Shear Strengthening of Composite Concrete Steel Plate Girders with Web Openings Using Steel Strips

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Abstract. The study aims to investigate behaviour plus influence on the final load resistance of strengthen girders containing openings in web which were 40\% of web height. This paper presents an experimental study of applying of five steel-concrete composite plate girder specimens that were loaded in shear predominantly. Three of those girders were considered as control girders, without web openings, containing circular web holes, and containing square web holes, respectively. Other two girders were strengthen girders. The slab reinforcement, dimensions of girders and compressive strength of concrete slabs were constant. Strengthening was made by using steel rings and strips which were welded to webs of strengthen girders to investigate influence of strengthening plan by steel welding on behaviour and final load strength for these girders. Findings illustrate increasing in final load strength of strengthen girders with circular and square web holes with about 57.38\% and 43.75\%, respectively in comparing to that for control girders. Moreover, the final shear capacity for the tested girders was also compared with that predicted by von Mises stresses.

Keywords: Composite Steel-Concrete; Shear Strength; Strengthening; Strengthening Steel; Web Openings.

1. Introduction

In new bridges and structures and, great ducts used in air-condition system, sewage pipes, electric cables, sanitary pipes and other services requirement to be providing. However, to provide such services, an unacceptably great structure height between floors is required. To solve this difficult, the web holes’ requirements to be prepared in every web of girders. This assistance extends pipes of services and decrease height of floor. Where, such holes of web change stress distribution in web of girders and finally decrease the bending and shear resistance of girders [1, 2, 3]. The advantage of steel-concrete composite beams is the high tensile strength of steel that has been combined with the high concrete compressive strength [4]. Using of concrete-steel composite beams with regular web-holes had been in increasing in structure of multi-story buildings [5,6]. In highway bridges and ship structures, the web holes are provided in girders in order to decrease the structure weight and to provide the space for services and maintenance [7-8]. Several investigation studies were accompanied with use of (CFRP) compound in together repairing and strengthening for webs of girders. These accompanied studies were concentrated on use of CFRP for girders with bending or axial stresses. As far as the studies on repairing and strengthening of webs of girders using CFRP were concerned, they were stated little. In the design of composite bridge plate girders containing openings in web taking into consideration the examination of effect of the holes in steel plate web on performance of the composite plate girders [9]. In 1997, Hassan [10] studied the behavior and resistance of composite girders containing web hole reinforced with strip loaded in shear predominantly confirming that reinforcement of web around hole is necessary to restore the resistance loss due to the presence of hole. Stiffening plates around web hole may increase the composite couple and hence increase the resistance of the beam beyond that of the basic composite beam without web hole.
2. Experimental program

In this investigation, five composite girders were simply supported, these girders had been tested to study of behaviour plus influence on final load strength for strengthen girders by steel plates, and they have steady positions and dimensions for web holes, where height of web holes was (240 mm). There are two kinds of composite girders had been using. The first kind is control girders that they are one girder has not web holes (CPG1), and two other girders contain circular, and square web holes were (CPG3) and (CPG2) respectively. Other type includes two girders that they strengthened by steel plates containing circular and square web holes are (CPG5) and (CPG4) respectively. All girders containing constant dimensions, where, they had been testing under one-point load in middle span at top of girder as illustrated at Figure (1) and Table (1). Depth of concrete slab and girder was using so as to study failure of shear. Concrete slab had been reinforced by two layers of diameter (6 mm) welded wire mesh containing spacing (150 mm) in two directions. The details for shear stud connector are satisfying to Euro code 4 limits [11] provisions as illustrated at Figure (2) and Table (2).

| Table 1. Details for Composite Girders (mm) |
|-------------------------------------------|
| GIRDERS | CPG1 | CPG2 | CPG3 | CPG4 | CPG5 |
|---------|------|------|------|------|------|
| Concrete Slab Width (hc) (mm) | 500  |      |      |      |      |
| Concrete Slab Thickness (h) (mm) | 150  |      |      |      |      |
| Concrete Slab Cover (Re) (mm) | 25   |      |      |      |      |
| Steel Flange Thickness (tf) (mm) |      | 10   |      |      |      |
| Steel Flange Width (hf) (mm) |      | 125  |      |      |      |
| Steel Web Thickness (tw) (mm) |      | 2    |      |      |      |
| Height of Steel Web (hw) (mm) |      | 600  |      |      |      |
| Bearing Stiffeners Thickness (ths) (mm) |      | 15   |      |      |      |
| Intermediate Stiffener Thickness (tit) (mm) |      | 20   |      |      |      |
| Depth of Steel Plate Girder (D of SPO) (mm) |      | 620  |      |      |      |
| Steel Web Panel Width (bw) (mm) |      | 600  |      |      |      |
| Height of Rectangular Opening (ho) (mm) |      | 240  |      |      |      |
| Diameter of Circular Opening (d) (mm) |      | 240  |      |      |      |

| Table 2. Details for Shear Stud Connector |
|------------------------------------------|
| Head diameter (B) (mm) | 28 |
| Head thickness (mm) | 8  |
| Stud diameter (d stud) (mm) | 16 |
| Stud total length (mm) | 100 |
| Stud stem length (G) (mm) | 92 |
| Stud longitudinal spacing (mm) | 100 |
| Stud transverse spacing (Str) (mm) | 65 |
3. Methods of Strengthening

**Kind1**: includes the strengthening for girder web (CPG5) by rings from steel plates with (4mm) thickness and (75mm) width at both sides of girder. At first side, one ring from steel plates had been welded around hole of web for every web panel in girder. At second side, for every web panel in girder, one ring from steel plates had been fixed around hole of web, as illustrated at Figure (3).

**Kind2**: includes strengthening for web of girder (CPG4) with using strips of steel plates with (4mm) thickness, (75 mm) width and (600 mm) length for both sides of girder. In first side, two strips from steel plates were fixed in parallel of flanges for every web panel in girder. At second side, for every web panel in girder, two strips from steel plates had been fixed in perpendicular to flanges, as illustrated at Figure (4).
4. Properties of Hardened and Fresh Concrete

Normal concrete in fresh case have slump (90mm) according to (ASTM C-143) [12]. At hardened case of concrete, compression resistance for cubes of size (150 mm) was (50.77 MPa) according to (BS1881) [13], splitting tension resistance for cylinders of size (150*300 mm) was (4.11 MPa) according to (ASTM C496) [14], as illustrated at Figure (5).

Table 3. Properties for Steel Components

| Component                      | Dimension (mm) | Yield Stress (MPa) | Ultimate Tensile Stress (MPa) |
|--------------------------------|----------------|-------------------|-------------------------------|
| Flange                         | 10 Thickness   | 391               | 425                           |
| Web                            | 2 Thickness    | 426               | 556                           |
| Intermediate stiffener         | 20 Thickness   | 301               | 419                           |
| Bearing stiffeners             | 15 Thickness   | 373               | 522                           |
| Steel plates for strengthening  | 4 Thickness    | 414               | 502                           |
| Wire mesh reinforcement        | 6 Diameter     | 543.86            | 569.5                         |
| Shear stud Connectors          | 16 Diameter    | 488               | 532                           |

Figure 4. Kind (2) for Strengthening (CPG 4) Girder

Figure 5. Compressive Strength plus Slump Test

Figure 6. Test of Tension Strength for Steel
5. Test Method and Equipment

Every one of girders is simply supported by pin (hinge) and roller across span (1200mm). Upper limit of load capability for test device (Avery) was 160 Ton. The composite girders were tested until mode of failure under influence applying load in centre span at top of girder, notice Figure (7). Central deflection for girders had been measured by dial gauge with accuracy (0.01) which was mounted in centre span beneath bottom flange for girder. In concrete slab, where the patterns for cracks plus load of initial crack had been indicated through the testing.

6. Evaluation of ultimate shear strength [2,19,20,21]

6.1. Composite girders without web hole:

Shear strength for concrete slab, $V_{cs}$:

$$V_{cs} = 0.79 \times b \times d_c \times \left( \frac{100 \times A_{rs}}{b \times d_c} \right)^{\frac{1}{3}} \times \left( \frac{400}{d_c} \right)^{\frac{1}{4}} \times \left( \frac{f_{cu}}{25} \right)^{\frac{1}{2}}$$  \hspace{1cm} (1)

Compute the pull–out strength for group of adjacent shear connectors existing on one face from plastic hinge at top flange of girder, $T_{gr}$:

$$T_{gr} = (\pi (B + (G - R_c) \times \cot \theta) + 2S_{t_d}) (G - R_c) \times \sigma_{ct} \times \cot \theta$$  \hspace{1cm} (2)

Compute the vertical shear interaction degree, $\gamma$:

$$\gamma = \frac{T_{gr}}{V_{cs}} \leq 1 \quad \text{and} \quad \nu_c = \gamma \times V_{cs}$$  \hspace{1cm} (3)

Inclination for web panel diagonal, $\theta_d$:

$$\theta_d = \tan^{-1} \left( \frac{h_w}{b_w} \right)$$  \hspace{1cm} (4)

The shear buckling coefficient, $k$:

$$k = 5.35 + 4 \left( \frac{h_w}{b_w} \right)^2 \quad \text{when} \quad \frac{b_w}{h_w} \geq 1$$  \hspace{1cm} (5)

$$k = 5.35 \left( \frac{h_w}{b_w} \right)^2 + 4 \quad \text{when} \quad \frac{b_w}{h_w} \leq 1$$

Elastic critical stress to be:

$$\tau_{cr} = k \times \frac{\pi^2 \times E}{12(1 - \nu^2)} \times \left( \frac{t_w}{h_w} \right)^2$$  \hspace{1cm} (6)

The tension membrane stress, $\sigma_{yt}$, by using Von–Mises yield principle:

![Figure 7. Setup of Testing for Composite Girder](image-url)
The distance of hinge in bottom and top flanges, $C_t$ and $C_b$:

$$C_t = J + \left( J^2 + \frac{2}{D} (M_{pt} + M_{cu}) \right)^{\frac{1}{2}} \quad \text{for } \gamma = 1 \quad (13)$$

$$C_b = \frac{2}{\sin \theta} \left( \frac{M_{pb}}{\sigma_{yt} * t_w} \right)^{\frac{1}{2}} \quad \text{for } 0 < \gamma \leq 1 \quad (14)$$

The final shear resistance for composite girder for any selected $\theta$, $\nu_{ult}$:

$$\nu_{ult} = \tau_{cr} * t_w * h_w + \sigma_{yt} * t_w * \sin^2 \theta (C_t + C_b) + \sigma_{yt} * t_w * h_w * \sin^2 \theta (\cot \theta - \cot \theta_d) + \gamma * \nu_{cs} $$

6.2. Composite girders containing circular holes in web:

$$k_m = k_b \left( 1 - \frac{d}{h_w} \right) $$

$$k_b = 8.98 + 5.6 \left( \frac{h_w}{b_w} \right)^2 \quad \text{when } \frac{b_w}{h_w} \geq 1 \quad (17)$$

$$k_b = 8.98 \left( \frac{h_w}{b_w} \right)^2 + 5.6 \quad \text{when } \frac{b_w}{h_w} \leq 1 \quad (18)$$

d: Diameter of the hole with using the residual laws above used for unperforated composite girder.

6.3. Composite girders containing square holes in web:

$$d^* = b_0 \sin \theta + h_0 \cos \theta \quad (19)$$

: is effective width for hole.

$$k_m = k_b \left( 1 - \frac{d^*}{h_w} \right) $$

$$\theta_m = 0.75 \theta_d * \left( 1 - 0.71 \frac{d_g}{h_w} \right) $$

$\theta_m$: is angle of tensile field of plates containing central rectangular holes.

d$_{g}^*$: is the diagonal for rectangular hole ($d_g = (b_0^2 + h_0^2)^{0.5}$)

With using of residual laws above used for composite girder no containing hole.
6.4. Proposed for Strengthening of Composite girders containing circular and square holes in web:

\[ D_v = \left( \frac{E_s \cdot t_w^3}{12(1 - \nu_s^2)} + \frac{2E_{f0}}{3(1 - \nu_{f0}^2)} \left( \frac{t_w^3}{2} + t_{f0} \right) - \left( \frac{t_w}{2} \right)^3 \right) 
+ \frac{2E_{f1}}{3(1 - \nu_{f1}^2)} \left( \frac{t_w^3}{2} + t_{f0} + t_{f1} \right) - \left( \frac{t_w}{2} + t_{f0} \right)^3 
+ \frac{2E_{f2}}{3(1 - \nu_{f2}^2)} \left( \frac{t_w^3}{2} + t_{f0} + t_{f1} + t_{f2} \right) - \left( \frac{t_w}{2} + t_{f0} + t_{f1} \right)^3 \right) \]

\[ \tau_{cr-m} = k_m \cdot D_v \cdot \frac{\pi^2}{h_w^2(t_w + 2t_{f0} + 2t_{f1} + 2t_{f2})} \]  

7. Results and Discussion

every one of girders was failed in shear predominantly, failure mode was diagonal splitting at concrete slab of composite girders whereas it was buckling at the web, after that forming the plastic hinges in top and bottom steel flanges. Composite girders (CPG1) without web holes and (CPG3) with circular web holes were control girders. After that, the girder (CPG5) with circular web holes and strengthened by steel rings. The findings illustrate that existence of circular holes in web reduces ultimate load resistance to 26.25%, and it increases deflection to 28.02%. The girder (CPG5) which was strengthened by steel rings, as illustrated at Kind 1 from strengthening, this composite girder illustrates increasing stiffness and ultimate load resistance with 57.38% in comparing to (CPG3), and it has decrease in deflection with 39.72% comparing with (CPG3), as illustrated at Figure (8). Girders (CPG1) without web holes and (CPG2) with square web holes were control girders, as well as the girder (CPG4) with square web holes had been strengthened by steel strips. The findings show that square holes in web decreased ultimate load resistance to 28.57%, and they increased deflection to 68.73%. The girder (CPG4) that it strengthened by steel strips as illustrated at Kind 2 from strengthening, this composite girder illustrates increasing stiffness and final load resistance than that for (CPG2) with 43.75%, and it has decrease in deflection with 46.31% comparing with (CPG2), as illustrated at Figure (9). Figure (10) shows mode of failure for girders. The comparing between the theoretical and experimental findings were studied. Furthermore, ultimate load strength was comparison to control girder, as illustrated at Table (6).
Figure 9. Load–Deflection Curve for the Girders (CPG 1), (CPG 2) and (CPG4)

A. Control Composite Girder (CPG1)

B. Girder with Square Web Holes (CPG2)

C. Strengthened Girder Containing Square Web Holes (CPG4)

D. Girder Containing Circular Web Holes (CPG3)

E. Strengthened Girder Containing Circular Web Holes (CPG5)

Figure 10. Composite Girders After Failure
Conclusions

1- Every one of strengthened girders show increase in ultimate load strength comparing to their control girders in a range (43.75% to 57.38%) for girders with square and circular web holes respectively.

2- Composite strengthen girders show higher stiffness and decreasing in values of deflection in range of 39.72% to 46.31% comparing to their control girders.

3- Final load resistance decreases in range 26.25% to 28.57% for composite girders containing circular and square holes in web respectively in comparing to the girder not containing holes in web.

4- The theoretical predictions achieved by von Mises stresses had been agreed to experimental findings.

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Table 4. The Experimental and Theoretical Findings of Final Load Resistance for Composite Girders in Comparing to Control Girders

| Girder | Pult (Ton) (Theoretical) | Pult (Ton) (Experimental) | Increase In Ult. Load Comparing to Their control (%) | Decrease in Ult. Load Comparing to CPG1 (%) |
|--------|--------------------------|---------------------------|---------------------------------------------------|------------------------------------------|
| CPG 1  | 55.40                    | 56                        | -                                                 | -                                        |
| CPG 2  | 29.42                    | 40                        | -                                                 | 28.57                                    |
| CPG 3  | 36.19                    | 41.3                      | -                                                 | 26.25                                    |
| CPG 4  | 50.53                    | 57.5                      | 43.75                                              | -2.67                                    |
| CPG 5  | 64.36                    | 65                        | 57.38                                              | -16.07                                   |
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