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Innovative Lightweight Floor Systems for Steel Framed Buildings

Nouveaux planchers légers pour bâtiments à structures métalliques

Neue Konzepte für leichte Deckensysteme in Stahlrahmengebäuden

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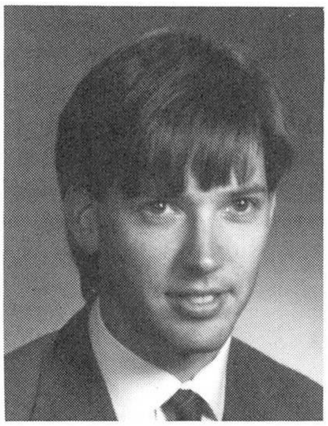

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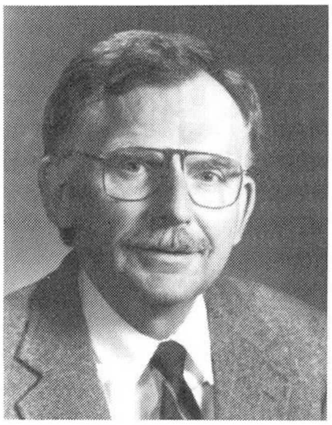

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SUMMARY
The floor system has always been one of the heaviest components of a building structural system, and therefore comprises a significant portion of the dead load. By developing substantially lighter-weight floor systems it should be possible to reduce the entire weight of a building structural system, from the framing members to the foundations. This paper presents some innovative concepts for constructing lighter-weight floor systems using various configurations of mixed materials.

RÉSUMÉ
Le plancher a toujours été un des éléments les plus lourds du système structural d'un bâtiment et, par conséquent, il représente un part important du poids propre de la structure. En développant des planchers bien plus légers, il devrait être possible de réduire le poids total de la structure d'un bâtiment, des portiques jusqu'aux fondations. Cette communication présente quelques nouvelles idées pour la construction de planchers légers, en utilisant des configurations différentes de mélanges de matériaux.

ZUSAMMENFASSUNG
Das Deckensystem war schon immer der schwerste Teil der Baukonstruktion und macht daher einen wichtigen Teil des Eigengewichtes aus. Durch die Entwicklung von wesentlich leichteren Deckensystemen soll es möglich werden das Eigengewicht der ganzen Baukonstruktion, vom Rahmen bis zum Fundament, zu vermindern. Dieser Beitrag beschreibt neue Konzepte für leichte Deckensysteme durch Verwendung von Verbundmaterialen.

1.0 INTRODUCTION

It is a constant challenge to engineers to seek innovative methods to build lighter weight structures. Sometimes it 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 aesthetically 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. A reduction in the dead load of this component may result in a subsequent reduction in the total weight of a building structural system. The objective of this investigation is to create or identify innovative lightweight floor systems that can effectively reduce the overall cost of steel framed building construction.

For many years the most common type of floor system used in steel framed buildings was a 102 mm thick concrete slab with the supporting beams completely encased in concrete. On top of this was a 102 mm topping slab which also contained all of the conduits and wires [1]. In all, these thick floor slabs accounted for a substantial portion of the dead load of a building.

During the early 1900's many new floor concepts were developed in an attempt to increase the fire ratings of buildings as well as reduce the dead load contributed by the floor system. Some of these include ceramic arch floor systems, the Columbian Floor System, Roebling Floor Systems, and The Rapp Fireproof Floor System [2]. Although these systems offered many advantages over thick concrete slab floors they eventually fell by the wayside. The two primary reasons for this were the dwindling supply of cinders used for the lightweight concrete fill material and the onset of steel deck floor systems [1].

The first cellular steel floor was used in a Baltimore & Ohio Railroad Co. warehouse in Pittsburgh, PA in the early 1920's. This cellular floor system was referred to as the "keystone beam", manufactured by the H.H. Robertson Co.. In early steel deck floors, the deck was the only load carrying structural element. The concrete slab was only necessary to provide a level surface and to obtain an adequate fire rating. More recent developments for the use of steel deck floor systems include steel deck that acts compositely with the slab, and composite beam action between the steel framing members and the slab through the use of shear studs. This composite beam action makes it possible for the design engineers to reduce the weight of the steel beams in the floor systems by as much as thirty percent [1].

At the present day, the most common types of floor systems used in typical steel framed buildings in the United States incorporate the use of cold-formed steel deck and concrete slabs, with or without composite beam action. Although profiled steel deck and concrete floors provide a lighter weight alternative to the thick concrete slabs of earlier years, little research has been conducted with regard to developing completely new floor systems that may result in even greater dead load reductions.

2.0 REFERENCE FLOOR SYSTEM

As a basis of comparison for the innovative light-weight floors being investigated, a series of reference floor systems were designed. In light of the advantages and the popularity of cold-formed steel decking, this configuration was chosen for all of the reference floor designs. Some of the systems were designed using hot-rolled shapes others use open web steel joists. All of the systems were designed using normal weight concrete, 22.78 kN/m^3, and two of the floors exploit composite beam action. A total of thirteen different systems were designed to allow a broader basis of comparison.

One of the primary disadvantages of lightweight floor systems is that they tend to be susceptible to annoying vibrations induced by human occupancy. The vibration characteristics of the reference floor systems were analyzed using the perceptibility criterion developed by Murray [3]. This is done by using the following inequality ($D > 1.38A_0f_1 + 2.5$), where D = required damping, A_0 = maximum initial amplitude of the floor system due to a heel-drop impact (in mm), and f_1 = first natural frequency of the floor system (in Hz). For use in the mathematical model, the heel-drop impact is approximated by a linear decreasing ramp function having a magnitude of 2.67 kN and a duration of 50 milliseconds. Based on the inequality developed by Murray, if the required damping is significantly more than 4%, then some sort of artificial damping may be necessary to make the floor system less susceptible to annoying vibrations.

All of the reference floor systems were designed using a superimposed live load of 3.35 kPa. The vibration analysis for each system only considers dead load plus a superimposed live load of 0.527 kPa. The average unit weight of the reference floor systems is 2.05 kPa, and the average required damping is 5.2%. One very obvious characteristic of all of the floor systems is that 80 to 88 percent of the total weight can be attributed to the concrete slab. As a result, it appears that the most significant weight reduction can be achieved by a reduction in the slab weight. Although lightweight concrete could be used to reduce the weight of the reference floors, normal weight concrete has been specified because it generally more available and less expensive.

3.0 FIBRE REINFORCED PLASTIC - PULTRUDED DECK

The first conceptual floor system to be discussed is a composite slab system constructed using a fibre reinforced plastic (FRP) deck with a concrete fill. The proposed deck is manufactured using the pultrusion process. Pultruded shapes are one of the most common types of FRP used in civil engineering applications and usually consists of glass fibre reinforcing with a polyester or vinylester resin. The components are combined by pulling the continuous glass rovings longitudinally through a resin bath where they are completely coated. Once coated they are pulled through a hot compaction die that cures the resin [4].

The pultruded deck consists of a series of 76.2 mm deep inverted T-beams on 76.2 mm centers. The beams are connected by intermediate flanges approximately 25.4 mm from the top flanges. A 25.4 mm concrete fill is placed on the top of the flanges (Fig. 1). The inverted T-beams and intermediate flanges are pultruded monolithically in 0.6 m to 0.9 m wide sections. The intermediate flange is located so that when composite action is considered most of the concrete is located above the neutral axis of the composite section. It was found that by assuming full composite action with the concrete, the rigidity of the section is at least doubled.

This type of deck configuration could be incorporated into a floor system by spanning the deck continuously over secondary framing members spaced at 0.9 to 2.1 m. The FRP deck itself weighs approximately 0.158 kPa. A normal weight concrete fill would add an additional 0.694 kPa. Compared to the reference floor systems this corresponds to a weight reduction of anywhere from 50% to 60%.

Despite the dramatic weight reduction this type of floor system has several disadvantages: high raw material costs, possible excessive deflections due to the low elastic moduli of the materials, poor vibration characteristics and potential fire rating concerns (which may be improved by using fire resistant resins).

4.0 STEEL GRID FLOOR SYSTEMS

Steel grid decking is another promising alternative to cold-formed steel deck/concrete slab systems. Steel grids were originally developed in the 1920's for use as a light-weight, but high strength bridge deck alternative to thick reinforced concrete slabs [5]. However, the grids manufactured for bridges would be far to heavy for use in building construction. An alternate form of steel grid floor system was developed in conjunction with this investigation (Fig.2).

The proposed system differs from present grid decks in several aspects. For example, the spacing on the primary bearing bars is increased to 457 mm rather than the usual 152 to 203 mm. The spacing on the secondary bars is also increased to 305 mm. This results in a much more open grid which in turn requires considerably fewer welds to fabricate. The primary bars used are 108 mm custom rolled I-beams. The secondary bars used are 25.4 mm by 4.76 mm rectangular bars. The secondary bars are installed such that the top of the bars are 12.7 mm from the tops of the 108 mm primary beams.

The biggest difference in the proposed deck is in the type of form pans used. Rather than install small square panels between the members of the grid, a continuous, light-gage cold-formed steel deck is placed with the ribs parallel to the 108 mm I-beams. Subsequently the profiled deck is supported both longitudinally by the top flanges of the I-beams as well as transversely by the tops of the secondary bars. The deck is installed during the fabrication process or during erection.

Finally, a 38.1 mm deep lightweight concrete slab is placed on the profiled steel deck. The entire configuration would weigh 0.895 kPa. This reduction in steel weight, along with lower fabrication costs, makes the proposed grid deck floor system feasible. This system also presents a significant reduction in the weight relative to typical floor systems.

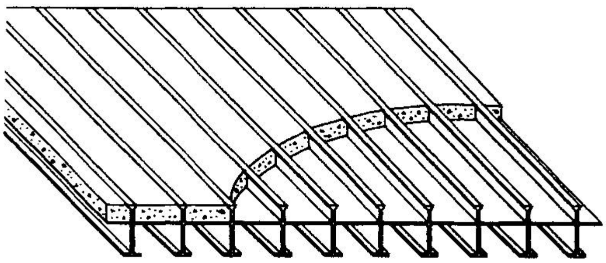

Fig. 1. (FRP) - Pultruded Deck

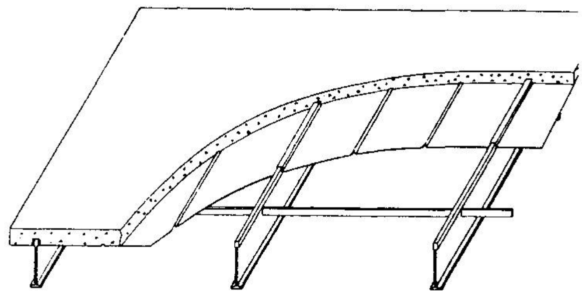

Fig. 2. Steel Grid Floor Systems

5.0 LONG-SPAN STEEL GRID

Another variation of the steel grid floor system was also investigated (Fig. 3). This system is similar to the previously discussed deck, except that the primary beams consist of a custom, hot-rolled shape that resembles an inverted T-beam rather than an I-beam. The beams are designed to be 178 mm deep with a very small top flange and very large bottom flange. These beams are then placed on 15 mm to 305 mm centers, and interconnected with 38.1x4.76 mm rectangular bars. A light gage profiled steel deck is placed continuously between the beams supported by the secondary bars. A light-weight concrete slab with a total depth of 51 mm is placed on top of the deck. Shear forces are transferred between the concrete and the steel beams by providing deformations in the top flanges of the steel beams similar to those found on typical reinforcing steel.

The primary benefit of this system is that it is able to span 9.1 m as a simply supported beam. This eliminates the need for any secondary framing members, and because the entire configuration is only 203 mm deep, it results in an overall reduction in the floor to floor height of the structure.

6.0 LONG-SPAN DECK/CONCRETE SLAB COMPOSITE FLOORS

The last floor system developed is a long-span deck and composite slab floor system. This system would consist of 190.5 mm deep, 14 gage cold-formed steel hat sections placed side by side with a shallow concrete slab poured above the top flanges (Fig. 4). The concrete itself is placed on top of a very light gage, shallow steel deck which is laid transversely across the top of the long-span deck and rigidly attached by self-tapping stand-off fasteners. In addition, the shallow profiled steel deck is designed so that shear forces can be transferred between the steel and concrete components.

The long-span deck acting compositely with the concrete slab is also capable of spanning up to 9.1 m. without the need for secondary framing members. The entire floor system is only 241 mm deep and weighs 1.436 kPa. As with the long-span steel grating, this system offers the potential for reducing the floor to floor height of a building. It may also be possible to use the cells of the deck to accommodate service requirements. These characteristics could aid in making steel framed buildings more competitive against concrete frames utilizing thin post-tensioned flat slab floors.

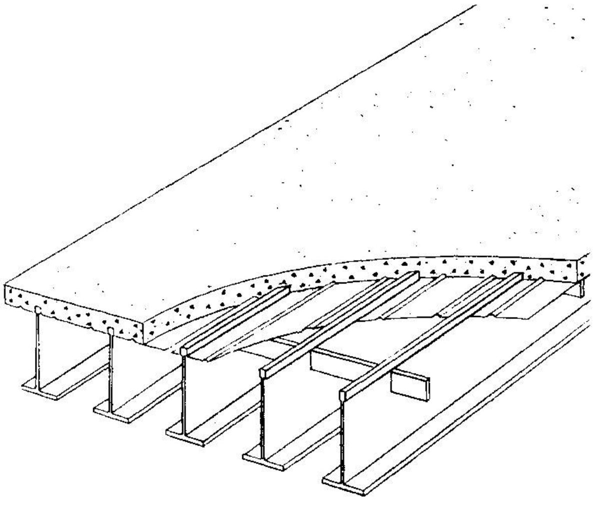

Fig. 3. **Long-Span Steel Grid**

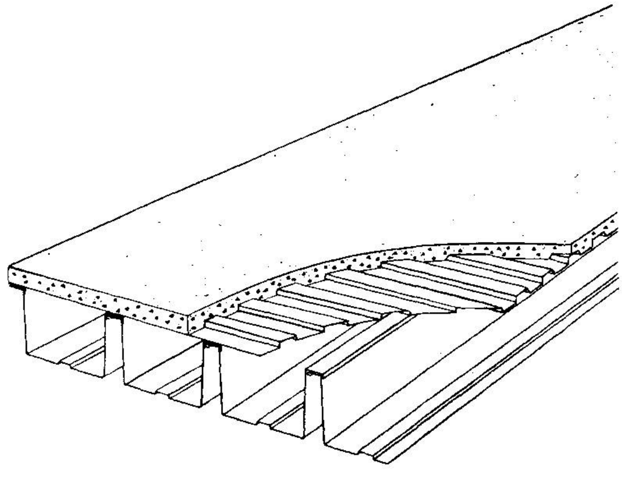

Fig. 4. **Long-Span Deck/Concrete Slab**

7.0 CONCLUSIONS

If strength were the only requirement, designing lightweight floor systems would be a fairly simple task. However floor systems perform a great many functions in addition to merely sustaining gravity loads without some sort of catastrophic failure. Subsequently, a host of behavioral characteristics have to be taken into consideration to successfully design and implement any innovative lightweight floor system.

Table 2, shown below, provides a quantitative comparison for some of the innovative floor systems investigated. The basis of comparison is the average reference floor system. The unit weights for the various systems include the weights of both the slab and framing components. The %SLAB value is the percentage of the total weight attributed to the slab component. The vibration characteristics for the proposed systems have been calculated using the mathematical models presented in Technical Digest No.5 of the Steel Joist Institute [6] as well as the perceptibility criterion developed by Murray [3].

Table 2: CHARACTERISTICS OF PROPOSED SYSTEMS

SYSTEM ANALYZED (Single Bay 9.1m x 9.1m)	WEIGHT kPa	WEIGHT %SLAB	VIBRATION RESPONSE f_n (Hz)	VIBRATION RESPONSE A_o (mm)	VIBRATION RESPONSE D_{REQD} (%)
RFS AVERAGE	2.052	85.1	5.68	0.340	5.16
FRP Deck w/2% steel reinf.	0.947	73.9	8.68	0.381	7.14
Long-Span Deck/Conc. Slab	1.193	64.4	5.04	0.483	5.84
Steel Grid (18in x 12in)	1.126	79.6	5.15	0.381	5.13
Long-Span Steel Grid	1.724	80.2	4.20	0.381	4.64

As indicated in Table 2, it is possible that some of the proposed lightweight floor systems may actually perform better than the reference floors with respect to vibrations. However the results of these vibration analyses should be verified by experimental testing in order to make a truly accurate comparison.

Overall, the systems which appear to have the most potential for further development at this time are the long-span deck/concrete slab concept and the steel grid floor systems. Both of these systems offer the advantage of lighter weight compared to present methods of construction. Although they do not necessarily represent the lightest alternatives investigated, it is believed that these two floor systems may offer the best performance with respect to the various functional requirements set forth.

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