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AN INNOVATIVE COLD-FORMED FLOOR SYSTEM

by

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1.0 INTRODUCTION

Optimizing the use of building materials has always been one of the primary goals of engineers. It is a constant challenge to seek innovative methods to build lighter weight structures. Sometimes this is achieved through the development of new building materials, other times it can be accomplished by creating entirely new types of structural systems. Often lightweight structures can be more asthetically pleasing because of their stream-lined appearance. However, in general the motivating factor in building lightweight structures is to reduce the overall cost. One portion of a structure which offers tremendous potential for weight reduction is the floor system. The floor system is one of the heaviest components in typical steel framed buildings. A reduction in the dead load of this component will result in a subsequent reduction in the total weight of the building structural system.

Although many innovative, if not interesting, floor systems where developed in the early part of this century, it was not until the early 1920's that the first cellular steel floor was used in a Baltimore & Ohio Railroad Co. warehouse in Pittsburgh, PA. This cellular floor system was referred to as the "keystone beam" system. In these early steel deck floors, the steel deck was the load-carrying structural element. The concrete slab was used only to provide a level surface and to obtain an adequate fire rating. Around 1950, wire mesh was welded to trapezoidal steel deck profiles so that the concrete slab would act compositely with the steel deck [Dellaire 1971].

As the use of cold-formed steel deck increased, further improvements were made. In the 1960's, deck manufactures began to produce decking with embossments and depressions to provide a better bond for the concrete. This also facilitated the use of thinner gage steel for the decks. One of the most significant advances in the use of steel decks was the development of composite beam design in the 1960's and early 1970's. Here composite action is developed between the steel deck, the concrete slab and the

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supporting beams by welding steel shear connectors through the deck to the beams. This composite beam action made it possible for design engineers to reduce the weight of steel beams in the floor systems by as much as 30% [Dellaire 1971]. Today, the most common types of floor systems used in steel framed buildings in the United States incorporate the use of cold-formed steel deck and concrete slabs, with or without composite beam action.

Recently an investigation was conducted to identify or invent new types of innovative lightweight floor systems that might reduce the overall cost of steel framed building construction [Hillman 1990]. One of the most promising floor systems is a long-span cold-formed deck and composite slab floor system. This system consists of a 7.5 in. (190 mm) deep, cold-formed steel, interlocking hat sections placed side by side with a shallow concrete slab poured above the top flanges as shown in Figure 1. The concrete is placed on top of a very light gage, shallow steel deck which is laid transversely across the top of the hat sections and rigidly attached by "stand-off", self-tapping screws which also provide shear connection between the concrete slab and the steel hat sections.

One of the benefits in using the long-span deck is the ability to span up to 30 ft. (9 m) between supports eliminating the need for secondary framing members within a bay. This results in a secondary floor system which is less than 10 in. (250 mm) in depth and offers the potential of reducing the floor-to-floor height of the structure. Because cold-formed steel sections are susceptible to buckling in compression, the deep hat sections cannot economically be used as the sole load carrying member for floor design loads greater than about 50 psf (2.4 kN/m^2). This deficiency can be overcome by using " stand-off" screws to cause composite action between the concrete and the hat sections. With the introduction of shear connection, the neutral axis is raised resulting in a reduction in the compression stresses in the top flange of the steel section. In addition, the slab provides some degree of stiffening to the compression zone and subsequent increase in the effective width with regard to buckling. These effects, combined with the additional load carrying capacity of the composite slab results in a more effective use of the long-span deck along with greater strength and stiffness.

2.0 TYPICAL DESIGN AND COMPARISONS

To evaluate the proposed cold-formed floor system, a 30 ft. by 30 ft. (9.1 m by 9.1 m) bay was designed and compared to conventional steel framed systems. The floor systems were designed to support a superimposed live load of 70 psf (3.4 kN/m^2) in addition to dead load. For the proposed floor, each composite hat-section was designed to support its tributary area for bending in direction of the span. That is, two-way slab action was not considered. The hat sections were 7.5 in. deep by 14 ga. (190 mm by 1.9 mm). The transverse deck was 9/16 in. (14 mm) 28 ga. (0.5 mm) centering material (form deck). Full composite action was assumed for the 2 in. (50 mm) thick, 4000 psi (27.0 mPa) normal weight concrete slab. The unit weight of the system is 30 psf (1.4 kN/m^2).

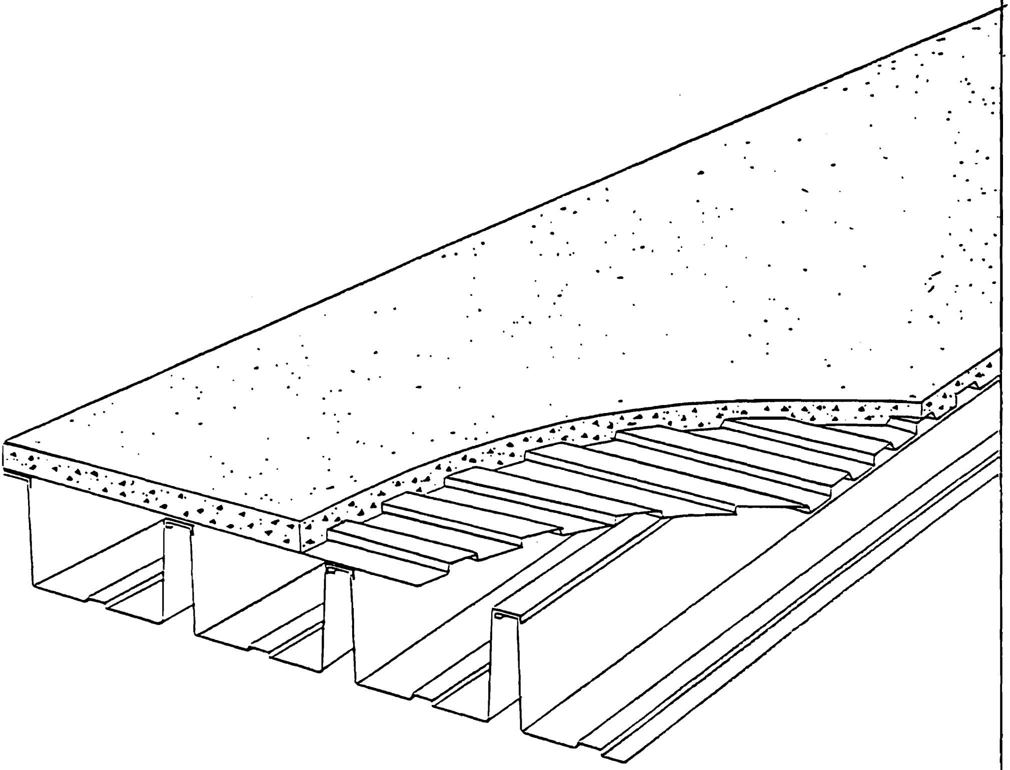

Figure 1. Long-Span Cold-Formed Deck/Concrete Slab Composite Floor System

As a basis for comparison of the proposed system, thirteen conventional floor systems were designed using both hot-rolled beams and open web-steel joists for supporting members. Two of the systems used composite beam action. The average weight of the floor systems is 42.8 psf (2.0 kN/m^2).

Theoretical values for the live load midspan deflection of the cold-formed floor system were calculated considering both one-way and two-way bending action. For one-way action, the deflection was calculated for a simply supported beam consisting of one hat section. For two-way action, the center bay deflection was calculated using Navier's solution for an orthotropic plate simply supported on all four sides [Szilard 1974]. The torsional rigidity used in this solution was modified to account for the closed section behavior of the deck sections. The predicted one-way defection is 0.82 in. (21 mm) and the two-way deflection is 0.75 in. (19 mm). These values are 1/439th and 1/480th of the span, respectively, well below the generally accepted value of 1/360 or 1 in. (25 mm). The live load deflections for the conventional floors were all less than 1/360 times the span.

Because of the very shallow depth and light weight, an obvious concern for the proposed floor system is annoying floor vibrations due to occupant activity. The vibration characteristics of the design were estimated using the mathematical models presented in the Steel Joist Institute Technical Digest No. 5 [Galambos 1988] and the perceptibility criterion developed by Murray [1981, 1990]. The perceptibility criterion is given by the inequality:

$$D > 35\, A_O\, f + 2.5 \qquad (1)$$

where D = required damping, A_O = maximum initial amplitude of the floor system due to a heel-drop impact, and f = first natural frequency of the floor system. For use in the model the heel-drop is approximated by a linear decreasing ramp function having a magnitude of 600 lbs (2670 N) and a duration of 50 milliseconds. Based on the inequality developed by Murray, if the required damping for conventional floor systems is significantly more than 4%, artificial damping may be necessary to make the floor system less susceptible to annoying vibrations. For the proposed cold-formed system, the required damping was found to be 5.8%. Vibration analysis were also performed for each of the conventional floor systems; the average required damping was 5.2%.

3.0 PROTOTYPE CONSTRUCTION, TESTING AND EVALUATION

Construction. To further evaluate the proposed cold-formed floor system, a 30 ft. by 30 ft. (9.1 m by 9.1 m) single bay prototype floor was constructed. The test floor used the design described in the previous section. Thirty sections of 7.5 in. by 14 ga. (190 m by 1.9 mm) long-span deck interlocked in an inverted hat position were used as the primary structural members. Placed transversely across these sections was 900 sq. ft. (82.8 m^2) of 9/16 in. by 28 ga. (14 mm by 0.5 mm) form deck. On top of this deck a concrete slab was placed with a total depth of 2 in. (50 mm). The concrete used for the slab normal weight had a normal cylinder strength of 4000 psi (27.6 mPa). The floor system was simply supported on all four sides by nominal 8 in. (200 mm) thick masonry walls.

The form deck was attached to the top flanges of the long-span deck sections using self-tapping, self-drilling fasteners. Approximately, one screw per 1 sq. ft. (0.09 m^2) of deck area was used. Most of the fasteners were standard 12-14, 1-1/4 in. (32 mm) long. The last six rows of fasteners at each end of the strong direction span were 12-14, 2-1/4 in. (57 mm) long, with a 1-1/4 in. (32 mm) long steel sleeve placed over the shank such that a significant portion of the screw is above the form deck. As a result these fasteners are embedded in the concrete slab and act as small shear connectors.

Load Testing. A test loading was conducted to measure the elastic response of the system. The floor system was loaded in increments to 65 psf (3.2 kN/m^2) design live load using concrete blocks. (The full design load was not applied because of the number of concrete blocks available at the time of testing). Displacement transducers were used to measure vertical displacements at center bay and at quarter points. The measured deflections were linear but slightly greater than that calculated from both plate and beam action at the full test load, 0.80 in. (20 mm) versus 0.76 in. (19 mm) for the beam solution and 0.70 in. (18 mm) for the plate action solution.

Serviceability Testing. The floor system was also tested for susceptibility to annoying vibrations from human activity. Vibrations were measured using a seismic accelerometer and the digital signals collected and filtered using a lap top computer. A "heel-drop" impact was used to induce the vibrations. Four vibration measurements were taken after each load increment: two with the accelerometer placed at the center of the bay and two at the center of the span, 7.5 ft. (4.5 m) from the edge of the slab (quarter point). For all measurements, the heel-drop impact was performed directly next to the accelerometer.

The natural frequencies were determined by processing the data using a Fast Fourier Transform (FFT) algorithm. The experimental first natural frequency for each load increment is shown in Figure 2 along with the first natural frequencies determined using both beam and orthotropic plate models. As seen on this plot, the measured frequencies are relatively close to the theoretical values.

The data obtained from the heel-drop impact is acceleration versus time. The Murray tolerance criterion requires displacement amplitude which can be obtained by integrating the acceleration versus time plots twice. Normally this works quite effectively for floor systems. However, the prototype floor system has three distinctive frequencies contributing to the energy in the system as shown in Figure 3. Figure 3 is the power density spectrum with 10 psf (0.5 kN/m^2) superimposed loading. The relative power in the second and third natural frequencies makes of use of the Murray criterion questionable, because it is based on a single degree of freedom model. Thus, comparisons to that criterion using experimental data were not made.

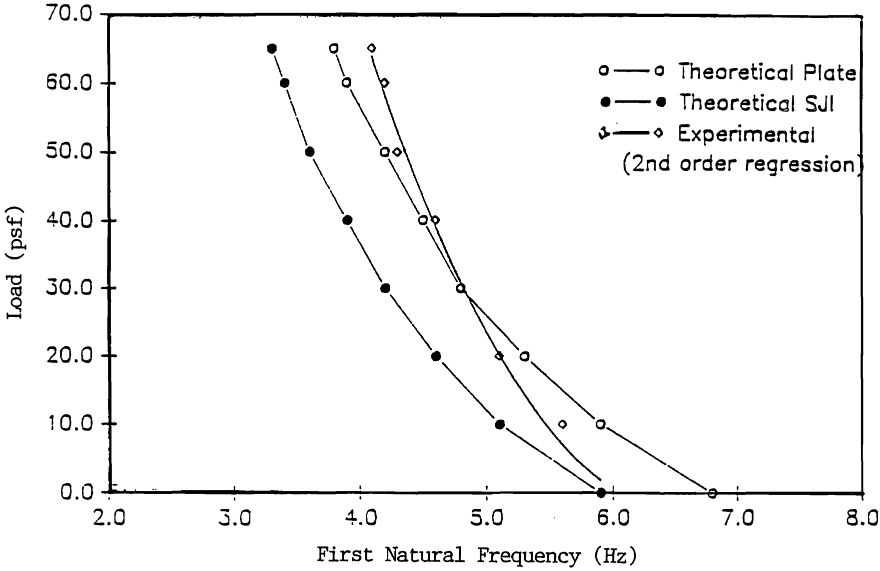

Figure 2. First Natural Frequency vs. Load

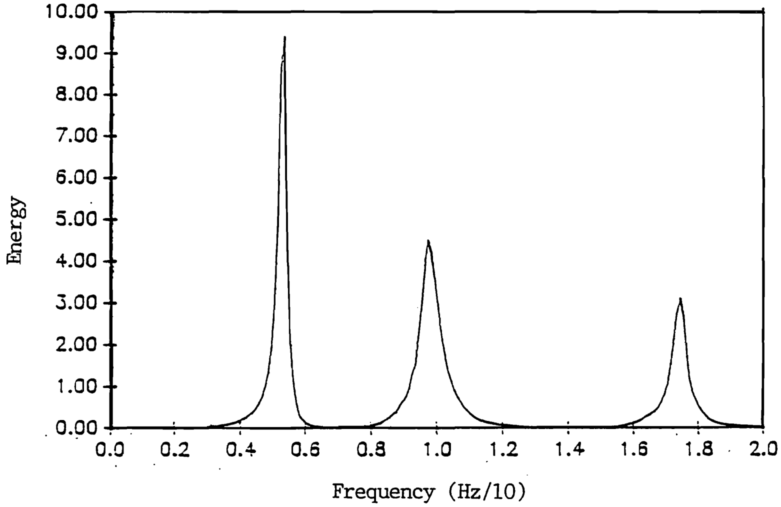

Figure 3. Power Density Spectrum with 10 psf (0.6 kN/m^2)

However, subjective evaluation of the prototype floor was solicited from six individuals involved with building construction or design. All rated the floor system as "satisfactory" with respect to motion induced by heavy walking or heel-drop impact. This result is encouraging and also indicates that the inherent damping in the floor system is greater than found in conventional concrete slab/steel beam or joist systems since the required damping from the Murray criterion is 5.8% which normally would indicate an unsatisfactory floor system.

4.0 IMPLEMENTATION

A crucial item necessary for the proposed cold-formed floor system, if it is to be a viable alternative to conventional floor systems, is the support details. Two potential details are shown in Figures 4 and 5. Figure 4 shows a composite girder with pour stops at the end of the hat sections. Figure 5 shows a stub girder detail where a tee-section is welded to a shallow, hot-rolled, H-section. The cold-formed hat sections are supported by the H-section.

Fire ratings of the proposed system are also needed. One or two layers of sheet rock can easily be attached to the underside of the system. Use of thicker lightweight concrete may also provide additional fire rating. However, fire tests are needed to determine the specific rating.

5.0 CONCLUSIONS

A cold-formed steel floor system has been proposed and tested. The system is shallower and weighs less than conventional systems. The system consists of deep long-span deck sections, a transverse shallow deck, "stand-off" shear connectors, and a thin concrete slab. Only standard engineering calculations are required for design. A prototype bay was designed and tested. The system performed as predicted to a loading of 65 psf (3.2 kN/m^2) and was found to be satisfactory with regard to floor vibration serviceability.

6.0 ACKNOWLEDGMENTS

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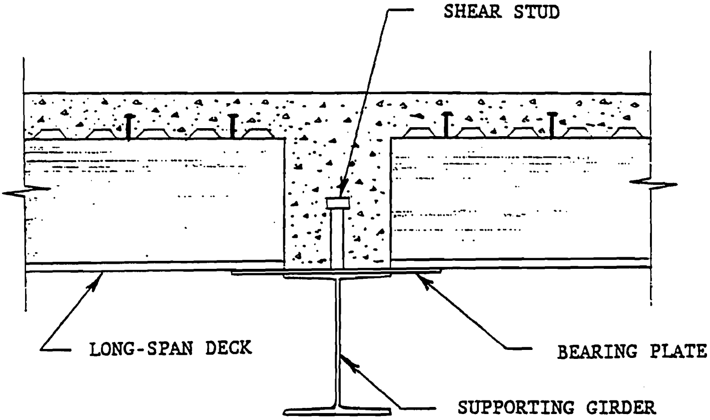

Figure 4. Proposed Connection Detail (Composite Girder)

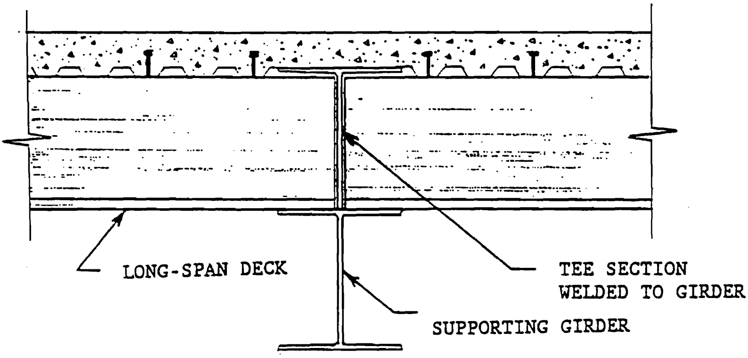

Figure 5. Proposed Connection Detail (Stub Girder)

APPENDIX- References

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APPENDIX - Notation

A_0 = maximum initial amplitude of the floor system due to a heel-drop impact.

D = required damping.

f = first natural frequency of the floor system.