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COMPOSITE CONSTRUCTION - APPLICATIONS

BY: ALBERT J. OUDHEUSDEN*

Synopsis

Recent developments in the design and construction of composite steel-concrete beams and slabs when these are used in combination with cold-formed sheet products are reviewed.

Introduction

Composite construction has gained much popularity in the design of modern steel structures, primarily because research in recent years has provided the necessary design information to allow exploitation of its inherent advantages. These are:

1. More efficient structural use of steel, especially high-strength steel. The size and weight of beams and girders can be reduced significantly while adding strength and stiffness at the same time. This frequently results in a cost reduction, due not only to savings in weight of steel, but also for fire protection, stairs, elevators, perimeter walls, etc. since story heights and depths of members are reduced.
2. The strength and stiffness of a composite section is larger than for an equal size non-composite beam and slab. This permits an increase in span and/or load-carrying capacity of the beam or slab without affecting structural performance negatively.
3. Other cost savings can accrue from reduced shipping costs, lower painting costs, and in conjunction with steel decks savings in reinforcing steel.

The principles of composite design are well known and are covered in various books on the subject. In this country the Design Specifications of the American Institute of Steel Construction govern the design of composite beams. The cold-formed steel design specifications of the American Iron and Steel Institute govern the design of forms and decks. Design criteria for composite form-reinforced slabs are being developed based on research at Iowa State University and proprietary test results furnished by various manufacturers of composite forms and decks.

Non-Composite Forms (Centering Devices)

Consider first the design of a composite beam, when permanent non-composite steel forms are used for the concrete slab (Figure 1). The corrugated sheet is designed to serve both as form for the wet concrete and working platform. After the concrete hardens, the formed sheet serves no further function and the concrete slab and beam support all loads.

Stud shear connectors are commonly used to transfer shear between the slab and the beam. Until recently, holes had to be provided in galvanized forms so that the stud could be welded directly to the beam. Today it is possible to weld the stud through several layers provided the galvanized sheets have a controlled coating weight, usually 1/2 ounce per square foot or less. Bare (uncoated) steel forms pose few welding problems. Other types of shear connectors, usually manually arc-welded, are also available, but they are usually somewhat more expensive to place.

The current AISC specifications do not provide criteria for the design of composite beams with a formed steel deck between beam and concrete slab. If the corrugations are parallel to the beam (Figure 1), this condition would be similar to a haunched slab and in general the composite beam behaves as if the slab were solid. However, when the corrugations are transverse (Figure 2) the composite system could behave substantially different when using forms of certain proportions as discussed later.

Research[1,2] principally by Professor Hugh Robinson at McMaster University and by Professor John Fisher at Lehigh University has demonstrated that the horizontal shear capacity is a function of rib geometry. The shear capacity of the connector alone does not determine the composite shear strength because cracking of the concrete in the deck flutes could reduce the shear transfer capacity. On the other hand, shallow corrugations have little or no influence on composite beam behavior and the beams can be designed as though the slabs were solid.

For forms having rib heights "h" up to 1-1/2", there is usually no significant reduction of beam stiffness in the working load range, provided the compressive stress block does not extend below the top of the rib configuration ($a \le t - h$) (Figure 3). The depth of the compressive stress block, "a", can be calculated from

$$a = \frac{A_s F_y}{0.85 f'_c b}$$

A_s = Area of steel beam
F_y = Specified minimum yield stress for the steel beam
f'_c = Specified compression strength of concrete
b = Effective width of the concrete slab

It is conservative to use the full slab thickness, t, in calculating section properties and number of shear connectors (Figure 4).

For composite beams and slabs with 3" deep decks the beam will tend to deflect more as the working load level is approached than if no steel deck were present. However, from a comparison of behavior of 3" rib decks in proprietary composite beam tests, the deeper deck will usually develop a beam stiffness equal to, or larger than the conventional slab at, or below the working load level, provided the shear connectors are welded directly through the steel deck to the steel beam; or, if the stud connectors are placed through holes in the deck and the sheet is tack-welded to the beam.

For the latter case the elastic section properties must be adjusted when the depth of the compressive stress block "a" falls below the top of form corrugations ($a > t - h$) (Figure 5). In this case the effective depth of slab can be taken as ($t - h$) and the slab area above the ribs can be used to calculate the required number of shear connectors.

A summary of test results to date on composite beams with slabs over corrugated or cellular steel decks indicates that: 1) Shear connection strength may be affected significantly by cell geometry; 2) shear connection strength tends to decrease, as rib height increases relative to rib width; 3) concrete around the shear connector governs the strength; 4) a more flexible connector can cause earlier failure of the concrete by shearing off the ribs; and 5) smaller diameter studs tend to provide a more efficient shear connection than proportionately fewer large diameter studs.

The following tentative design recommendations have been proposed by Professor Fisher of Lehigh University for composite beams with formed metal deck up to 3" high, placed with ribs transverse to the beams: 1) Flexural stresses at the working load level should be determined on the basis of

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moment of inertia for the transformed composite section. Full slab depth, t, should be used when determining effective width of slab. 2) Stud shear connectors located in the ribs can be designed on the basis of an allowable load:

$$Q_{rib} = k \frac{w}{h} Q_{AISC}$$

k = coefficient proposed equals 0.50

w = width of rib

h = rib height

Q_{AISC} = shear connector strength given in AISC specifications

Studs should extend above the top of the rib into the solid portion of the slab. 3) If the concrete is made with ASTM C330 lightweight aggregates, the above allowable shear connector strength, Q_{rib}, should be multiplied by a factor

$$\sqrt{\frac{E_c^{LW}}{E_c^{NW}}}$$

E_c^{LW} = Modulus of Elasticity for lightweight concrete

E_c^{NW} = Modulus of Elasticity for normal weight concrete

4) Until further research is completed, studs larger than 3/4" in diameter should not be used. 5) For rib heights between 1-1/2" and 3" the transformed properties of the composite beam should be calculated on the assumption that concrete below the top of the steel deck ribs is not effective. 6) For full flexural capacity, the maximum horizontal shear force "V_h" shall be taken as the smaller of

$$V_h = \frac{1}{2}\left[0.85\ f'_c\ b\ \ (t - h)\right]$$

or

$$V_h = \frac{A_s F_y}{2}$$

An extensive research project has been initiated at Lehigh University on composite beams and slabs, including 3" deep decks. These tests hopefully will verify the above recommendations wherever they are based on limited or proprietary information.

Composite Open-Web Joists

Washington University, St. Louis, Missouri, has conducted an exploratory research program for the Steel Joist Institute aimed at determining the feasibility of establishing design criteria and/or safe load tables for composite joists (Figure 6). The principal advantage of composite joists is improved stiffness and a reduction in joist weights. However, these weight savings are in part offset by the cost of shear connectors. It is frequently possible to maintain a single size for the cold-formed top chord of all joist sizes, which can lead to economies in manufacturing.

Composite Forms and Decks

Composite metal decks, i.e. those cold-formed steel forms that will interact with the concrete to serve also as reinforcing steel for the concrete slab, have the following obvious advantages: 1) They are left in place permanently; 2) the forms are light in weight and easily handled and placed, which reduces installation time and minimizes on-site labor; 3) they provide a safe working platform; 4) they can reduce the problem of scheduling the various trade unions on the job; and 5) after the concrete hardens they become the reinforcing steel of the slab. Metal forms are usually placed by ironworkers who also erect the structural steelwork and field-weld the shear connectors. For all practical purposes carpenters would be needed only for forming around columns, openings, etc., and possibly for placing the shoring, if needed; 6) there is usually only a minimal amount of temperature steel to be placed; 7) the steel forms can be blended easily with pre-engineered raceways for electrification - communication - and air-distribution systems.

Today there are almost a dozen manufacturers producing proprietary composite form systems. In the steel industry we realized some years ago that with so many different systems being promoted, some published design or performance criteria would be needed to evaluate the load-carrying characteristics of these forms. Otherwise, the customer or the approving building code agency would have no basis on which to make a judgment, except to have every manufacturer supply test data for each construction situation that could arise. This would be costly and creates a situation which could affect the use of such forms adversely. AISI, therefore, sponsored a research program at Iowa State University under the direction of Professor Ekberg to develop a basis for the necessary design criteria by investigating various types of composite form systems.

The most common composite forms on the market are of a type resembling forms "O" (Figure 7) and "I" (Figure 8) in which the shear transfer between form and concrete is obtained by means of regularly spaced embossments pressed into the surface of the form. A mechanical interlock occurs if these embossments are of the proper size and depth. For design purposes it is not customary to depend on bond between the steel and concrete, because bond will be destroyed under overloads or dynamic loading. However, in most cases bond does exist and will improve the performance of the slab under normal service loads.

Another type form included in the Iowa State research program is form "G". Form "G" (Figure 9) depends for shear transfer on T-wires welded to the forms at a variable spacing and anchored in the concrete.

Almost all composite decks tend to be stronger than needed for stress considerations; i.e. a tensile failure of the steel is highly improbable. The normal mode of failure is in shear-bond. For form type "G" it depends on the number, size and spacing of T-wires provided. A gradual concrete crushing failure can occur for thin slabs.

It is anticipated that design criteria will be based on ultimate strength concepts using a load-factor approach to determine design loads. Due consideration will he given to effects from repeated loading, and deflection limits under short- and long-time loading. Shoring is used to control deflections of longer spans. Generally, it has minor effect on the ultimate strength of a composite slab.

It is common construction practice to provide only a nominal reinforcing such as 6 x 6 - 10/10 welded wire mesh over interior supports to control shrinkage and cracking of slabs designed as simply-supported beams. The T-wires of form "G" may be adequate for this purpose if enough wires are provided. If the composite slab is designed on a continuous span basis, then adequate negative reinforcing steel must be provided.

Applications

Figure 10 is a cut-away for form type "I" showing use of a blend duct system.

Figure 11 shows typical forming and reinforcement around openings.

Figure 12 shows planking which must be used to distribute concentrated working loads prior to placing and curing of the concrete.

Figure 13 shows a blend system including the header duct.

Figure 14 - standard header ducts for activating cellular panels.

Figure 15 - cut-away for form type "O" system.

Figure 16 - an example of welded studs and embossments on the steel deck.

Figure 17 - cut-away of a "Keystone" type deck.

Figure 18 - cut-away for form type "C" system - note the T-wires.

Figure 19 - closeup of a special type shear connector.

The composite form systems shown in Figures 10 to 19 are currently sold to manufacturer's specifications and recommendations as contained in their respective catalogs.

Fire Protection

Another item of considerable importance in these composite form-reinforced slab systems is the fire protection needed to obtain a one, two, or three-hour U. L. fire rating. This requires a series of standard ASTM fire tests for systems with (a) no protective fireproofing on the form, (b) a spray-on type fireproofing on the form (Figure 20), or (c) with a suspended fire-rating ceiling. Most of the unprotected systems have two-hour, and, in some cases, three-hour fire ratings, if lightweight concrete is used. Fire ratings vary with the slab thickness.

If the intended applications include ducts as part of the floor system for wiring or air conditioning, etc. (blend systems), these ducts must also be included in the slabs used for the fire tests.

Future Work

It is hoped that some tentative design criteria based on the Iowa State Research will be published in the near future. However, these design recommendations are still subject to change and therefore detailed formulations have been omitted. In the meantime, the research work on composite forms is continuing in order to evaluate: 1) the effect of concentrated and line loads; 2) the effect of slab width and the influence of slab continuity; 3) the degree of interaction between composite beams and composite slabs, including the shear connection; 4) temperature and shrinkage steel requirements; 5) influence of cut-outs; 6) the amount of permanent set due to long-term loading; 7) the effects of using lightweight concrete; and 8) the effect on bond of surface condition of the steel.

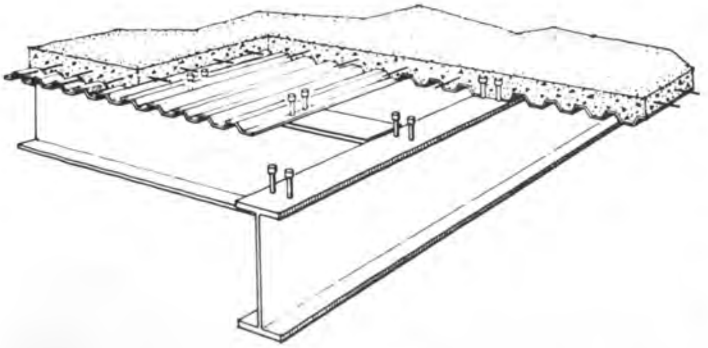


Figure 1

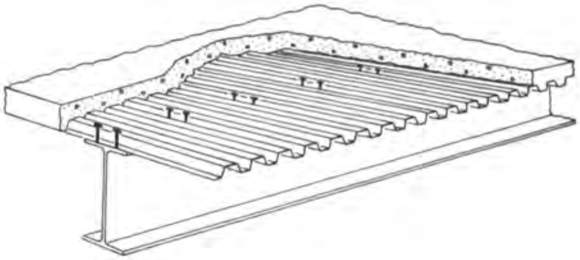


Figure 2

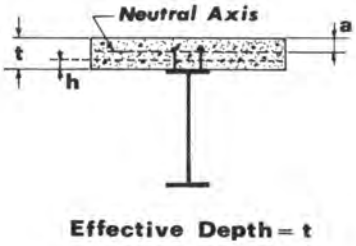


Figure 3

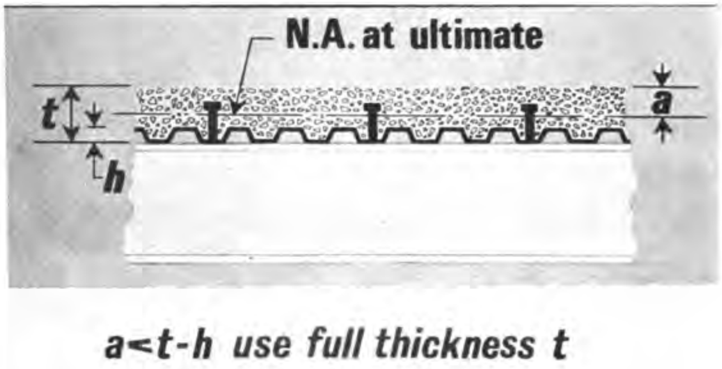


Figure 4

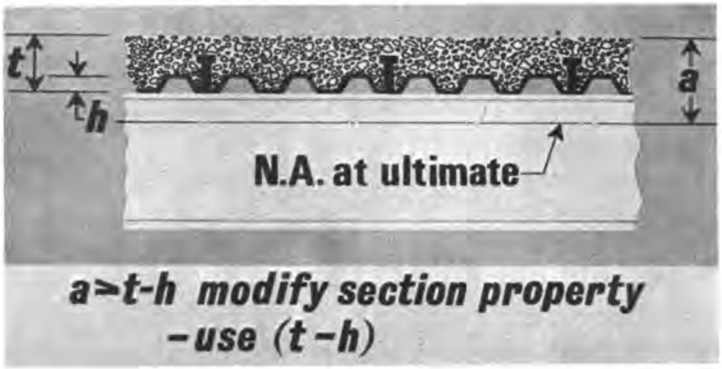


Figure 5

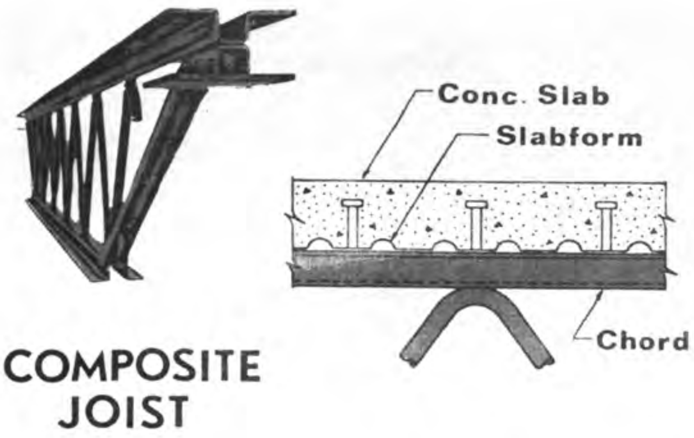


Figure 6

Figure 10

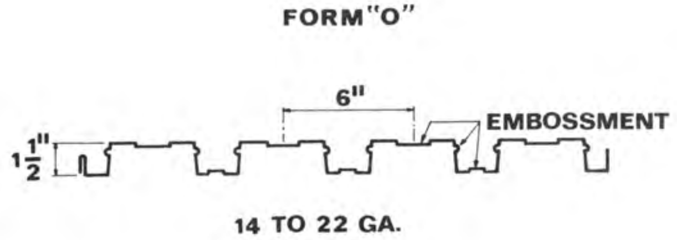
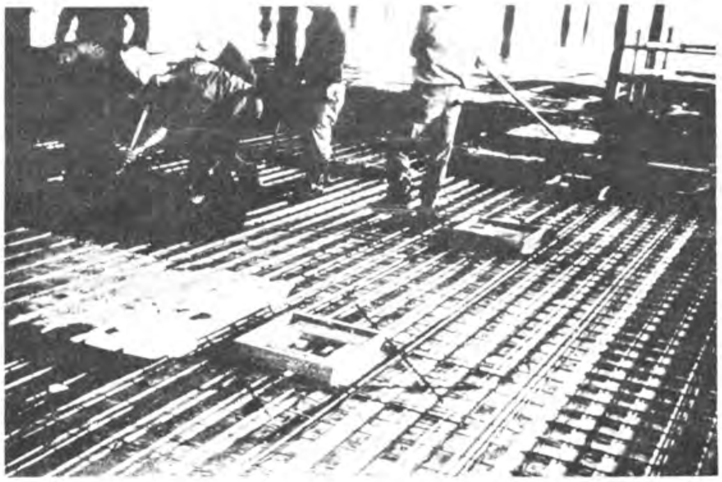


Figure 7



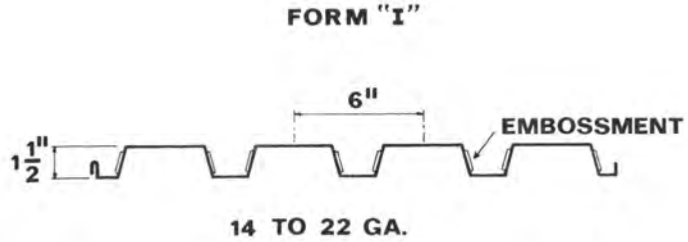


Figure 8

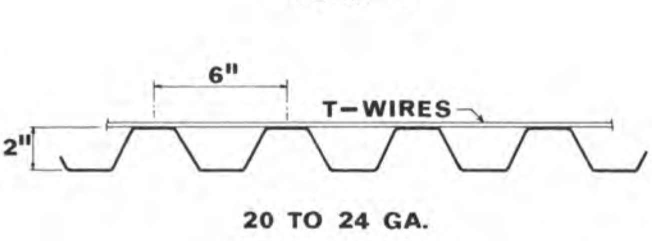


Figure 9

Figure 12

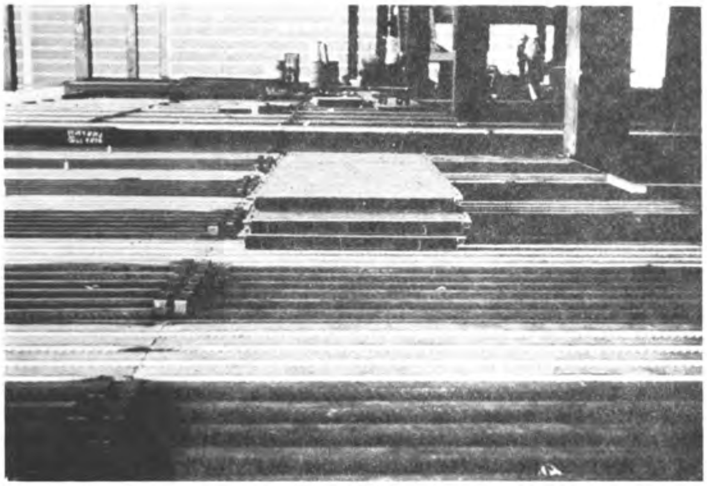


Figure 13

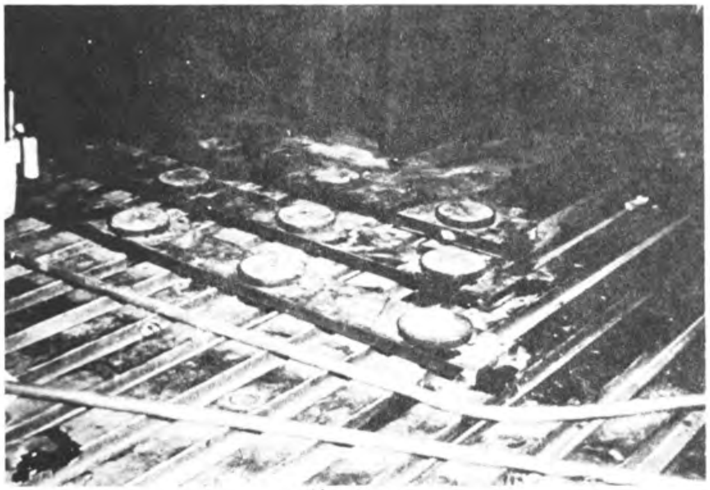


Figure 14

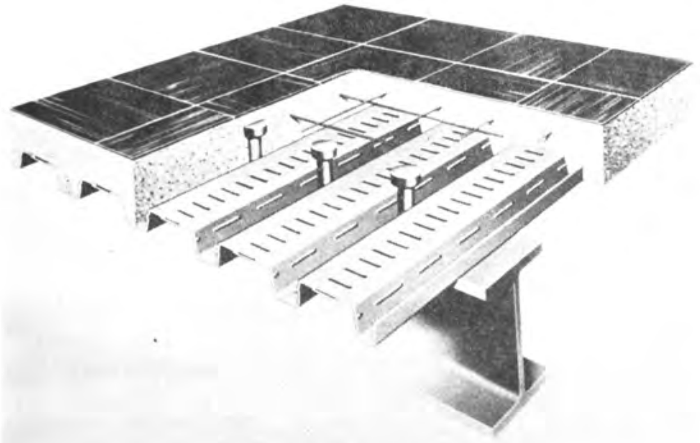


Figure 15

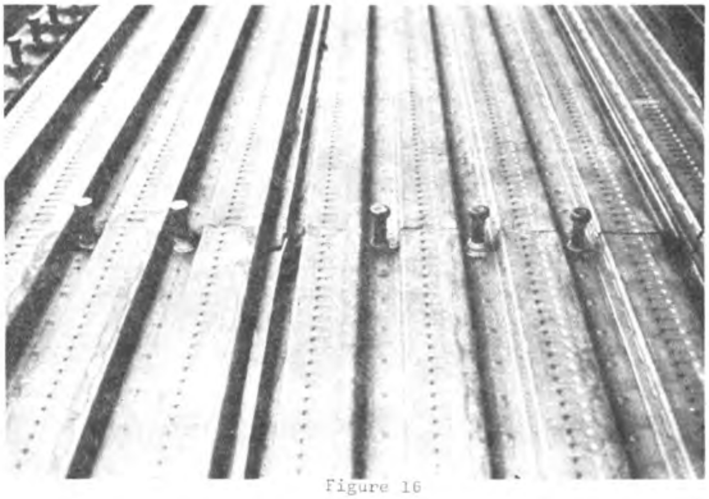


Figure 16

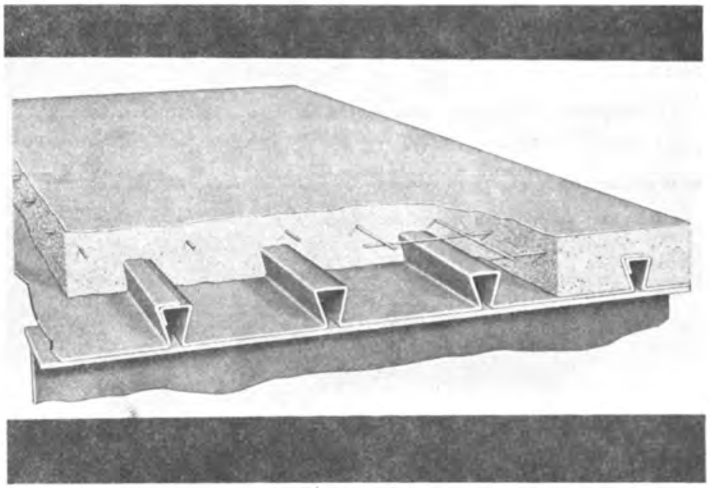


Figure 17

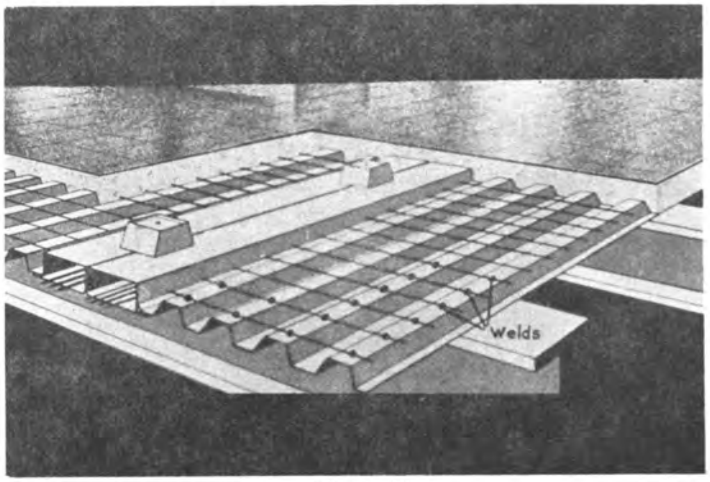


Figure 18

Figure 19

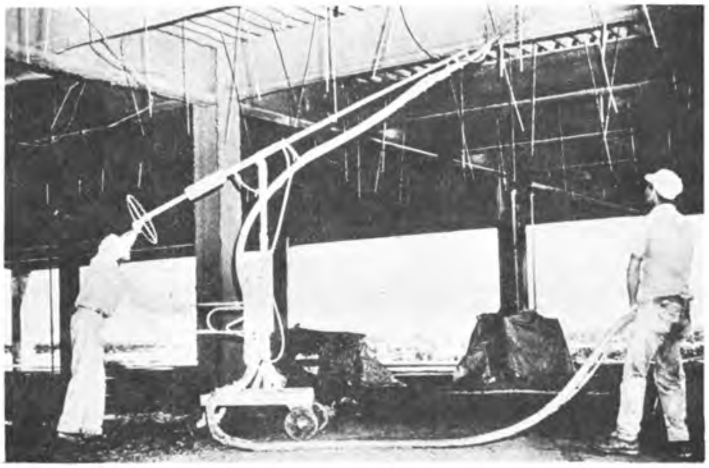


Figure 20

Conclusion

Composite form systems are gaining rapid and widespread acceptance in steel-framed building construction because of their relative ease and economy of construction. There seems to be no valid reason why they could not be used also in concrete framed buildings.

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