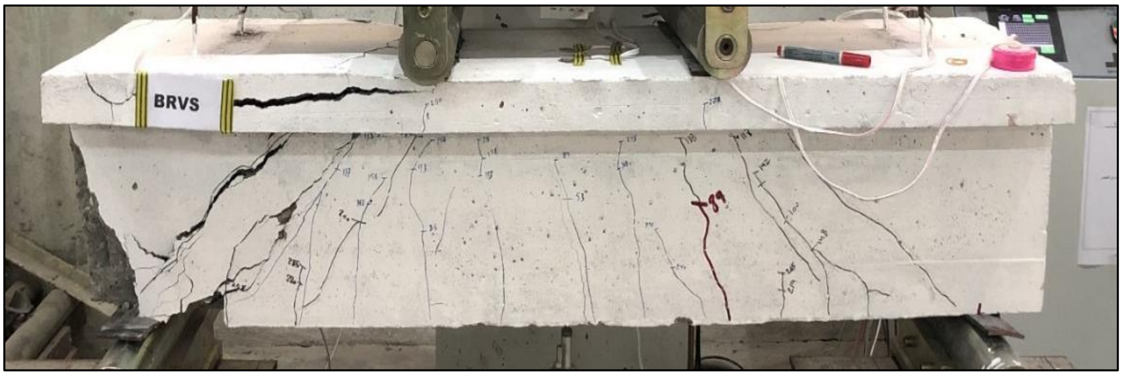


Figure 8. Failure mode of box girder (BRVS)

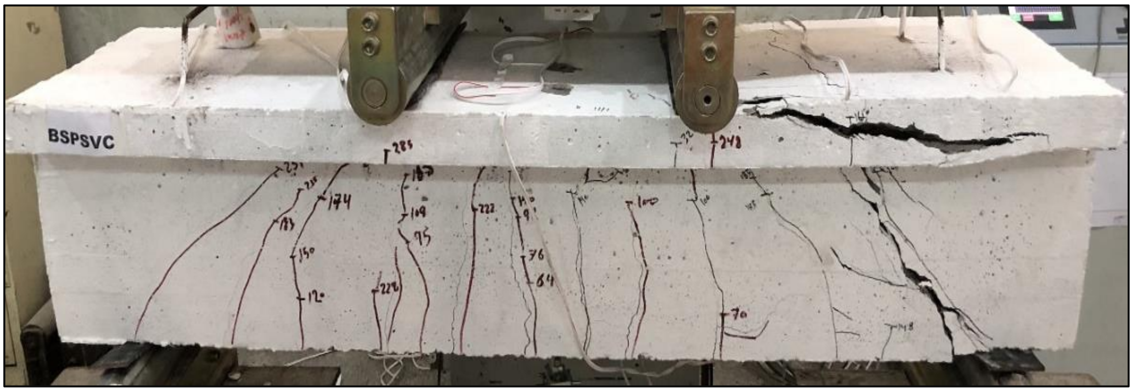


Figure 9. Failure mode of box girder (BSPSVC)

Figure 10. Failure mode of box girder (BSPSHC)

Figure 11. Failure mode of box girder (BCC)

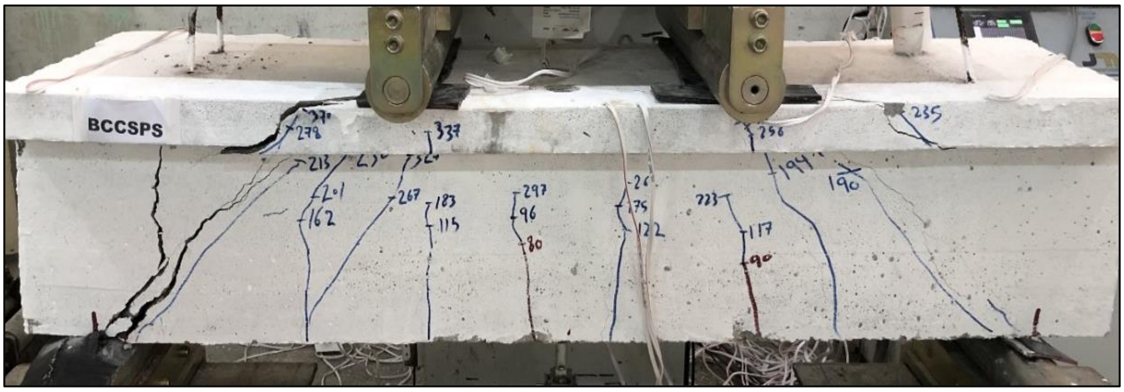


Figure 12. Failure mode of box girder (BCCSPS)

4.3. Deflection

The experimental data of UTM-LST VFE-2 model at high angle of attack is presented here. More experiments are needed to verify this complicated flow topology.

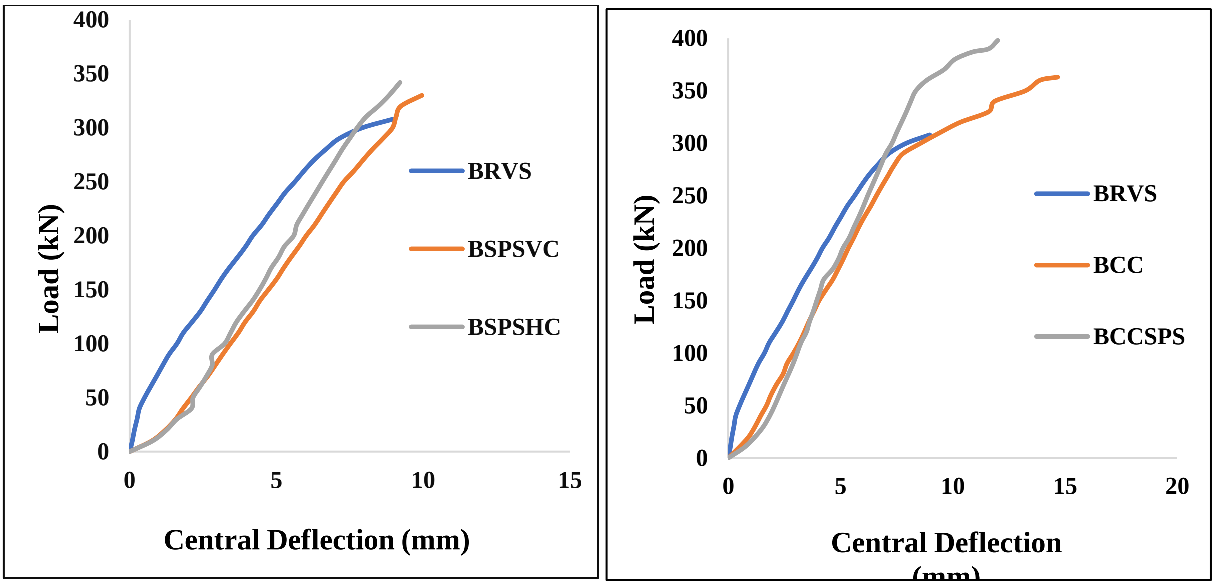


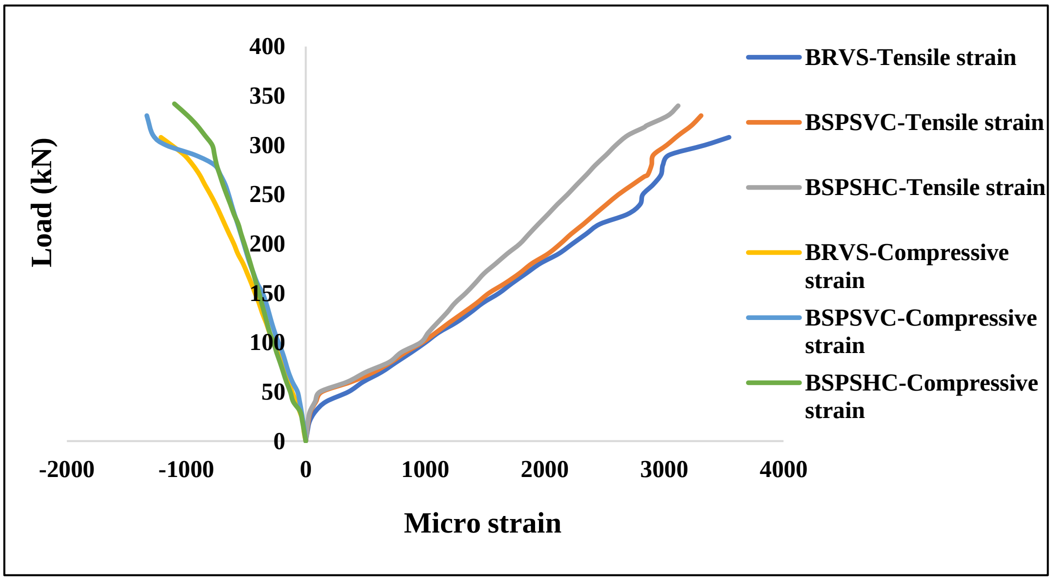
Figure 13. Deflection-load relationship (a) First group (b) Second group

4.4. Strain

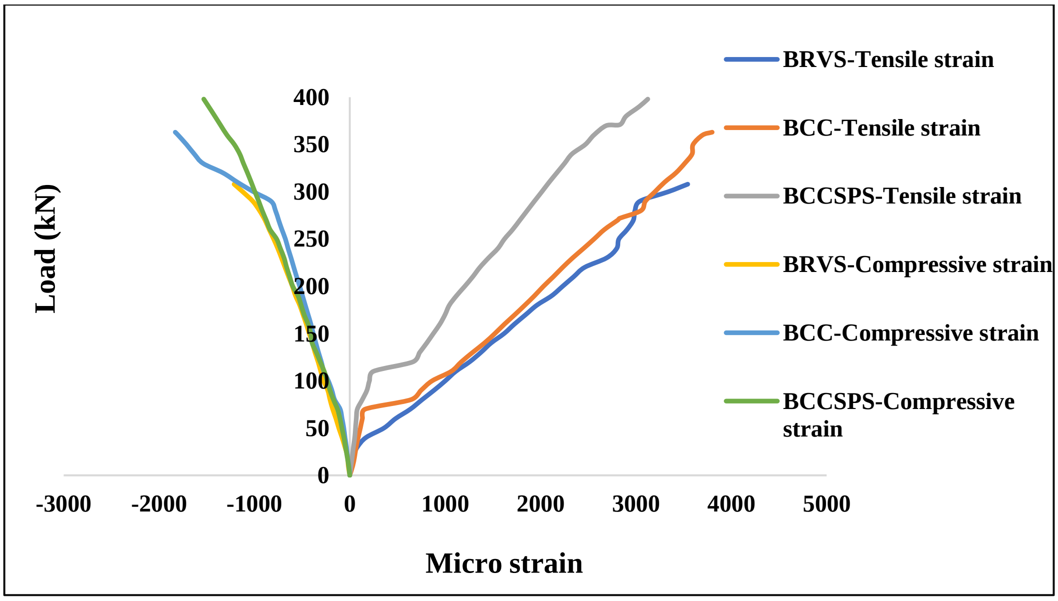
The strains are measured by using electrical resistance strain gauges fixed at the middle of the top of concrete face, and the middle of the intermediate bottom of the intermediate longitudinal reinforcement bar. The strain-load relationship for the first and second group are shown in Fig.14.

For the first group, the tensile strain and the concrete compressive strain for the specimens (BSPSVC and BSPSHC) is less than in the specimen (BRVS) at the same load of (70%) from the ultimate load of the control specimen (BRVS). In comparison with the control box girder (BRVS), the tensile strain at the ultimate load for the specimens (BSPSVC and BSPSHC) decreased by (6.6% and 12.02%) respectively, and the concrete compressive strain at the ultimate load for the specimen (BSPSHC) decreased by (9.31%), while it increased in the specimen (BSPSVC) by (9.72%), this increment id due to the increase in the ultimate load.

For the second group, the tensile strain and the concrete compressive strain for the specimens (BCC and BCCSPS) is less than in the specimen (BRVS) for the same load of (70%) from the ultimate load of the control box girder (BRVS). Compared with the control specimen (BRVS), the tensile strain at the ultimate load for the specimen (BCC) increased by (7.22%), this increment is due to the increasing in the ultimate load, while in the specimen (BCCSPS), the tensile strain at the ultimate load decreased about (11.82%), the concrete compressive strain at the ultimate load for the specimens (BCC and BCCSPS) increased by (50.86% and 26.21%). All the steel plates in the first and second group did not reach the yield strain.



(a) First group



(b) Second group

Figure 14. Strain-load relationship

5. Conclusions

1. The ultimate load of the box girder strengthened by vertical and horizontal corrugated steel plate increased by (7.14% and 11.03%) respectively compared with the control box girder, also, the ultimate load of box girder with rectangular cell with horizontal corrugated steel plate is more than in box girder with rectangular cell with vertical corrugated steel plate by (3.63%), which indicates that the horizontal corrugated steel plates is more efficient.
2. The ultimate load of the box girder with circular cell and the box girder with circular cell with steel plate strengthening increased

by (17.85% and 29.22%) respectively compared with the control box girder with rectangular cell, which gives the indication that using circular cell lead to increase the load capacity of the box girder for the same web thickness, also, the ultimate load of the box girder with circular cell with steel plate strengthening is more than in box girder with circular cell without strengthening by (9.64%).

3. The crack width of the box girder with corrugated steel plate strengthening decreased compared with the control box girder.
4. The crack width decreased in the box girder with circular cells with and without steel strengthening compared with the control box girder with rectangular shape.
5. The deflection of the box girder with corrugated steel plate strengthening is less than the control box girder for the same load.
6. The ultimate deflection of the box girder strengthened by vertical and horizontal corrugated steel plate increased by (10.916% and 2.6%) respectively compared with the control box girder.
7. The deflection of the box girder with circular cell and the box girder with circular cell with steel plate strengthening is more than in the control box girder with rectangular cell for the same load, also, the ultimate deflection of these box girders increased by (63.5% and 33.7%) respectively compared with the control box girder with rectangular cell.
8. The steel tensile strain and concrete compressive strain in the box girders with vertical and horizontal corrugated steel plates are less than in the control box girder for the same load.
9. The steel tensile strain and concrete compressive strain in the box girder with circular cells with and without steel strengthening are less than in the control box girder with rectangular shape at the same load.

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