Behavior of Composite Beams with Cold-formed Steel Joists and Concrete Slab

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BEHAVIOR OF COMPOSITE BEAMS WITH COLD-FORMED STEEL JOISTS AND CONCRETE SLAB

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Abstract

A new composite beam and floor system has been developed herein to achieve a stronger strength and ductility, as well as to yield a more economical design purpose. This new composite beam system consists of three elements: reinforced concrete slab on corrugated cold-formed metal, back to back cold-formed steel joists, and cold-formed furring shear connector. The shear connectors are screwed through the top flange of the support joists in order to provide vertical interlocking and horizontal shear resistant between the concrete slab and the cold-formed steel joists. The self-drill fasteners are used for fastening the furring shear connector through the metal deck into supporting joists.

To understand the behavior of the new composite beam, a total of six large-scale bending tests were conducted to obtain the positive moment capacity, vertical deflection, and end slip of proposed composite beam system. Comparing with the non-composite section, the proposed composite section presents a better performance for both strength and ductility.

The present experimental test results are also compared with the proposed analysis and design method which is not currently available in the AISC or AISI specifications.

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Introduction

In the late twenty century, a new composite section system was introduced to the building construction industry. This new composite system uses a cold-formed steel beam to substitute for a hot-rolled steel beam to provide a lighter weight structural system. Several new types of shear connector have also been proposed (Abdel-Sayed (1982), Ruiz, et al (1995), Maximiliano, et al (1998, 2000), Hanaor (2000), Nakamura (2002), Gemini Structures Systems (2005), Yu and LaBoube (2010)).

In this research, a recently patented composite beam and floor system by Hsu, et al (2010) (**Figures** 1 and 2) which has been experimentally and analytically studied, and was designed to achieve a higher strength and ductility, as well as to yield a more economical design purpose. This new composite beam system consists of three elements: reinforced concrete slab on corrugated cold-formed metal deck, back to back cold-formed steel joists, and continuous cold-formed furring shear connector. The continuous shear connector is screwed through the metal deck and the top flange of the support joists in order to provide vertical interlocking and horizontal shear resistance between the concrete slab and the cold-formed steel joists. The hex screws are used for fastening the furring shear connector through the metal deck into the supporting steel joists. Thus, the key success of an efficient composite system comes from an innovative shear connector, fasteners, and the strength of the cold-formed steel joists. The new configuration of composite beam system provides an easier procedure to construct with lower cost and lighter weight.

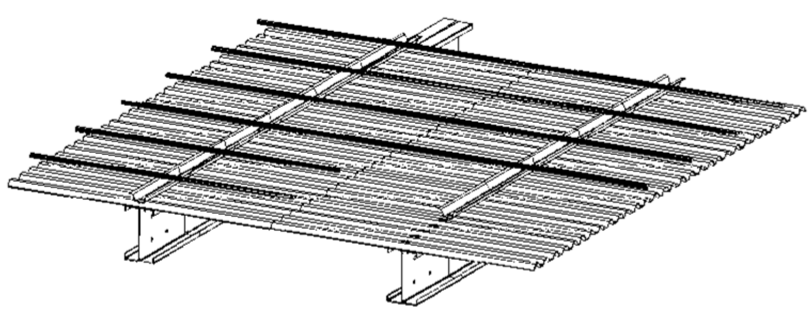

Figure 1 – Composite beam system before casting

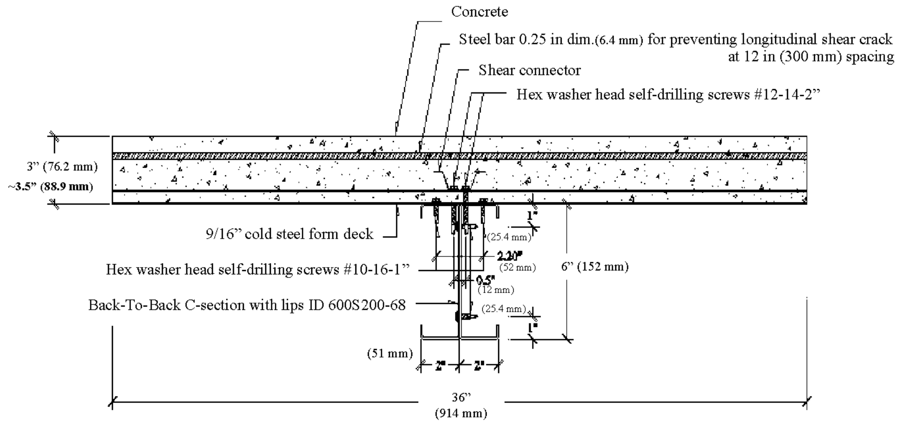

Figure 2 - Composite section and details of connection (Specimens CB2, CB4 and CB5)

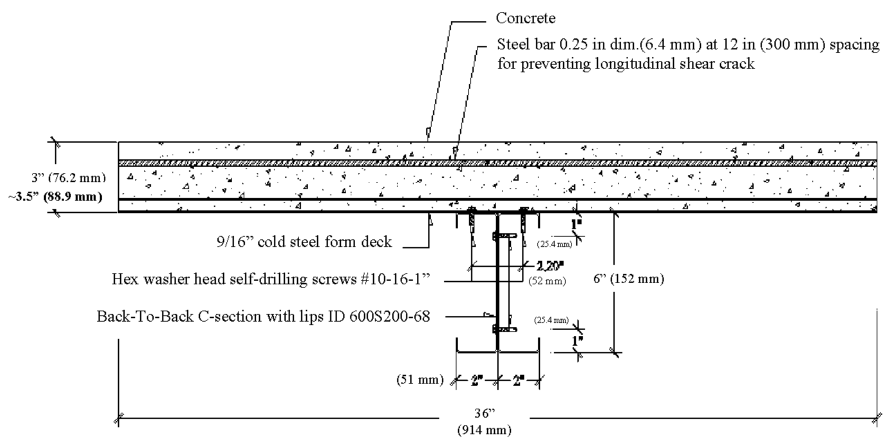

Figure 3 - Non-composite section and details of connection (Specimens CB1and CB 3)

Experimental Program

The experimental program described herein was used to study the structural behavior of both non-composite (**Figure** 3) and composite beams (**Figure** 2). To investigate the composite behavior, a set of beam specimens were tested under flexural bending. Axial strain gages were installed on each beam to evaluate the strain distribution of the beam section under bending until failure. Moreover, the non-composite section without shear connector was examined to reveal the improvement of the composite section. The strength and deformation results from these half-scale structural tests provide the design guideline and background information for the proposed composite section. The improvement of composite beam action in terms of loading capacity, deflection, and ductility of the composite section are verified and discussed herein.

Composite and Non-composite Beam Specimens

In this research, a total of six beam specimens were tested: Two non-composite Specimens CB1 and CB3, three composite Specimens CB2, CB4 and CB5, and a steel section CB6.

Materials

- Cold-formed steel joists (C section) with lips ID section 600S200-68 (12 ft or 3.7 m), F_{ya} = average yield strength= 45 ksi or 310 MPa.
- Normal Strength Concrete of 3,000 psi (21 MPa) (unit weight: 145 lb/ft3 (23.89 kN/m3).
- Cold-formed furring channel (Shear Connector) (**Figure** 4). The continuous shear connector has an elastic modulus of 29,000 ksi (20.26 GPa) and its yield strength is 33 ksi (228 MPa).
- Self-Drilling Fastening Hex Screw #10-16-3/4", 0.19 in.-diameter (4.83 mm), #12-14-2", 0.21 in.-diameter (5.33 mm).
- Gage 20 Cold-formed steel deck (0.036 in.- thickness (0.914 mm)).

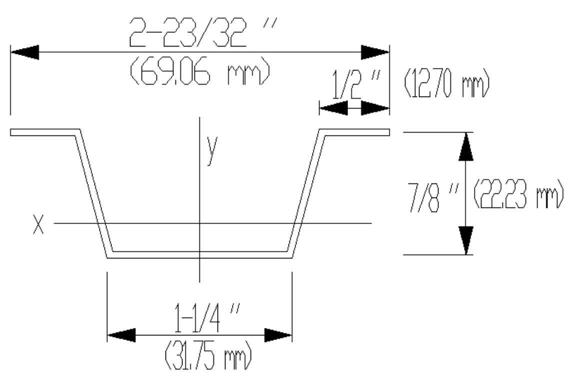

Figure 4 - Furring channel section

All beam configurations are listed in **Table** 1. A total of six beam specimens were tested under four-point loading. Three types of the beam specimens were tested. They are composed of a steel section, two non-composite sections and three composite sections at present study. The span length of beams was 12-ft (3.6 m). The concrete flange width was design using the effective width concept (Span length (ft) /48). The cold-formed steel joist sizes were chosen on the basis of an innovative design concept to locate the position of neutral axis of a gross section within the solid concrete slab. In doing so, the local buckling in steel joists could be effectively prevented.

Instrumentation and Testing Procedure

A four-point loading configuration was used to induce a bending moment (**Figure** 5). Loading was performed using a closed loop Material Testing System (MTS) with a 220-kip (980 kN) load cell. The vertical deflection measurements were measured at the mid-span of the beam. Five electrical strain gages were placed at different five locations at the mid-span of all beam specimens to reveal the strain distribution and the location of neutral axis. The five locations include bottom steel flange, middle steel web, top steel flange, shear connector or top level of metal deck, and top fiber of concrete flange. The strain data obtained were plotted to obtain the strain distribution across the beam section. The strain distribution under different applied loading stage was used to verify the composite action.

All beams were statically and monotonically tested to failure in a single load cycle to obtain the ultimate flexural load. The beam specimens were prepared and the bending tests were conducted at the Structures Laboratory, New Jersey Institute of Technology. The maximum deflection was controlled at 5.0 in. (127 mm) with the initial rate of 0.1 in./min (2.54 mm/min) and the maximum rate of 0.5 in./min (12.7 mm/min).

Flexural Test Results and Discussions

Table 2 summaries all present flexural test results. In **Figure** 6, a similar load-deflection behavior from zero until 8000 lbs (35.58 kN) for Specimens CB1 and CB2 is shown. During the experiment, the non-composite Specimen CB1 showed separations between the concrete slab and cold-formed steel joists on both end supports, while the composite Specimen CB2 had smaller separations. For composite Specimen CB2, the tilting and bearing of fasteners was noticed at the shear zones of the specimen. Subsequently, Specimen CB1 could not carry any more applied load after reaching 9950 lbs (44.46 kN), whereas Specimen

CB2 reached a loading capacity of 11300 lbs (50.26 kN) at flexural failure. As illustrated in **Figure** 6, the composite section has substantially increased its ductility as compared to that of the non-composite section.

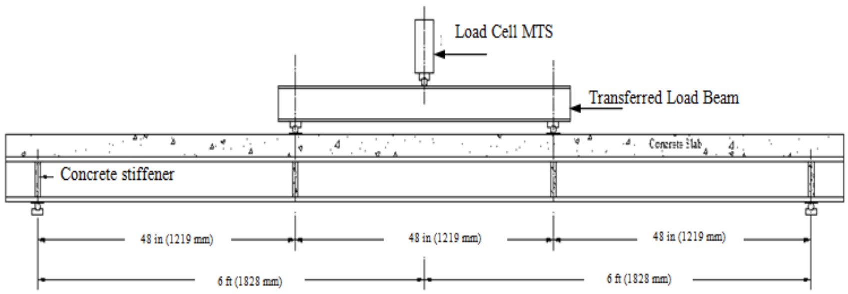

Figure 5 - Four-point bending test setup

Test Specimens

Table 1 - Configurations of the Tested Beam Specimens

Specimen	Studs Size	Span Length (ft) (m)	Type of Fastener	Concrete Thickness (in x in) (mm x mm)	Concrete Strength f'_c (psi) (MPa)	Remark
CB1	600S200-68	12 3.6	#10	3” x 36” 76 x 915	2700 18.62	Normal Weight Concrete (145 pcf or 23.87 KN/m^3)
CB2	600S200-68	12 3.6	#10/#12	3” x 36” 76 x 915	2700 18.62	
CB3	600S200-68	12 3.6	#10	3.5” x 36” 76 x 915	3200 22.06	
CB4	600S200-68	12 3.6	#10/#12	3.5” x 36” 76 x 915	3200 22.06	
CB5	600S200-68	12 3.6	#10/#12	3.5” x 36” 76 x 915	3200 22.06	
CB6	600S200-68	12 3.6	- -	- -	- -	No concrete slab

Table 2 - Summary of Flexural Test Results

Remark	Specimen	Concrete strength *f'c* (psi) (MPa)	Maximum Load (lbs) (kN)	Mid-Span Deflection at maximum load (in) (mm)	Mode of Failure	Note
Point Loads Without transverse bars in concrete slab	CB1	2300 15.86	9950 44.26	1.042 26.47	Flexural and brittle failure	Non-Composite section
	CB2	2300 15.86	11300 50.26	3.021 76.73	Longitudinal shear crack in concrete slab and flexural failure	Composite section
Line loads With transverse bars in concrete slab	CB3	3200 22.06	14200 63.16	3.05 77.47	Flexural failure with less ductile	Non-Composite section
	CB4	3200 22.06	18100 80.51	4.75 120.65	Flexural and ductile failure	Composite section
	CB5	3200 22.06	18348 81.61	5.22 132.59	Flexural and ductile failure	Composite section (with bent in rib)
Point load	CB6	NA -	5752 25.58	1.48 37.59	Lateral and torsional buckling	No concrete

As illustrated in **Figure** 7, both Specimens CB3 and CB4 show a similar structural stiffness from zero until 9000 lbs (40.03 kN). During the tests, the non-composite section CB3 developed the separation between the concrete slab and cold-formed steel joists on both end supports. The concrete slab and cold-formed steel joists deformed at different rate since no shear connector was provided for the section. Due to the stronger concrete strength of slab than the previous Specimens CB1 and CB2, the tensile cracks were not run through the top section of the slab. Consequently, the slab was able to carry more applied load by itself. The cold-formed steel joists started to carry the load alone after completely separating from the concrete slab. The compression buckling started to show up under a line load at 12000 lbs (53.38 kN). Finally, the non-composite section failed and buckled at applied load of 14200 lbs (63.16 kN). For composite section CB4, the applied load arrived at 18100 lbs (80.51 kN).

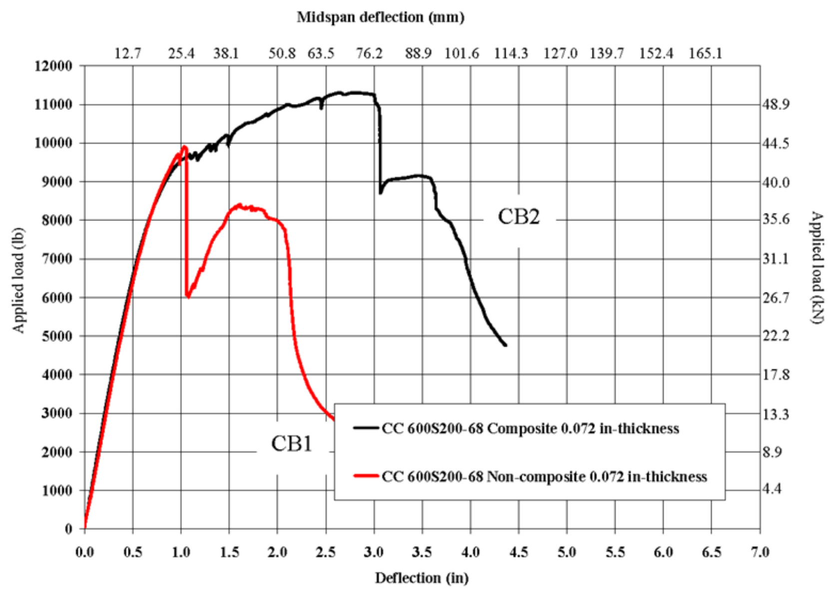

Figure 6 - Applied loads versus mid-span deflection curve for Specimens CB1 and CB2

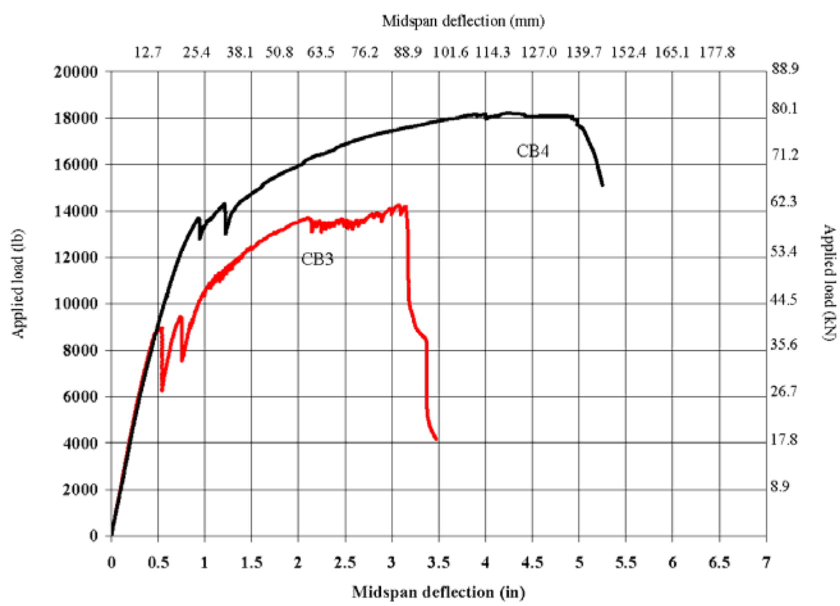

Figure 7 - Applied loads versus mid-span deflection curve for Specimens CB3 and CB4

For Specimens CB4 and CB5 as illustrated in **Figure** 8, the experiments were aimed at studying the composite action of the composite section when the shape of the continuous shear connector was modified in Specimen CB5 by increasing the bond resisting area of the proposed shear connector. Both lips of the continuous shear connector were cut and bend up every 2 in. to add the bearing contact area to the concrete. The proposed composite section CB4 failed at applied load of 18100 lbs (80.51 kN), whereas the composite section with modified shear connector CB5 failed at applied load of 18348 lbs (81.61 kN). Both Specimens CB4 and CB5 reached the flexural failure and achieved large ductility. The loading capacity of the proposed composite section was increased by less than 2% as compared to the proposed composite section with modified shear connector. The ductility of the structure was increased by 15%. More details of the test results can be found in Punurai (2007), and Punurai, et al (2012).

Neutral Axis and Assessment of Composite Action

The integrity of the composite action was assessed by measuring the strain distribution of a section under applied bending loads. The strain gages were installed at mid-span location of bottom, middle web, top flange, proposed shear connector, and top of concrete slab, respectively. **Figure** 9 depicts the neutral axis of composite section CB4, and the neutral axis of this section is located at the concrete slab which is about 7.45 in. (189.2 mm) from the bottom flange of cold-formed steel joists. Based on the test results of **Figure** 9, one can conclude that the centroid of proposed composite beam cross section, has been purposely located at the concrete slab so that the cold-formed steel joists are subjected to only tensile forces, thus preventing the cold-formed steel joists from compression buckling.

Analysis and Design Methods

The shear design strength including tilting and bearing of fasteners can be determined based on Section E4.3 of the AISI Specifications (2002). The tension design strength of the fasteners including pull-out, pull-over is based on Section E4.4 of the AISI Specifications (2001). The Specification requirements can be applied to fasteners with diameter between 0.08 in. (2.03 mm) to 0.25 in. (6.35 mm). The flexural design procedures for non-composite section, as recommended by the AISI Specifications (2001), are composed of two procedures: The Procedure I is called as the initial of yielding while the Procedure II is named as the inelastic reserve capacity.

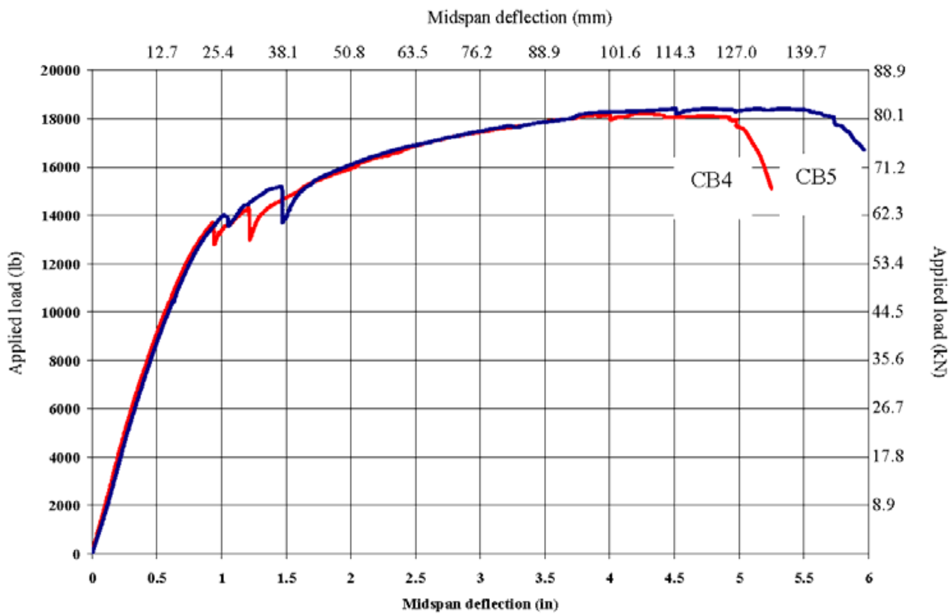

Figure 8 - Applied loads versus mid-span deflection curve for Specimens CB4 and CB5

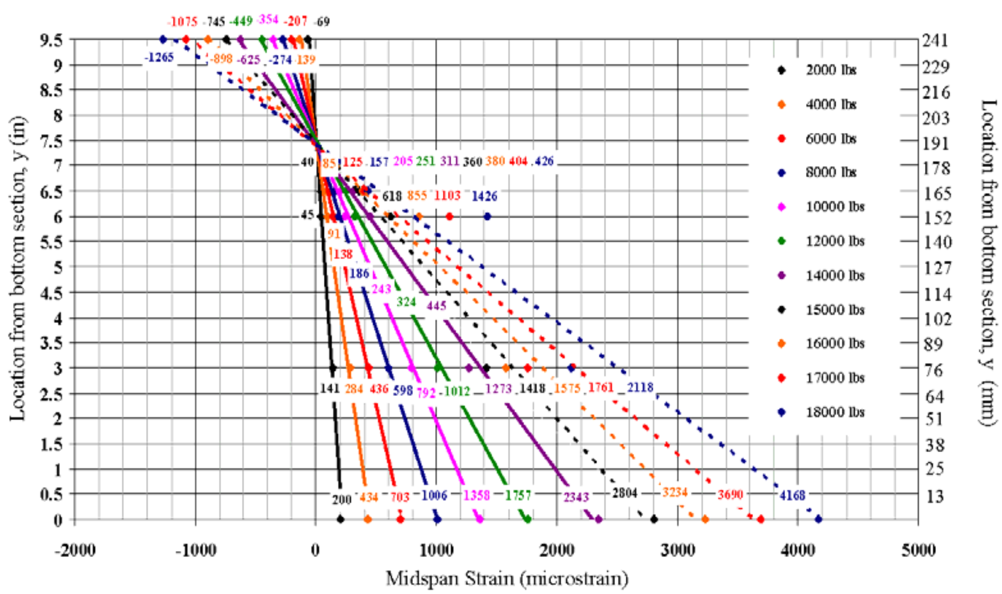

Figure 9 - Applied loads versus strain distribution at midspan for composite section CB4

Flexural design procedures of composite sections consisting of cold-formed steel joists and concrete slab are not readily available in the existing literature, and the current AISI Specifications (2001) do not provide any guidelines and provisions at all for such a composite section. Recently, Hsu, et al (2012) proposed the analysis and design procedures of composite section that are similar to those for the built-up and composite sections described in the AISC Specifications (2010) with some modifications. The structure is assumed to bend in a plane parallel to the webs, and the twisting effect can be ignored when the section strength is computed. Thus the flexural design procedures of composite section are also composed of two procedures: The procedures I is named as the initial of yielding, and the Procedure II is called as the inelastic reserve capacity.

For Procedure I, the area of concrete solid is transformed to an equivalent area of cold-formed steel joists. The total force equilibrium of the section is then used to locate the position of neutral axis when the bottom fiber of the section has reached the yielding stress. The flexural moment can thus be determined using the moment equilibrium equation. For Procedure II, the cold-formed steel joist section has been assumed to reach their full plastic stress when the outer fiber of concrete slab reaches a strain value of 0.003. The total force equilibrium in then used to locate the position of plastic neutral axis. The flexural moment can therefore be calculated from the summation of forces multiplied by their moment arms. More detailed analysis and design procedures can be found in Hsu, et al (2012), and Majdi and Hsu (2011).

Comparison of Analysis and Test Results

Table 3 shows the comparisons between the present flexural test results and the calculated ultimate strengths using the proposed analysis and design methods by Hsu, et al (2012). For Specimens CB1 and CB2 when rebar No.3 has not been transversely reinforced in the concrete slab, the analytical maximum loads using Procedure I bending are closer to those of experimental maximum loads. For Specimens CB3 and CB4, however, their analytical maximum loads using Procedure II bending are closer to those of experimental maximum loads. It is because that rebar No.3 has been properly reinforced in the concrete slabs of Specimens CB3 and CB4, thus prevent the concrete from the longitudinal shear crack. Note that Specimen CB5 has cut and bent in the ribs of the continuous shear connector , thus the experimental maximum load has been increased slightly. Specimen CB6 is a simple beam made of steel joists only; it was tested for the comparison with composite and non-composite beams. The design of Specimen CB6 is based on the AISI Specifications (2001).

Table 3 - Comparisons between Test Results and Calculated Values

Section	Experimental maximum Load (lbs) (kN)	Analytical maximum load by computer program (lbs) (kN)			Exp./ Analysis.			Mode of Failure	Remark
		Fasteners shear	Proc. I bending	Proc. II bending	Fasteners shear	Proc. I bending	Proc. II bending		
CB1 *no transverse reinforced*	**9950** **(44.26)**	-	7607 (33.84)	**8573** **(38.13)**	-	1.31	**1.16**	Flexural and brittle failure	Longitudinal Shear crack in concrete slab make the structure become a non-composite built-up section (Point Load Pattern)
CB2 *no transverse reinforced*	**11300** **(50.26)**	10215 (45.44)	**8973** **(39.91)**	14334 (63.76)	1.11	**1.26**	0.79	Longitudinal shear crack in concrete slab and flexural failure	Longitudinal Shear crack in concrete slab make the structure become a non-composite built-up section (Point Load Pattern)
CB3	**14200** **(63.16)**	-	8053 (35.82)	**9020** **(40.12)**	-	1.76	**1.57**	Flexural failure with less ductile	(Line Load Pattern)
CB4	**18100** **(80.51)**	10898 (48.48)	10084 (44.86)	**15706** **(69.86)**	1.66	1.79	**1.15**	Flexural and ductile failure	
CB5	**18348** **(81.61)**	10898 (48.48)	10084 (44.56)	**15706** **(69.86)**	1.68	1.82	**1.17**	Flexural and ductile failure	
CB6	**5750** **(25.58)**	-	**5125** **(22.80)**	5850 (26.02)	-	**1.12**	0.98	Lateral and torsional buckling	(Point Load Pattern)

Conclusions

Based on the experimental and proposed analysis results obtained, the following conclusions can be drawn:

- The study of six large scale composite beams indicates that the proposed system presents the better performance of structural ability for both ultimate strength and ductility of the section. Based on present test results, the ultimate strength and ductility of proposed composite section can be increased by 14-38% and 56-80%, respectively, as compared to a non-composite section or built-up section.
- The continuous cold-formed furring shear connector and self-drill fastener can withstand the integrity of the composite section long enough for the section to reach the flexural strength failure. According to the present experiments, the non-composite section and proposed composite section have similar behavior at the initial stage. After the concrete slab starts to crack, the compression buckling in compression flange of steel joists has been observed in the non-composite section, while the composite section can withstand more loads without buckling and can reach its full flexural strength.
- The continuous cold-formed furring shear connector can help distribute the transfer mechanism of horizontal shear force. According to the load and end slip measurements, the proposed composite section shows a better continuity of slip behavior than the non-composite section which allows the fasteners to well adjust their position. From the observations, the composite specimen failure is caused by the tilting and bearing of fasteners, and is then followed by the compression buckling of compression flange of steel joists.
- As presented in **Table** 3, the proposed analysis and design methods herein have been found to be able to predict the ultimate strength capacity of the new composite beam and floor system in terms of both shear strength of fasteners and flexural strength of composite beams. Furthermore, Elastic Analysis Approach (Procedure I) can be used to determine the flexural strength of the new composite system if the concrete slab has not been properly reinforced by the transverse bars, or Inelastic Analysis Approach (Procedure II) will be used to evaluate the flexural strength if the transverse bars have been properly designed in the concrete slab.

Appendix - References

- Abdel-Sayed, G. (1982), "Composite Cold-Formed Steel-Concrete Beams", Journal of Structures Division, American Society of Civil Engineers, Vol. 108 (ST11), pp. 2609-2622.
- American Institute of Steel Construction. (2010), "Specifications for Structural Steel Buildings (ANSI/AISC 360-10)", Second Printing, Chicago, IL.
- American Iron and Steel Institute Standard. (2001), "North American Specification for the Design of Cold-Formed Steel Structural Members", 1st Edition, Washington, DC.
- Gemini System III Floor System. (2005), "Gemini Structure Systems", A Canada Corporation, Composite Buildings, Multi-floor Buildings, website. Retrieved March 1, 2006 from the World Wide Web: http://www.geministructures.com/c_multi-floor.htm.
- Hanaor, A. (2000), "Tests of Composite Beams with Cold-Formed Sections", Journal of Constructional Steel Research, Vol. 54(2), pp. 245-264.
- Hsu, C.T.T., Punurai, S., and Munoz, P.R. (2010), "Composite Floor System Having Shear Force Transfer Member", U.S. Patent No. 7,779,590. Filed on June 19, 2007. Patent Article Published in www.FreshPatents.com, Jan. 3, 2008. Received the U.S. Patent on August 24, 2010.
- Hsu, C.T.T, Majdi, Y. and Punurai, S. (2012), "Analysis and Design of Composite Beams with Cold-Formed Steel Joists and Concrete Slab", Technical Report 2012-02, Dept. of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, January 23, 34 pages.
- Maximiliano, M., Walter A.N., Jose., J.S, and Roberto, M.G. (1998), "Cold-Formed Shear Connectors for Composite Constructions", 14th International Specialty Conference on Cold-Formed Steel Structures, October 15-16, St. Louis, Missouri, USA. pp. 409-421.
- Maximiliano, M., Walter A. N., Roberto, M. G., and Jose., J. S. (2000), "On the Structural Behavior of Composite Beams using Cold-Formed Shapes", 15th International Specialty Conference on Cold-Formed Steel Structures, October 19-20, St. Louis, Missouri, USA. pp. 307-319.
- Majdi, Y. and Hsu, C.T.T. (2011), "Technical Manual for Analysis and Design of Composite Floors with Cold-Formed Steel and Concrete Slab Having Continuous Furring Channel", Technical Report 2011-01, Dept. of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, 87 pages.
- Nakamura, S. I. (2002), "Bending Behavior of Composite Girders with Cold-Formed Steel U Section", Journal of Structural Engineering, ASCE, September, Vol. 128(9), pp. 1169-1176.

– Punurai, S., Hsu, C.T.T., Munoz, P.R. and Punurai, W. (2012), “Experimental Investigation of Composite Beams with Cold-Formed Steel Joists and Concrete Slab”, Technical Report 2012-01, Dept. of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, January 23, 33 pages.
– Punurai, S. (2007), “Behavior of Composite Beams with Cold-Formed Steel Joists and Concrete”, Ph.D. Theses, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, New Jersey, U.S.A., May, 205 pages.
– Ruiz, A., Clark, M. P. and Tooth, R. G. (1995), “Reinforced Structural Member for Building Construction”, United States Patent Number 5,414,972.
– Yu, W. W. and LaBoube, Roger A. (2010), “Cold-Formed Steel Design”, Fourth Edition, John Wiley and Sons, Inc., September.

Appendix - Notations

F_{ya} = Average yield strength; f'_c = Maximum compression strength of concrete