DESIGN AND CONSTRUCTION PROBLEMS OF STEEL FORMED DECK FLOORS IN STEEL BUILDINGS

Abdulaziz M. Al-Hamad

Assistant Professor of Structural Engineering, Department of Building Sciences and Technology, King Faisal University, Dammam, Saudi Arabia. e-mail: ahamad@dammam.kfu.edu.sa

ABSTRACT

Some design construction problems related to steel formed deck and concrete slab floors in steel buildings built in Dammam, Saudi Arabia are presented. Their description and effects on building performance in daily use and possible causes are discussed.

Omitted concrete slab reinforcement results in severe cracks due to mechanical equipment vibrations. This changes the floor stiffness and its dynamic response characteristics, which in turn amplifies the resulting vibrations, and creates an uncomfortable feeling for the building users. Improper design considerations for impact loads due to mechanical equipment and their poor isolation from supporting floor causes excessive deflections that are aggravated when coupled with water leakage and resulting corrosion of steel elements. Weak lateral stiffness of the floor system due to poor connection detailing and weak joist lateral stiffness causes horizontal movement of the floor system.

These construction problems may be explained by improper interpretations and application of different codes requirements, divided design and construction responsibilities among designers and builders, and lack of periodic inspection and maintenance. Such problems may provide partial explanation to the relatively low acceptance of this type of construction in Saudi Arabia compared to other parts of the world.

Keywords: *design Problems, construction problems, steel buildings, steel structures, slab reinforcement, floor vibrations, connection detailing, periodic maintenance.*

الملخص

يعرض البحث بعض مشاكل التصميم والتشييد المرتبطة بالارضيات المكونة من الالواح الفولاذية المشكلة مع البلاطة الخرسانية في بعض المباني الفولاذية التي بنيت في الدمام بالمملكة العربية السعودية، ويشمل وصف هذه المشاكل وتأثيرها على أداء المباني ومسبباتها المحتملة.

إن حذف التسليح للبلاطة الخرسانية من الأرضية ينتج عنه تشققات واسعة فيها بسبب الاهتزازات الناتجة عن الاجهزة الميكانيكية بالمبنى. وهذا يغير جساءة (قساوة) الأرضية وخواصها الديناميكية، مما ينتج عنه زيادة في مقدار الإهتزازات فيعطي شعورا بعدم الراحة لدى المستخدمين للمبنى. التقدير غير السليم لتأثير إهتزازات الأجهزة الميكانيكية على تصميم الأرضية وضعف العزل لهذه الإهتزازات عنها يزيد مقدار الهبوط فيها، والذي يتعاظم مع حدوث تآكل وصدأ للأجزاء الحديدية بسبب تسرب المياه تحت هذه الأجهزة. كما أن ضعف المقاومة الجانبية لنظام الأرضية بسبب

التركيب غير السليم لأجزائه مع بعضها البعض مضافا إليه ضعف الجساءة الجانبية للكمرات الثانوية ينتج عنه حركة أفقية غير مرغوبة للأرضية.

يمكن تفسير حدوث هذه المشـاكل بالأخطاء في تطبيق و/أو تفسير إشتراطات ومتطلبات مواصـفات البنـاء (building codes)، توزيع مسئوليات ومهمات التصميم والتنفيذ للمبنى بين جهات مختلفة، والنقص في عمليات الكشف الدوري والصيانة. إن وجود هذه المشاكل الإنشائية في المباني الفولاذية يمكن أن يعلل جزئيا القبول المحدود لهذا النوع من المباني في السعودية مقارنة بدول العالم الأخرى.

1. INTRODUTION:

Steel structural systems are not popular for office buildings in Saudi Arabia. Many factors limit their popularity to industrial uses in the form of one-story, large span frames. Some of these factors are related to the availability of experienced contractors and manufacturers. In addition, past experience of some steel office buildings, where unexpected problems were encountered that affect their serviceability and performance in daily use, may have created negative impression of steel material in office buildings. In this paper, some problems related to the steel formed deck floor system in steel buildings are presented, along with their description and their effects on building performance and daily use, and possible causes.

The formed deck floor: this system is one of the popular slab systems used in steel buildings, and is widely used by local contractors in Saudi Arabia. The main attraction of this system is the use of the formed (also called corrugated) steel sheets as shattering during concrete placement, which increases construction speed, complementing the main advantage of steel as a fast construction material. In this system, concrete slab -or layer- is cast on formed steel deck, which is carried by and connected to steel beams.

Building codes provide the designer with the flexibility to select the appropriate system for designing the formed deck floor. The wide ranging options available to the designer allows him to include or exclude several factors in his design, such as the use of composite deck-slab action, use of composite beam-slab action, and use of reinforcements in the slab. The inclusion of these variables in the design depends on design assumptions and availability of construction equipment.

Neglecting the delicate interaction between these different factors may result in a deficient design that exhibits poor performance characteristics and negatively affects the use of the building, as explained below. Corrosion problems exaggerated these problems.

Some buildings that exhibited such problems in Dammam area were examined by the author and the results are presented in this paper. A description of the inspected buildings, and the problems encountered in them are discussed in detail, followed by conclusions.

2. DESCRIPTION OF INSPECTED BUILDINGS:

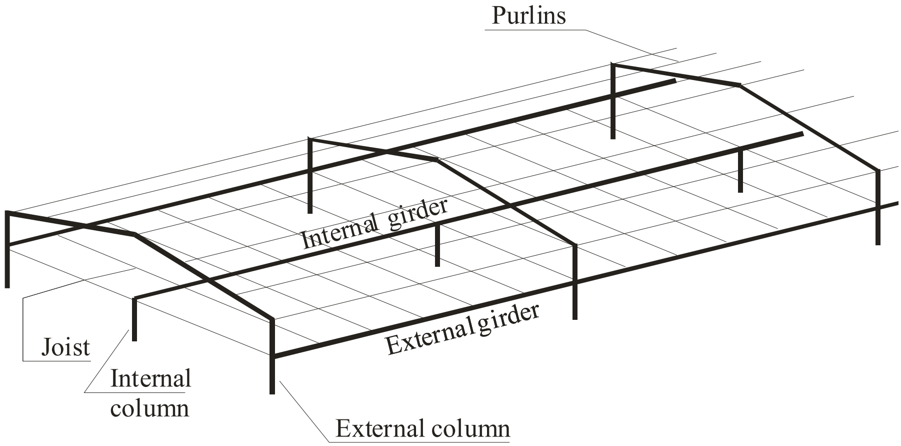
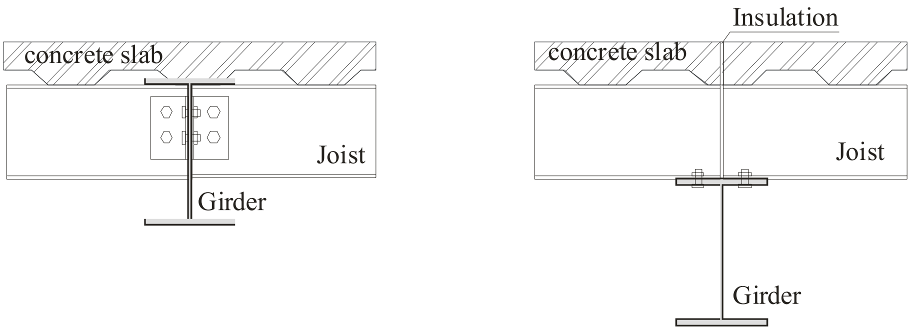


Figure (1) Typical frame layout for steel building.

Several buildings were inspected, two of them are two stories high and others are one story buildings. For the two story buildings, the main structural system is made of single-bay steel frames across the building width. These frames have their two columns located at the exterior walls of the building, and their beams located at the roof level and carrying the roof, with frame span of about 12 to 14 m and column height of approximately 7 m. The steel frames are repeated along the building length with distance between adjacent frames of about 6 m. In the first building, the columns have varying cross section, increasing with height, the beams are gabled, and the beam-to-column connection is moment resisting, making the frame a rigid one. Figure (1) shows a typical layout of the building framing system. The second building has external columns with constant cross-section, horizontal beams, and the beam-to-column connection is simple one.

The flooring of the upper story –also called mezzanine floor- in both buildings is carried by three lines of girders extending along the building length, two connected to the external frame columns and the third located at the middle point of the frame span and is carried by a one-story high column. Two joist beams extend across the building width, and are connected to the three girders, creating two separate bays across the building. The joists have a spacing of about 1 m along the building length, and carry the formed steel sheets, which carry the concrete slab layer, with the sheet corrugation extending perpendicular to the joists. In both buildings, the steel joist is connected to the steel sheets using screws that are 12 mm in length and 5 mm in diameter. These screws provide support for the joist during concrete placement. No shear studs or other types of shear connectors were used.

For the mezzanine floor, the formed steel sheets for both buildings have about 40 to 50 mm height, and about 0.5 mm thickness, and the concrete layer has total depth of 100 mm and minimum depth of 60 to 50 mm. No slab reinforcement was used in the first building, while the second had a steel wire mesh slab reinforcement made of 6 mm wires at 100 mm spacing in both directions. The concrete slab was separated in the second building along a line extending above the middle girder; i.e., there was discontinuity in the joists and the concrete layer at that line; steel sheets were only overlapped.



(a) Joist and girder at same level (b) Joist placed above girder

Figure (2) Floor system construction: (a) in first building, (b) in second building.

In the first building, the joist was made of hot-rolled steel plates welded to form a built-up W-section; the joist web is connected to the girder web through an angled plate at one side using two bolts between the connection plate and each web, Figure (2-a). The top flanges of the joists and girders were at the same level, and the steel sheets are laid on them. In the second building, the joist is made of two cold-formed channel sections bolted together back-to-back using two lines of bolts across the web height to form a composite W-section. The joist lower flange is directly connected to the upper flange of the girder using two bolts, while the steel sheet is laid at the top flanges of the joists, Figure (2-b).

Roofing for both buildings is made of z-purlins that extend between the frame beams and carry sandwich-panel formed steel sheets. These panels have standard dimensions of 65 mm total thickness and their formed steel sheets are 0.5 mm thick.

These buildings were evacuated because of poor performance resulting from several factors. First, the cracks in the concrete slab of the mezzanine floor created uncomforting feeling among users. In addition, excessive leakage due to rain and near the water circuits caused corrosion damage to some steel beams, columns, and sheets, as well as other parts such as partitions, floor tiles, and false ceiling. No proper air conditioning zoning was implemented, where upper and ground stories in these buildings were not properly separated. This created uncomfortable feeling of excessive cooling in the ground floor and insufficient cooling in the upper floor in the summer, and similar problems in the winter; improper thermal insulation of the building external walls contributed to this problem.

Other factors, such as poor soil investigation and/or poor foundations design resulted in visible settlement of some column foundations, further reinforcing the negative feeling of the buildings. Prefabricated partitions and external walls displayed signs of deterioration due to weathering, water leakage, and foundation settlements. These buildings were in service for only 10 to 15 years.

3. CONSTRUCTION PROBLEMS OF FORMED DECK SLABS:

Main problems related to design and construction of formed deck slabs in these buildings are: missing slab reinforcement, excessive floor deflection, and lateral deflection of the floor due to weak lateral stiffness. Detailed discussion of these problems follows.

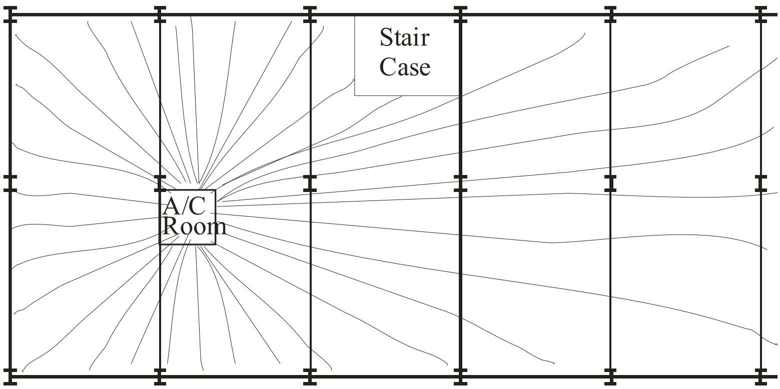
3.1. Missing Slab Concrete Reinforcement:

Slab reinforcement has two main functions, to carry tensile stresses when required, and to prevent cracks due to secondary stresses resulting from shrinkage, creep, temperature, and impact and vibration loads. For traditional reinforced concrete slabs (without steel deck floor) reinforcement carries mainly tension stresses, and is designed according to codes for reinforced concrete design, such as the American Concrete Institute Building Code Requirements for Structural Concrete (ACI 318-95) [ACI, 1995].

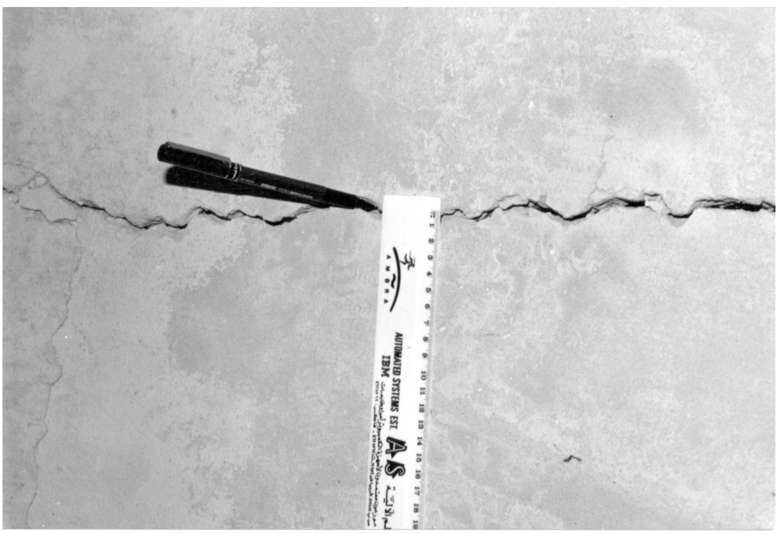
For composite concrete-steel deck and steel beam systems, neither the ACI code nor the American Institute for Steel Construction [AISC, 1989] deals directly with the requirements for reinforcement for the concrete layer. For composite sections, the ACI Building Code limits its treatment to those made of two (or more) layers and of concrete, but excludes the steel-concrete composite sections; it refers to the AISC specifications for covering them. The AISC code, on the other hand, does not deal with the requirements for slab reinforcement of composite steel-concrete system, but it requires the section to act as one unit for proper composite action.

For the individual concrete layer, the ACI building code treatment of “concrete slabs” is applicable and the need for reinforcement in this layer is subject to the same general requirements for concrete slabs; i.e., it has to be designed for tensile stresses when present. The code deals with two types of structural concrete slabs: reinforced concrete and plain concrete. For reinforced concrete slabs, a minimum ratio of steel reinforcement in the slab is required to resist primary tensile stresses or secondary stresses. For plain concrete, tensile stresses are resisted by concrete and hence should be limited to less than the allowable tensile stresses so that no cracks are formed in the section [ACI, 1995, Sect. 22.5]. In both cases, appropriate design for impact loads and vibrations is required.

From the above discussion, concrete reinforcement in formed steel decks can be omitted only if appropriate conditions are satisfied. First, the concrete layer must be properly supported so that stresses are minimal and tensile reinforcement is not needed; this may be satisfied by using a formed steel sheet that is strong enough to carry the loads applied to the slab without buckling [Bernard et. Al., 1993]. Second, the concrete layer does not have to resist shrinkage and temperature strains; this may be satisfied if the steel sheet has embossing or indenting to restrain the concrete layer, and/or by welding steel wires to the deck perpendicular to the forms direction [Owens and Knowles, 1993]. Third, the concrete layer must be isolated from vibrations to avoid cracks due to them [ACI, 1995]. If one of these conditions is not satisfied, the slab must be provided with its own reinforcement to resist tensile stresses, if present, and to resist vibrations and/or shrinkage and temperature effects.



(a) Cracks pattern in the concrete layer of the mezzanine floor due to one unit.



(b) Major crack in the concrete layer.

Figure (3) Cracks in non-reinforced concrete layer due to air handling units vibrations.

In the first inspected building, the absence of concrete layer reinforcement coupled with poor isolation of HVAC equipment (i.e., air handling units) and use of smooth formed steel sheets (as opposed to embossed or indented sheets) subjected the concrete layer to severe cracks in the whole floor area. These cracks had a radial pattern having its center at the HVAC equipment location. They were most severe in both size and concentration near the HVAC equipment and became less frequent and smaller as the distance from the HVAC unit increased. Since the floor has two HVAC units located towards the opposite ends of the building, there were two patterns of cracks radiating from the locations of those two units, and crossing at the middle area of the building, Figure (3-a). The cracks also followed the paths of conduits for electrical wiring embedded in the concrete layer.

These cracks divided the concrete slab into discrete blocks that were in continuous movement against their adjacent blocks. Continuous floor vibration caused grinding and some loss of interlocking between these concrete blocks, leading to further deterioration and increased crack widths with depth equal to the full slab depth. Crack widths up to 8 mm at the slab surface were measured in the areas near the HVAC units, Figure (3-b).

As a result, the floor stiffness decreased, and its response to vibrations was governed mainly by the stiffness of the steel beams and formed steel sheets. Decreased stiffness caused the floor to become more resonant to the induced vibrations and increased vibrations magnitude. This follows basic dynamics, where the floor vibration increases as its stiffness decreases. Occupants began to notice these vibrations with time, and eventually felt uncomfortable with them and complain about them. Such noticeable vibrations were more distracting and annoying in quiet office settings where legs of chairs vibrated noticeably. This situation may be categorized as "easily perceptible" [Vannoy and Heins, 1979].

A possible contributing factor to missing reinforcement in the concrete layer is the subcontracting of the design and manufacture of steel portion of the project to specialized firms by a general contractor, who carries out the rest of the project including the installation of the steel parts and the concrete work. Without clear documentation and direct supervision, some of the design assumptions may be violated or improperly implemented; neglecting the slab reinforcement is such an example.

3.2. Excessive Floor Deflection:

This problem was noticed mainly in the floor bays under HVAC equipment in the upper floor level of the second building (with slab reinforcement). The excessive deflection caused water leakage from the unit assembly to accumulate at the center of the floor underneath it. The accumulated water seeped through the concrete layer, and with passage of time, it caused severe corrosion of the steel sheet and the two middle joists. Severity of corrosion completely consumed the upper flanges and most of the web of these joists, Figure (4), causing loss of their strength; this in turn increased the floor deflection. Sheet corrosion is illustrated in Figures (4) and (5).

Figure (4) Corrosion of steel joist before (left) and after dismantling the floor (right).

Figure (5) Relative movement of floor at the line above the middle girder.

Permanent slab deflection measured after removal of the equipment was 70 mm over a span of 7 m. This large deflection caused visible cracks at the top of the concrete layer at the edges of the slab under discussion. When the building was dismantled, the two middle joists under each of the two HVAC units on the floor were the only joists that fell apart and hanged from their ends.

The cause for initial excessive deflection may be attributed to neglecting the special design considerations for the equipment heavy weight and its impact loads; the floors under HVAC equipment had the same structural design as the rest of the buildings. In addition, poor isolation of the equipment increased the effect of the unit vibrations on the floor.

3.3. Weak Lateral Stiffness of Slab:

Another problem that was noticed in the second building was the relative movement of the slabs in the two adjacent bays -extending across the building- against each other, where the concrete slab was separated along a line extending above the middle girder. This movement may be due to one or more of the following several factors. First, the joists were erected above the girders, as illustrated in Figure (2-b) above. Second, the joists were constructed of two cold-formed channel sections, connected back-to-back by two lines of bolts across the joist height. These bolts were low grade ones with simple tightening (i.e., no pretensioning which produces friction resistance), allowing the channels to easily move against each other when subjected to lateral loads perpendicular to its axis. In other words, this type of construction provided weak joist lateral stiffness, allowing relative movement of the joist top flange against its lower flange. As a result, the two sets of joists in the two adjacent bays across the building moved by a distance of about 20 mm, as seen in Figure (5).

Further slab movement may have been prevented by contact between the edge of the slab and the column located at the slab edge, and/or shear force in the bolts joining the two channel sections due to relative slip between the channel sections. Both loads on the column and bolts due to slab movement were not accounted for in the design.

4. CONCLUSIONS:

Some design and construction problems in formed deck and concrete slab floors of steel buildings and their effects and possible causes were presented in this paper. The following conclusions may be drawn:

1. The importance of proper interpretation and implementation of code requirements for reinforcement of concrete layer in formed deck slab systems, and their implementation in actual construction. Distributed design and construction responsibilities among different parties may contribute to these problems.

2. Floor design should account for effects of mechanical vibrations and shrinkage/temperature strains through slab reinforcement. Severe cracks of the concrete slab result from ignoring these effects.

3. The floor should be properly isolated from mechanical vibrations to avoid excessive floor deflection and/or cracks in concrete.

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4. The importance of attention to details; improper connection detailing between the joist and the girder resulted in noticeable lateral movement of the floor due to its weak lateral stiffness.

5. Poor periodic inspection and maintenance aggravates the effects of these problems and increases their damage to the building.

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