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A Review of Composite Bridge Girder of Cold-formed Steel Plate and RC Deck

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ABSTRACT

Objective: *This paper presents a review of earlier studies on the behavior of composite bridge girders made up of reinforced concrete (RC) decks and cold-formed steel plates. The objective is to examine the behavior of cold-formed steel composite girders under different load conditions and identify gaps in the research, especially concerning various cold-formed steel sections.* ***Method:*** *The behavior of cold-formed steel bridge girders was classified based on the loads applied and the shape of the cold-formed steel plate. Experimental and analytical studies have been conducted on cold-formed steel tub bridge girders and cold-formed steel tub bridge systems.* ***Results:*** *The study indicates that research on cold-formed steel bridge girders has focused mainly on steel tub sections, with limited research on other shapes, such as the double-C steel section. The studies considered different loads applied to the composite bridge girders, but there is a gap in understanding the behavior of various shapes of cold-formed steel girders.* ***Novelty:*** *The novelty of this paper lies in its identification of the lack of research on the double-C steel section of cold-formed composite girders and the need for additional studies. Future research should focus on the ductility, ultimate capacity under static and fatigue loads, and the interaction degree effect on the behavior of cold-formed composite girders. This will help fully comprehend the behavior of different cold-formed composite girder sections.*

INTRODUCTION

In order to shorten the construction procedure and lower the costs of bridge design and construction, a composite girder constructed with cold-formed steel plate and RC deck system has been suggested as a viable solution [1], [2], [3], [4], [5]. The cold-formed steel composite girder is conveyed to the bridge site following full prefabrication. Prefabrication is a common way in bridge engineering that involves the prefabricated and onsite assembly of certain bridge components, hence reducing costs for cutting and welding plates. The overall cost of folded-plate bridge girders was 20% lower than the engineer's projection, and the constructed duration was 33% less than that of a comparable conventional bridge [1].

The composite bridge girder consists of a cold-formed steel section and a precast or cast-in-place reinforced concrete slab connected to the steel section by shear connectors (see Figure 1). The steel section girder is being manufactured with a high-capacity press-brake. Plates are positioned in the press-brake and cold-bent to get the specified bend radius. Another method of cold-formed composite girder construction is prefabrication [5, 6].

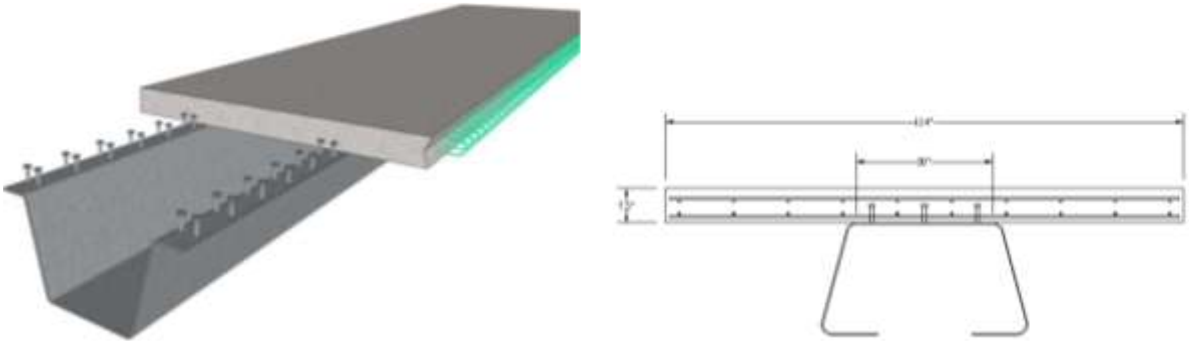

(a) (b)

Figure 1. Cold-Formed Steel Composite Girder Proposed by (a) (Michaelson, 2014) [7], (b) (Burner, 2010) [8].

RESEARCH METHOD

The shape of a cold-formed steel section affects the behavior of the composite girders under static and fatigue loads. Research on specific shapes has been conducted recently, and some have been well covered in this context. This paper presents a review of earlier studies on the behavior of cold-formed steel composite bridge girders. The literature review indicates the development of shallow, cold-formed steel tub girders for short-span bridge applications. Static and fatigue tests of cold-formed steel tub girders were conducted, and the trapezoidal box girder with ultra-high-performance concrete (UHPC) joints was evaluated. The behavior of cold-formed steel girders will be classified based on the applied load test and the cold-formed steel shapes.

Research Study Conducted on Cold-Formed Steel Girder under Static Load

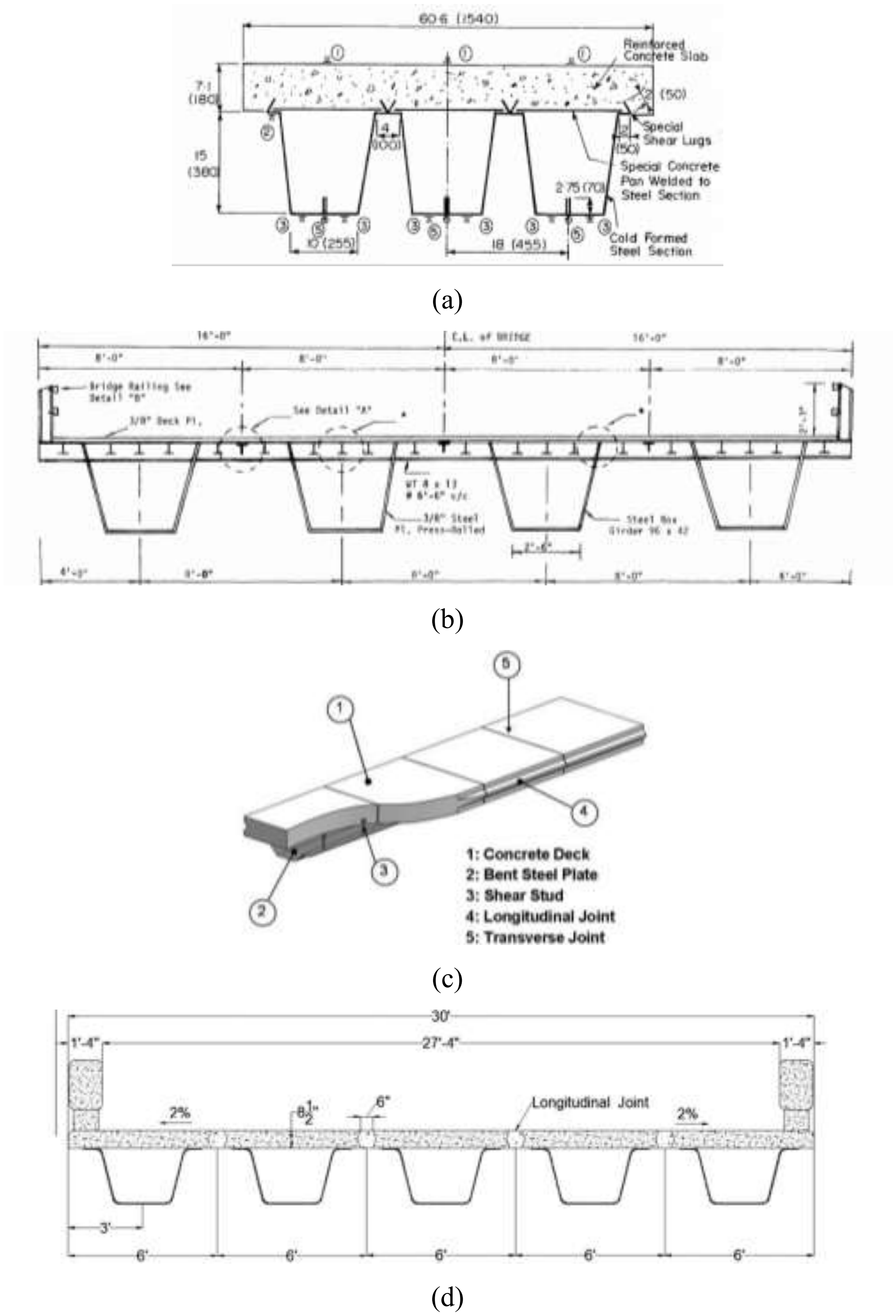
Cold-Formed Steel Tub or Box Bridge System

Kennedy and Madugul (1978) [9] investigated a full-scale composite bridge girder of cold-formed steel and an RC deck slab. The composite structure consists of three steel box sections and RC deck slabs, shown in Figure 2(a). The steel box sections were fabricated by brake-forming half sections of steel sheet and welding them together to form boxes with the special V-shaped shear connectors (lugs). The results indicated that the composite girder carrying the ultimate capacity load was adequate. The shear connectors (lugs) were quite successful in shear transfer and distributed concentrated loads effectively.

Taly and Gangarao (1979) [10] suggested a new T-Box bridge girder system using a composite tub girder from a steel plate bent by a press brake. The designed girders were fabricated from a prestressed concrete deck connected to a steel tube girder using a shear stud plate welded to the top flange. The overall width of the steel section and the pre-stressed concrete deck was 3 feet and 6 feet, respectively, as shown in Figure 2(b). Various bridge widths were used by attaching adjacent tub girder units. The steel plate diaphragm and bearing stiffener were put in the ends. An alternative method of concrete-steel composite girders was employed with WT steel sections welded to the steel plate deck to improve the longitudinal stiffness of the orthotropic deck. Due to their closed shape, the researchers found that tub girders have greater torsional stiffness than typical I-beam sections.

Burgueño (2008) [11] studied the numerical analysis of a wholly prefabricated system of composite box girders for highway bridges. The composite box girder system consists of a cold-formed box steel girder connected to a reinforced concrete deck by shear studs, as shown in Figure 2(c). Burgueño studied the behavior of the composite bridge systems, composite bridge girders, joints, and the vibration properties of the bridge systems. The initial objective of the research was to identify a solution for the longitudinal joining of the continuity between the girder and deck. The study determined that composite steel and precast concrete girder/deck components constitute a secure and efficient choice for short-span highway bridges.

Deng et al. (2016) [4] conducted the experimental and numerical assessment of short-span bridges with folded plate girders, as shown in Figure 2(d). The buildability and ultimate load were assessed through design and testing. To comprehend the behavior of the girder sample under various loading cases, Finite Element (FE) analysis was employed. Conventional design calculations and finite element analysis were proven with the experimental results. A bridge model was developed using the ANSYS software to facilitate the bridge's behavior under various types of loading. Hand calculations yielded reasonable predictions, while FE analysis predictions were more accurate. Deng concluded that the ultimate capacity of the bridge girders was more than the bridge demand, and the bridge had adequate ductility until collapse.



(a)

(b)

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(d)

Figure 6. (a) Composite bridge proposed by Kenndy and Madugul (1978) [9], (b) Taly and Gangarao innovated Bridge System (1979) [10], (c) Composite Steel Box Girder Burgueño (2008) [11], (d) folded plate girders Deng et al. (2016) [4]

Double C-section Composite girder

Malite et al. (2000) [12] studied a composite beam constituted of cold-formed steel shapes (double channel) and connected to the concrete slab by cold-formed shear connectors. The dimensions of the steel beam and the concrete slab were identical in all four tests, which included both partial and full interaction as well as concentrated and uniformly distributed loads, as shown in Figure 3. A theoretical and experimental analysis was conducted to assess the behavior of beams. The author showed that the behavior of beams was not affected by the degree of interaction in the initial period of tests. After the slip occurred, the behavior of the beams was affected by the degree of interaction.

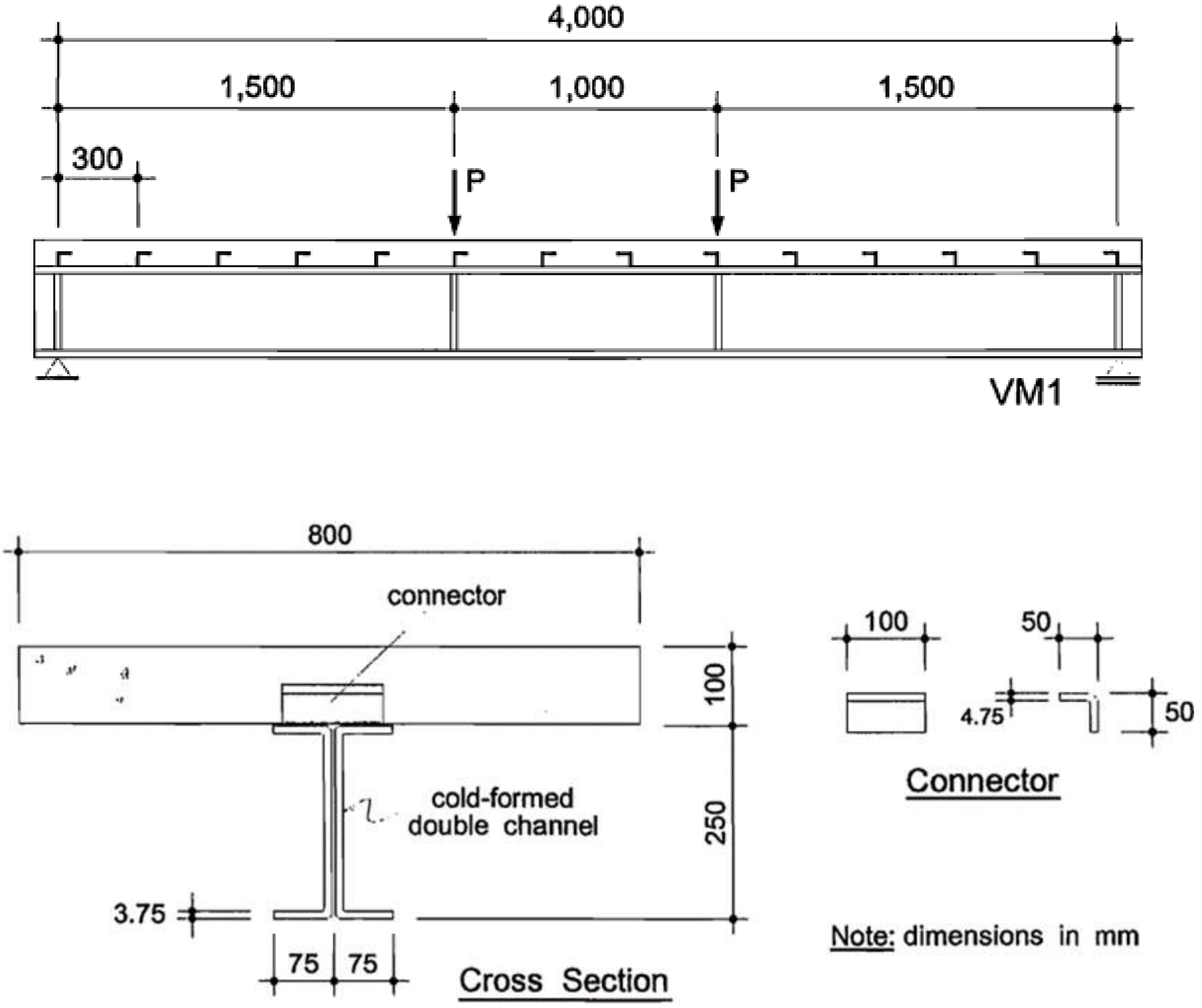


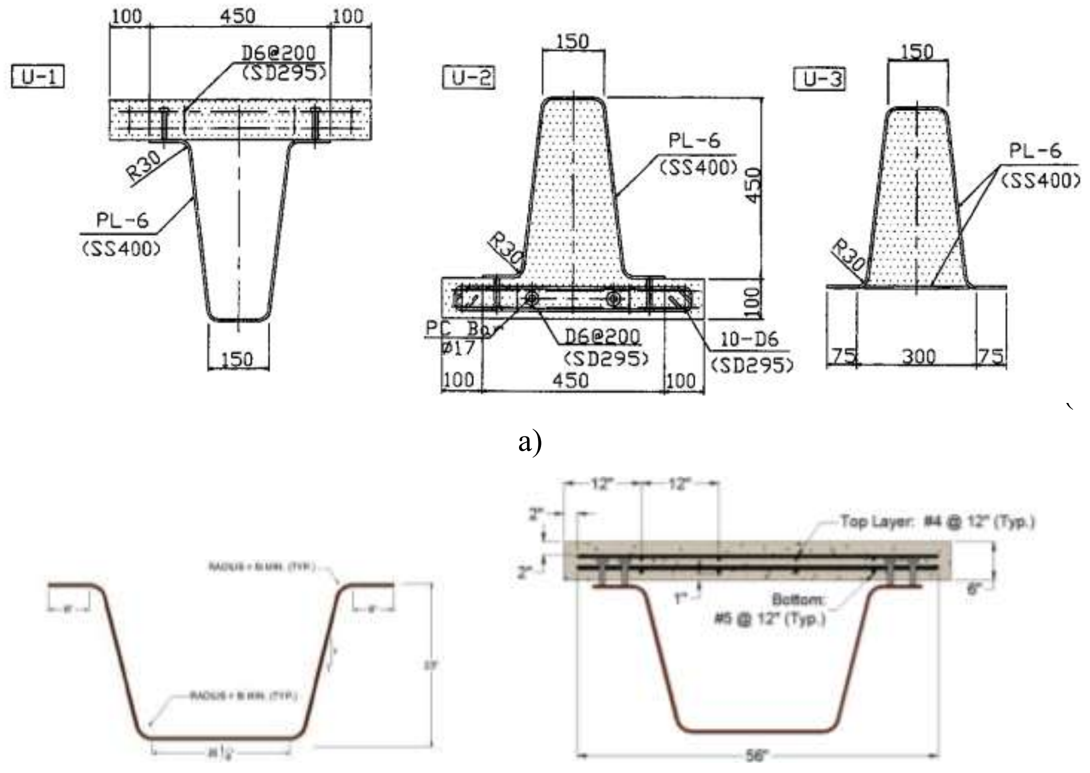
Figure 3. Dimensions of the composite beams [12].

Cold-Formed Steel Tub or Box Composite Girder

Nakamura, S. (2002) [13] proposed a novel composite bridge girder made of cold-formed steel, as illustrated in Figure 4(a). Nakamura studied the static bending behavior of the composite girder models. The composite girder consisted of two parts. The first part is located in the middle support with prestressed concrete. The other part is located at the end span of the girder and does not contain prestressed concrete. The study tested three specimens of girder. The first specimen featured a steel U section and an RC slab, the second included a concrete U girder with two PC bars, and the third incorporated an additional steel plate along with a tension-free concrete slab. Each model had a different self-weight reduction method. The deflection of the first girder increased directly with load P before the yield point, and the load reached a maximum of 630 kN at point P, just before the concrete slab collapsed. The second girder's deflection was below zero at the initial stage, but continued to increase directly until a maximum at P of 720 kN. The third girder's initial inclined angle was smaller due to lower bending rigidity. Nakamura demonstrated that the novel composite girder had enough bending strength and deformation capacity, indicating that this new composite girder is realistic and workable.

Kelly (2014) [14] studied the behavior of non-composite press-brake-formed steel tub girders. The girder proposed by Kelly is composed of a cold-formed steel plate and a reinforced concrete slab poured in place without shear studs, as shown in Figure 4(b). The experimental test was carried out on two non-composite girders. Four stages were adopted to develop the composite bridge girder system. First, a review of previous studies of non-composite bridge girders was conducted. Second, flexural testing of non-composite girder specimens was carried out. Next, ABAQUS software was used to assess the behavior of the composite girder. Finally, experimental test results were compared to nonlinear finite element analysis. The researcher indicated that the proposed composite bridge girders were economical compared to traditional short-span bridge solutions.

Michaelson (2015) [7] progressed the shallow press-brake-formed steel tub girders of short-span bridges. The girder proposed by Michaelson is a composite of a steel tub section formed by press-brake and a reinforced concrete deck (RC) cast in place, connected to the tub steel girder by shear studs, as shown in Figure 4(c). The composite bridge girder system was developed in five steps: design methodology, specimen flexural testing, employing ABAQUS software to evaluate composite girder behavior, comparing composite girder behavior with AASHTO LRFD specifications [15], and a feasibility analysis setup. The experimental test was carried out on two specimen pairs; the first was a composite girder, and the other a non-composite. Experimental tests were compared to nonlinear finite element analysis, and the results were accurate until failure. The researcher concluded that the proposed composite bridge girders were economical compared to traditional short-span bridges.



a)

(b)

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Figure 4. (a) Test samples by Nakamura (2002) [13], (b) non-composite press-brake-formed steel tub girder, [14], (c) Composite bridge girder of Michaelson (2015) [7]

Research Study Carried out on Cold-Formed Steel Girder under Fatigue Load

Cold-Formed Steel Folded Plate System Bridge

Burner (2010) [8] studied the performance of the composite folded plate girder system under the action of fatigue loading. The rebar details in the closure area between the attached slabs were investigated (Figure 5). The fatigue loading is carried out by subjecting the girder to a 75-year lifetime loading equivalent. To investigate the behavior of joints between attached slabs, six slab specimens with closure areas were subjected to both positive and negative moments. The author found that the strain distribution through the girder remains constant, and the steel bends remain unaffected after 219,000,000 cycles. The FPG system, cost-effective and easy to install, was compared to headed bars for jointed slab construction, highlighting the benefits of hooked rebar.

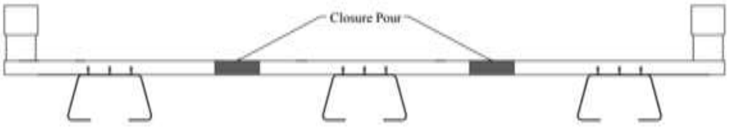


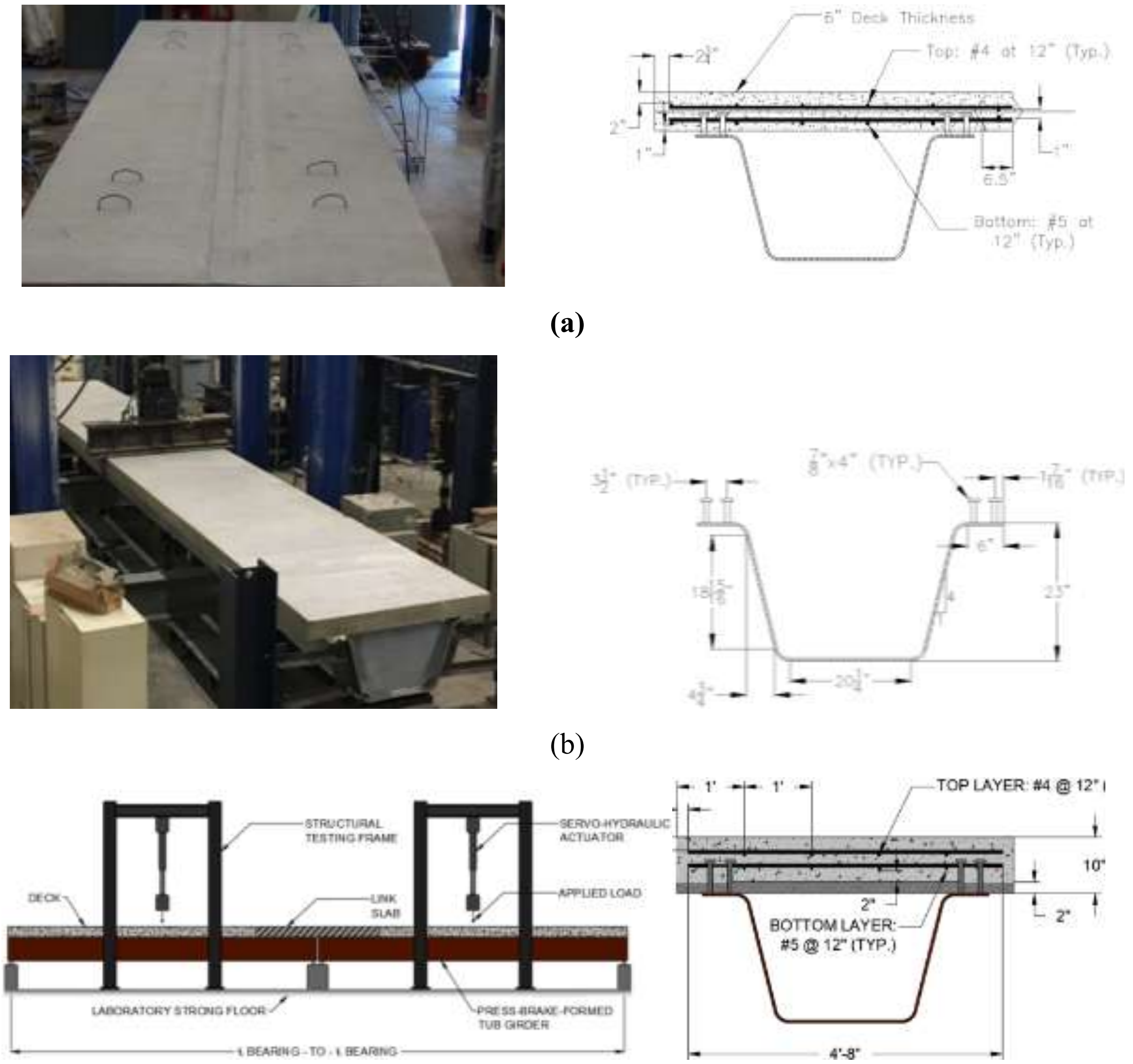
Figure 5. Folded plate girder system [8]

Cold-Formed Steel Tub Composite Girder

Kozhokin (2016) [16] studied a trapezoidal box girder with a joint made of ultra-high-performance concrete (UHPC), reaching a strength of 24 ksi (165 MPa). The trapezoidal box girder consisted of a cold-bending standard plate connected to the deck by shear connectors. The reinforced concrete (RC) deck was poured in place, as shown in Figure 6(a). UHPC was used to create hardy joints connected between the trapezoidal box girders. The composite tub girder system was investigated experimentally. The composite tub girder system consists of two composite box girders jointed with UHPC and subjected to fatigue loads. The fatigue loading is carried out by subjecting the girder to an equivalent 75-year lifetime loading. Results indicated that the joint transferred loads from directly loaded girders to nearby ones throughout the test, notwithstanding the failure of low-strength concrete utilized for deck construction.

Tennant (2018) [3] investigated how the uncoated and galvanized press-brake-formed composite tub performed during fatigue. The author studied the extreme heat effect of the galvanized girders under fatigue loading. Two composite tub girders were tested: the first, an ungalvanized steel tub girder, and the other, a galvanized steel tub girder, as shown in Figure 6(b). The fatigue loading is adopted by subjecting the girder to a 75-year lifetime loading. The mid-span vertical deflections of the uncoated and galvanized steel specimens were 0.974 in. and 1.208 in., respectively, at loads of 92.50 kPa and 93.00 kPa, after completing 2,900,000 loading cycles. The experimental results indicated that the galvanization of steel tub girders is not effective in the fatigue behavior of press-brake-formed tub girders.

Tennant (2022) [17] focused on developing the cold-formed steel tub girder system (Figure 6(c)), which was performed in several steps. First, the background studies on the cold-formed steel tub composite girders were summarized. Next, the development of analytical modeling techniques was performed by comparing them with live load field tests and laboratory tests. The parameters affecting the distribution factors of live loads were investigated. Analytical modeling was used to evaluate the effect of the bearing line skew on the capacity of the cold-formed steel tub composite girders (PBFTGs). Finally, an experiential fatigue test was applied to the two PBFTGs linked by a joint slab to evaluate the joint in continuously press-brake formed tub girders. The author shows that cold-formed steel tub girders can be extended into continuous girder spans with joint slabs in the short-span bridge.



(a)

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Figure 6. (a) Cold-Formed Tub Girder Modular Unit [16], (b) the ungalvanized and galvanized composite tub girders [3], (c) cross-section of the composite bridge girder [17].

Cold-Formed Steel Tub System Bridge

Gibbs (2017) [6] conducted a field behavior evaluation on a press-brake-formed steel tub composite girder. The Amish Sawmill Bridge was the first bridge of a cold-formed steel tub girder designed, constructed, and occupied for traffic (Figure 7(a)). The experimental and analytical testing was carried out on the Amish Sawmill Bridge. The results indicate that the shallow, cold-formed composite tub girders are an economical and empirical solution to the short-span bridge.

Barth (2021) [5] conducted a field test of the cold-formed steel tub bridge (Fourteen Mile Bridge) under the action of live loads. The specimens were 35 feet (10.67 meters) in length and had a total depth of 27 inches (686 mm). Figure 7(b) shows that the modular unit is a shallow trapezoidal box girder cold-formed by a press-brake. ABAQUS software was used to generate a Finite Element (FE) model of the bridge. The experiential and analytical results were utilized to determine live load distribution factors. Evaluations of the suggested FEA methodologies and empirical findings showed a favorable convergence of results.

Tumbeva et al. (2023) [18] proposed a new approach for the fabrication of cold-formed tub composite girders (PBTGs). A built-up cold-formed steel tub girder system was employed, including a web cold-formed and bolted to individual top flanges and flat bottom plates, as shown in Figure 7(c). The ultimate innovation is that this system forms a "kit-of-parts," where various component sizes are employed to obtain span lengths or required capacities. The researchers investigated a system submission with design details. Finite element modeling validated the two checking bridges and evaluated internal redundancy if a flange or web was suddenly lost.

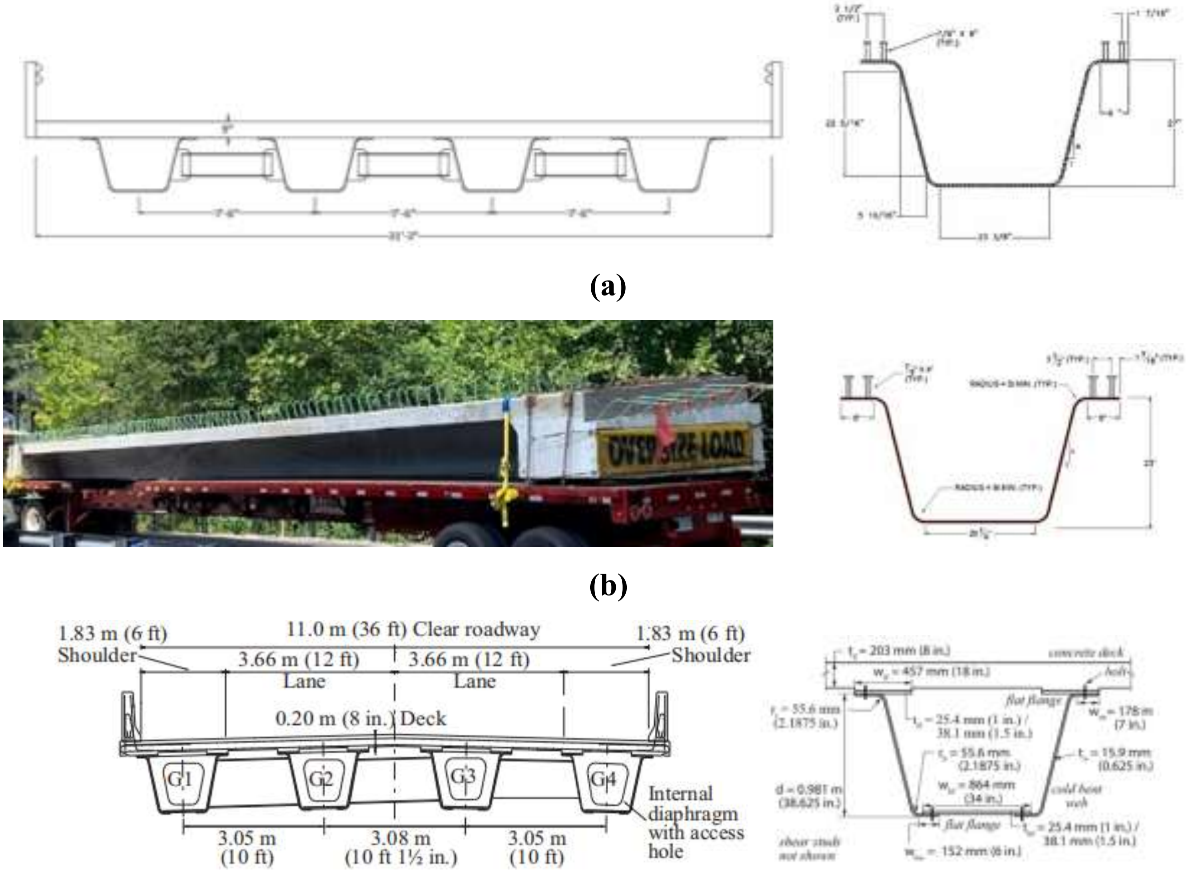

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Figure 7. (a) Amish Sawmill Bridge Gibbs (2017) [6], (b) Fourteen Mile Bridge Barth (2021), (c) Built-up press-brake formed tub girder of Tumbeva et al. (2023) [18].

RESULTS AND DISCUSSION

Summaries of Results

Tables 1 and 2 note that reviewing the results of literature studies reveals variation in the structural behavior of the tested composite girder under static and fatigue loads. Some experiments demonstrated a satisfactory initial response to the load, followed by cracking and gradual collapse, while other models exhibited sudden failure after exceeding the load limit.

As presented in Table 1, Most mode failures were observed to be mid-span flexural, while some collapsed at contact points or joints. Some studies have emphasized the importance of improving the integrity of composite girders, particularly composite panels. The experimental and analytical results showed a strong correlation, indicating that the proposed FEA techniques can accurately predict LLDFs in future research (Table 2).

Although these results hold significance, it's crucial to acknowledge that a direct comparison of the load values in these studies may lack accuracy. This variability is due to the different span lengths and steel plate thicknesses between models, making each test an independent design case. Therefore, these values are presented for illustrative purposes only and should not be used for direct quantitative comparison.

Table 1. Summarizes the studies, detailing the parameters used and results of the static load test.

Reference	**span length m**	**Steel Section**	**Concrete**	**Behavior study**	**Ultimate load kN**	**Failure mode**
[9]	9.1	box girder	conventional	flexural testing	667	Crushing of concrete in compression.
[10]	19.8	tub girder	conventional and prestressed	flexural testing	-----	-----
[13]	3.8	tub girder	conventional	flexural testing	410	The concrete slab crushed, and the top flange buckled.
[12]	4	double channel	conventional	flexural testing	178	Rupture of the concrete at the shear connector.
[11]	3.65	tub girder	conventional	validated analytical flexural simulations	-----	Stress at connections, joint opening.
[14]	11.59	tub girder	non	flexural testing	418	The girders collapsed due to horizontal and torsional elastic bending.
[7]	12.19	tub girder	conventional	flexural testing	1352	crushing of the concrete deck.

Table 2. Summarizes the studies, detailing the parameters used and results of the fatigue load test.

Reference	span length m	Steel Section	Concrete	Behavior study	Results	Failure mode
[8]	12.5	tub girder	conventional	stiffness	The initial stiffness and the stiffness recorded at the test's end show a 1.9% difference	Flexural cracking, bar slip, and concrete crushing.
[16]	10.67	tub girder	conventional and (UHPC).	flexural behavior	The maximum moment is 1083 kN · m after 2800000 cycles.	The deck failed after 1,635,000 fatigue cycles.
[4]	15.68	folded plate	conventional	flexural behavior	The maximum moment at each loading line is 6242 kN · m at 1419 kN	Concrete crushing.
[6]	9.45	tub girder	conventional	Live load.	-----	-----
[3]	18.3	tub girder	conventional	flexural behavior	-----	The specimen collapsed under ductility, with the concrete crushed.
[5]	10.67	tub girder	conventional	Live load	The suggested FEA methodologies reliably forecast LLDFs.	-----
[17]	7.62	tub girders	conventional and (UHPC)	span extension, LLDFs		-----
[18]	29.6	tub girder	conventional	Kit-of-parts strength	Fast fabrication	-----

Research Gaps and Future Directions

The important variable of composite bridge girders is the shape of the cold-formed steel section, as various cross-sections can be formed, unlike the conventional composite girder (I-section). Therefore, it is necessary to study the behavior of the cold-formed steel composite girders with various shapes under static and fatigue loading. The literature review of the cold-formed steel girder research under static load showed that many parameters and different shapes were studied individually. However, research on the cold-formed composite girders under fatigue loading has recently focused extensively on the steel tub-section girder. Therefore, it is essential to understand the effect of shape on the behavior of cold-formed composite girders under static and fatigue loading.

CONCLUSION

Fundamental Finding: The review indicates that while experimental and analytical studies have been conducted on cold-formed steel tub bridge girders and bridge systems, there has been limited research on other shapes of cold-formed steel composite girders. **Implication**: The findings suggest that the current body of research is incomplete, especially concerning various shapes of cold-formed steel girders. This implies that a more diverse range of composite girders, beyond just steel tub shapes, needs to be studied to better understand their performance. **Limitation**: A significant limitation of the current research is the lack of studies on alternative shapes of cold-formed steel composite girders, such as the double-C steel section. This gap restricts the comprehensive understanding of cold-formed composite girders under different loading conditions. **Future Research**: Future research should focus on investigating the ductility and ultimate capacity of other cold-formed sections of composite girders under static and fatigue loads. Additionally, it is crucial to study the interaction degree effect on the behavior of cold-formed composite girders with various loads, to fully comprehend the performance of each section. It is highly recommended that investigations be expanded to include different shapes of composite girders.

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