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BENDING CAPACITY OF COMPOSITE COLD-FORMED STEEL AND CONCRETE OF A STRIP PLATE STRUCTURE

S. Haris
Department of Civil Engineering, Andalas University, Padang – 25163, Indonesia

Zaidir
Department of Civil Engineering, Andalas University, Padang – 25163, Indonesia

R. Thamrin
Department of Civil Engineering, Andalas University, Padang – 25163, Indonesia

L. Buthi
Department of Civil Engineering, Andalas University, Padang – 25163, Indonesia

ABSTRACT

This paper presents experimental and analytical studies of composite cold-formed steel and concrete of a strip plate structure. Observations were carried out for six specimens. The first three specimens were reinforced concrete structures as the reference to the other three specimens of composite cold-formed steel and concrete structure. All specimens had equal section width of 150 mm. There were three section depths, i.e. 80 mm, 100 mm, and 120 mm. The specimen was placed on the simple support and was subjected by two point loads which increased monotonically until ultimate condition reached. Flexural crack on the specimen were observed. Crash on the top fiber of composite specimen of 80 mm was found. Flexural crack on the concrete part and fracture on the cold-formed steel occurred on the specimen of 120 mm which caused the specimen split into two parts. Ultimate bending capacities of composite specimens from experimental test were compared to analytical calculations using RCCSA software. Good agreements were achieved between these two methods.

Keywords: Composite structure, Cold-formed steel, Bending capacity, Experimental test, Analytical study

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1. INTRODUCTION

Cold-formed steel has been used many years for residential building in various types of structural systems, i.e. roof truss, wall panel and floor system. For these applications, cold-formed steel elements were usually arranged in the form of truss structures. Use of cold-formed steel in different scheme, such as in composite cold-formed steel and concrete structures have also been studied by many researchers.

Performance of composite cold-formed steel and concrete beams has been investigated in [1] and it was found that the composite beams had good ultimate load carrying capacity and bond strength. Lip-channel section of cold-formed steel was determined as the most suitable one to be used for the composite beams. In [2], the channel sections with round embossments were used to improve the bonding characteristic between concrete and cold-formed steel. Based on 32 specimen test results, empirical formulas to predict the shear-bond strengths and the bending capacities were proposed. A new composite beam system was proposed in [3] that reinforced concrete slab on corrugated cold-formed metal deck was supported by a back to back cold-formed steel beam. On the contrary to cold-formed steel arrangement in [1] and [2], the channel section in inverted position was investigated in [4]. Beam capacities and failure conditions observed during experimental tests were well corresponded to the prediction if stand-off screws as shear connectors provided adequate resistance for composite action. Meanwhile, study of cold-formed steel and concrete for column elements have also been reported in [5, 6]. It was found that cold-formed steel could be used to replace the reinforcing bars.

In this study, bending behavior of composite cold-formed steel and concrete was investigated for a strip plate structure. The strip plate structures had section depth of 80, 100, and 120 mm; these depths were in the range of thickness of structural plate. A typical channel section of the cold-formed steel was used in the composite structure. The typical channel section, denoted as C.75.35.075, is available and widely used in residential constructions in Indonesia.

Experimental tests were conducted for six specimens: three specimens of composite cold-formed steel and concrete and three specimens of reinforced concrete. Longitudinal reinforcing bar in the three later specimens has equivalent values of section area and yield stress to the channel section of cold-formed steel. Analytical calculation using a cross section capacity of RCCSA was performed and the results were compared to the experimental ones.

2. EXPERIMENTAL STUDY

Two type of strip plate specimens have been tested in this study. In Figure 1, cross sections of the specimens are shown. The first type was reinforced concrete strip plate with two tensile bars of 13 mm in diameter which were positioned 25 mm from the outermost bottom fiber. For the second type, two channel sections of cold-formed steel were placed side by side at the bottom of the specimen to form a composite cold-formed steel and concrete. Dimension of the channel section was 75 mm in height, 35 mm in width and 0.75 mm in thickness; center of gravity of the channel section was 11.1 mm from the bottom of the strip plate. The channel section was directly applied to the composite structures without any treatment. Data of specimens were collected in Table 1.

Each type of strip plate consisted of three specimens with different plate depth (*h*), i.e.: 80 mm, 100 mm, and 120 mm. All six specimens had equal width (*b*) of 150 mm and member length of 2300 mm. Concrete material was prepared by a commercial ready mix concrete company with target strength was 30 MPa. However, compression test for five cylinder specimens after 28 days of concrete mixing showed lower results than the expected one for which the average value was 25.1 MPa. For the reinforcing bars, tensile test showed that the yield stress was of 327.7 MPa which was also lower than expected at 390 MPa for a standard deformed bar.

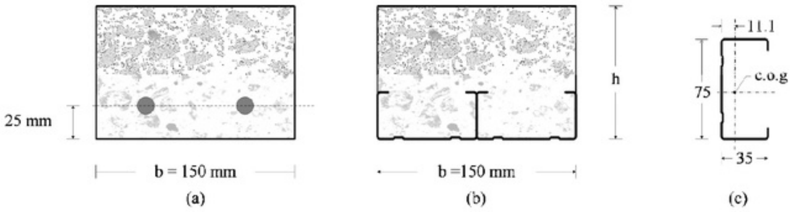

Figure 1 Cross section of the specimens: (a) reinforced concrete, (b) composite cold-formed steel and concrete, (c) dimension of the channel section

Table 1 Specimen data

Specimen ID	**Depth (h)**	**A_s or A_{cfs}***	
		nominal	**% to A_{tot}**
RC–h80	80 mm	265.4 mm2	2.2 %
RC–h100	100 mm		1.8 %
RC–h120	120 mm		1.5 %
CS–h80	80 mm	234,0 mm2	2.0 %
CS–h100	100 mm		1.6 %
CS–h120	120 mm		1.3 %

As is area of longitudinal bars for reinforced concrete (RC); Acfs is area of channel section for composite cold-formed steel and concrete (CS)

Material properties of the cold-formed steel were examined under tensile test according to ASTM Standards for Metals Test [7]. Tensile specimen was taken from the section web; the main tensile zone was 57 mm in length and 12.5 mm in width. Both ends of the specimen were extended and then connected to Universal Testing Machine through additional clamps to ensure that slip did not occur during tension test. The specimen was pulled with a constant speed of 1 mm per minute to mimic a static monotonic load until failure. The average values of yield stress and ultimate stress of the cold-formed steel were 528.3 MPa and 537.9 MPa, respectively. Modulus of elasticity for reinforcing bars and the channel section was taken similar, i.e E = 200.000 MPa.

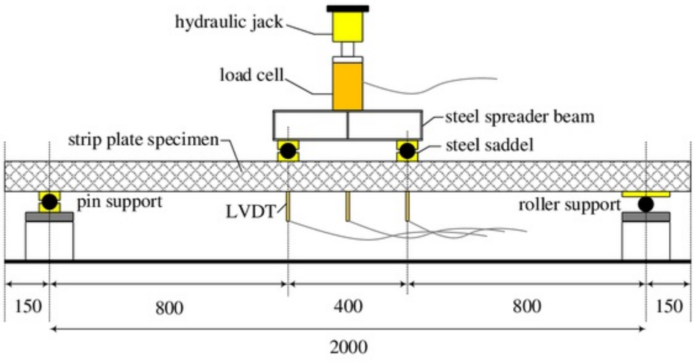

Figure 2 Schematic diagram of the loading test (dimensions in mm)

Schematic diagram for the loading test is illustrated in Figure 2. The specimen was placed on the simple supports with clear span of 2000 mm, remaining the end anchorage length of 150 mm for each support. A 500 kN capacity hydraulic jack was used to generate a load which increased monotonically until ultimate condition reached. The monotonic load was transferred to the specimen through a steel spreader beam and steel saddles resulting two points loading scheme. The pure bending moment span length between two steel saddles was 400 mm, left the shear span length of 800 mm. The load generated by the hydraulic jack was measured by a load cell which placed above the spreader beam. Three LVDTs were used to measure the displacements in the mid span and locations of the point loads. A data logger was used to record the load data from the load cell and displacements data from the LVDTs.

3. ANALYTICAL STUDY

Bending capacity of the strip plate cross section for both types of specimens was calculated based on moment-curvature relationship theory as presented in [8]. In this method, the cross section of the strip plate is divided into a finite number of concrete and reinforcement layers as shown in Figure 3. In this analytical model the cold-form steel is considered as the reinforcement layer and connection between the cold-form steel and concrete surface are assumed perfectly bonded. Hence, the strain distribution along the height of the cross section can be assumed to be linear. The strain for each element, ε_i, in the reinforced concrete cross section for each incremental step can be calculated using a given value of curvature, φ, and the lever arm of each element, y_i, as shown in Eq. (1).

$$\boldsymbol{\varepsilon_i = \varepsilon_o - (\varphi\, y_i)} \qquad \textbf{(1)}$$

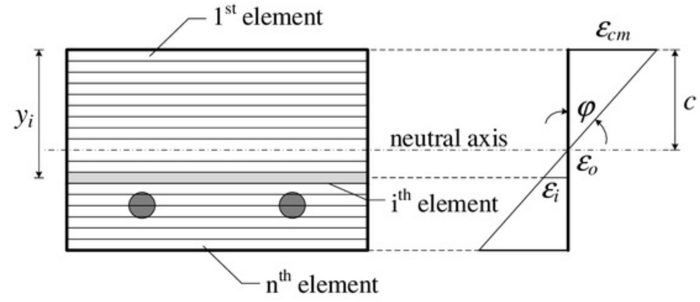

Figure 3 Reinforced concrete cross section with linear strain distribution [10]

From the strain distribution calculated using Eq. (1) and assumed stress-strain law of concrete, steel and cold-form steel, the stresses acting on each concrete element, reinforcement layer and the cold-form steel, σ_i, can be calculated as:

$$\boldsymbol{\sigma_i = f(\varepsilon_i)} \qquad \textbf{(2)}$$

The stress-strain law equation of concrete in compression used in this study is adopted from literature [9] and calculated using Eq. (3), i.e.

$$\boldsymbol{f_c = \frac{f'_{cc}\, x\, r}{r - 1 + x^r}} \qquad \textbf{(3)}$$

The stress-strain relationship of concrete in tension is a linear model up to the maximum tensile strength without a tension stiffening effect. Meanwhile, the stress-strain law for steel bars and cold-form steel used in this study is a bi-linear model.

Using calculated stresses from the previous step and area of each element, A_i, the internal forces, F_i, for each of the concrete elements and reinforcement layers can be obtained using Eq. (4).

$$\boldsymbol{F_i = A_i\,\sigma_i} \quad \textbf{(4)}$$

An iterative procedure is needed to obtain the neutral axis position. The value of axial strain, ε_o, must be adjusted to obtain the correct position of neutral axis until the equilibrium of the internal forces is satisfied. Finally, internal moment, M, for each load step in the strip plate cross section can be calculated as:

$$\boldsymbol{M = \sum F_i\,y_i} \quad \textbf{(5)}$$

Analytical values of deflection are obtained from curvature distribution corresponding to each incremental step along the beam length and can be calculated as:

$$\boldsymbol{\delta = \int_0^{L/2} x\,\varphi\,dx} \quad \textbf{(6)}$$

The calculation process was helped by a computer program developed by the author namely Reinforced Concrete Cross Section Analysis (RCCSA) [10]. The complete details and application of the layered element procedure can be found in the literature [10-12].

4. TEST RESULTS AND DISCUSSION

Similar responses to the applied load were observed for the reinforced concrete specimens. First flexural crack was in the constant moment zone for RC-h80 and RC-h120, and near to point load for RC-h100 (Figure 6). The corresponding loads for the first crack were 1.3 kN, 2.7 kN, and 7.8 kN for RC-h80, RC-h100 and RC-120, respectively. However, after these initial cracks, the specimen had still significant resistance to the load until the ultimate condition occurred, see Figure 8. More flexural cracks were found in the constant moment zone as the load increased. The flexural crack propagated on diagonal direction up to the top fiber at the ultimate state.

For the composite cold-formed steel and concrete specimens, different crack patterns were found (Figure 7). The first crack on the CS-h80 specimen occurred at 15.6 kN, but this crack was not propagated further. Ultimate condition was indicated by crushing on the top fiber of the specimen at the load of 17.0 kN. For the CS-h100 specimen, the first crack which was not propagated further was observed at 19.0 kN. At the load of 21.5 kN another crack was initiated under the steel saddle and propagated almost horizontally to the support zone; it caused a sudden failure that prevented the specimen to resist additional load. This failure caused the upper-right side specimen was separated from its main part. It was also observed that the channel section was buckled about 250 mm from the right support.

Flexural cracks were found dominantly on the CS-h120 specimen. The first crack occurred just outside of the constant moment zone at the load of 22.3 kN. Other flexural cracks developed on this zone until the ultimate load achieved at the load of 31.0 kN. Fracture occurred on the channel section and the specimen split into two parts when the load was totally removed.

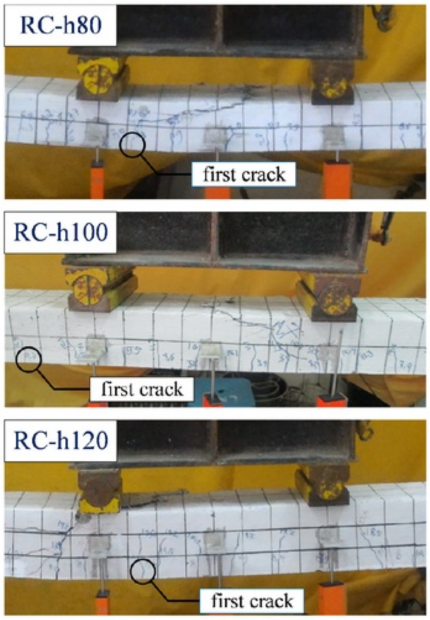

Figure 6. Crack pattern of the reinforce concrete specimens

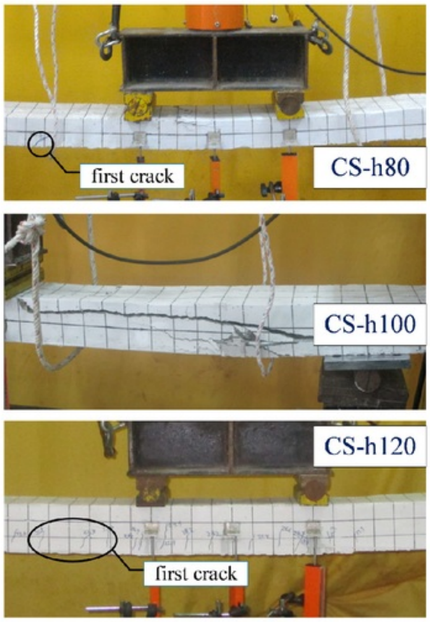

Figure 7. Crack pattern of the composite cold-formed steel and concrete specimens

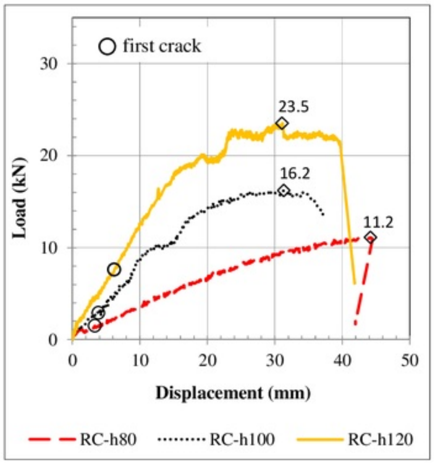

Figure 8. Load-Displacement Curve for the reinforce concrete specimens

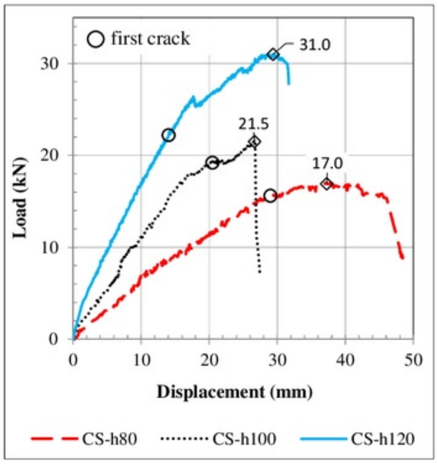

Figure 9. Load-Displacement Curve for the composite cold-formed steel and concrete specimens

4.1. Analysis of the crack and the ultimate condition

Analysis of crack pattern was focused on the composite cold-formed steel and concrete specimens since the reinforced concrete specimens showed normal crack patterns. The first crack on the composite specimen occurred after significant load has been applied. In average, the first crack load was about 85% of the ultimate load; it was almost four times bigger than the reinforced concrete specimen ones. The channel section which was placed on the bottom had significant contribution to prevent flexural failure of the specimen.

For the CS-h80 specimen, which the channel section area was 2.0 % of the total area of specimen, flexural cracks did not exist on the constant moment zone. Ultimate condition for this specimen was due to crash on the upper fiber of the section. The crash indicated that the concrete part in the upper fiber could not resist compression stress acting on it, while the tension stress on the bottom was well restrained by the channel section without any failure.

Because the section depth increased, the concrete compression part of the CS-h120 specimen gave more contribution to bending capacity than the CS-h80 specimen. Besides, the section depth increment also affected the crack pattern during loading test. In contrary to the CS-h80 specimen, several flexural cracks were found on the constant moment zone; the failures determined the ultimate state of the specimen.

Different failure condition was found at the CS-h100 specimen. The flexural cracks were not developed at this specimen although its initial response was similar to the CS-h80 specimen. An imperfection during concrete pouring to the formwork was suspected as one factor that caused the sudden failure of the specimen

4.2. Comparison to analytical calculation

Comparison between analytical calculations and experimental results are shown in Figure 10. It is noted that the channel section of the cold-formed steel was considered as the reinforcement bar placed 11.1 mm from the bottom. The load-displacement curves as well as the ultimate load predicted by RCCSA software were closed to the experiment. For each specimen, the prediction curve was almost coincide with the experimental curve, especially in the beginning of the curves. In average, the analytical method calculated the ultimate load differed within the range of 2.3 – 10.6 % to the experimental results.

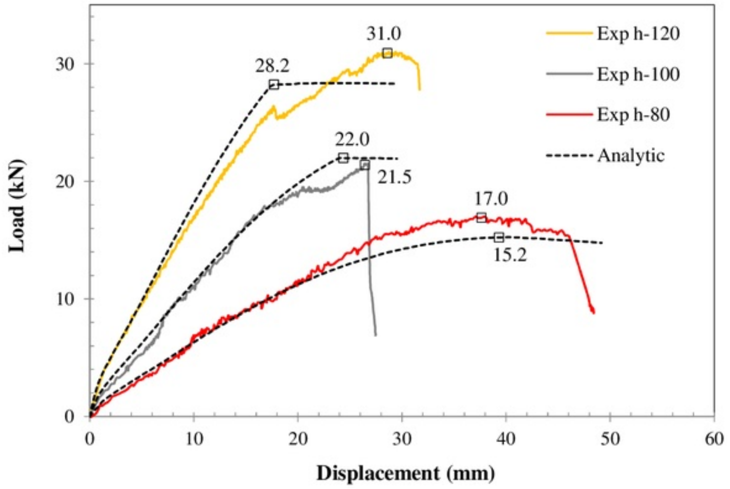

Figure 10 Comparison between experimental results and analytical prediction

5. CONCLUSION

Experimental tests to obtain bending capacity of composite cold-formed steel and concrete of a strip plate have been conducted. The cold formed section placed on the bottom of the section was effective to prevent earlier flexural cracks on the specimens. Specimen with different section depths showed different crack patterns as well as the ultimate condition. Comparison between the experimental tests and the analytical study showed good agreements which the results varied within the range 2.3 – 10.6 % for the ultimate load.

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