A Study of Residential Flooring Systems

by

James Keith Carlat

B. S., Kansas State University, 1969

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1970

Approved by:

Peter B. Cooper

Major Professor

TABLE OF CONTENTS

INTRODUCTION 1

The Problem 1
The Purpose 1
Scope 1

LITERATURE SURVEY 3

Introduction 3
"Traditional" Flooring Systems 5
Alternate Flooring Systems 7

DESIGN PROCEDURE AND RESULTS 10

Introduction 10
Design of Flooring Systems 11
Discussion of Designs 18
Comparison of Flooring System Costs 18
Discussion of Cost Comparison 19

DISCUSSION OF OTHER FACTORS 22

Construction Equipment 22
Construction Details 22
Fire Resistance 24

CONCLUSIONS 26

RECOMMENDATIONS FOR FURTHER STUDY 28

ACKNOWLEDGEMENTS 30

REFERENCES 31

APPENDICES 33

A. Figures 33
B. Flooring System Designs 36
C. Timber Floor Design Calculations 37
D. Concrete Floor Design Calculations 39
E. Non-Composite Joist System Design Calculations 41
F. Form Decking Subfloor Design Calculations 42
G. Composite Joist Design Calculations 43
H. Flooring Designs and Costs 46
I. Building Materials Costs 52

INTRODUCTION

The Problem

One of the critical needs facing the United States in the 1970's is the development of adequate housing. The Federal Government estimates that 26 million additional dwelling units will be needed within the decade 1968-1978. (1) The present rate of residential housing construction must be greatly accelerated to meet the demands of our expanding population. To accomplish this goal innovations will be required in many areas including land development and utilization, financing and construction. This study is concerned with housing construction, and involves a study of alternative flooring systems for residential buildings.

The Purpose

The purpose of this research is to develop and evaluate a number of alternatives to the conventional flooring system predominantly used today. This conventional type of flooring system consists of timber floor joists with plywood decking as a subfloor. All the systems studied are compared on a material cost basis recognizing that a more economical system might not be obtained. The results of the study, however, should prove useful in future feasibility studies and for possible adoption of one or more of the alternative systems examined.

Scope

The investigation is limited in scope to a study of flooring systems of steel and concrete construction and a comparison of these systems to the conventional timber joist and plywood subfloor system. The steel-concrete systems examined are similar to those currently used in multi-story steel frame buildings. These include open-web steel joists with cast-in-place concrete floors using reuseable forms or form decking with or without composite joist action. Both standard and light-weight concrete are considered.

Each system is analyzed to determine the proper proportioning and spacing of components to satisfy strength, stability, and deflection requirements utilizing current design criteria. The cost of materials required for construction is then determined for each system. To make these comparisons as meaningful as possible, data on material cost were obtained from an arbitrary construction market as of a preselected construction date. Labor requirements are discussed in a qualitative manner. A qualitative comparison of other aspects such as fire resistance and construction details is also presented.

LITERATURE SURVEY

Introduction

Since the earliest days of American homebuilding, wood has been the basic building material. The continued use of timber flooring systems has not been entirely the result of standard practice or tradition. Lumber has been plentiful and the cost of the conventional flooring system has been such that alternatives have received only limited consideration. The huge number of dwellings the homebuilding industry must furnish in the next few years raises questions of the practicality and economy of alternate flooring systems. The National Association of Home Builders (NAHB) estimates that a 50% boost in tree cutting will be required to meet the demand for lumber. (1) Presently a 50% increase in cutting cannot be realized because there simply are not enough trees of harvestable age. (1)

Since March 1, 1970, lumber has been classified by a new grading system termed the "American Softwood Lumber Standard". (2,3) This new standard allows a reduction of cross section dimensions while maintaining the same allowable load carrying capacity of the old grading standard. In addition, the dimension reduction should help to offset the developing shortage of lumber. The dimension change did not result in a price decrease, since lumber is still sold according to nominal dimensions (i.e., as though a 2"x6" were actually 2"x6" and not 1½"x5½").

In an effort to meet the housing goal and to promote innovation in the industry, Congress enacted the Housing and Urban Development Act of 1968. This legislation established in the

Department of Housing and Urban Development (HUD) a program called "Operation Breakthrough". (4,5,6,7) "Operation Breakthrough" was designed to provide 6 million subsidized dwelling units for modest income families and to encourage the development of new ideas in home building. (8) From this work, a number of new designs and procedures should be available for use by local builders to help meet the 26 million unit goal.

The homebuilding industry is highly fragmentized. In 1969 the largest homebuilder in the United States (Levitt and Sons) supplied only 6800 dwellings, approximately one per cent of the total production. (9) It is obvious that even with "Operation Breakthrough" and the increased number of non-housing corporations it has drawn into the housing industry, a major portion of American housing must be constructed by the small homebuilding contractors.

In addition to improvements in land utilization, financing, construction methods and similar phases of housing development, HUD hopes to improve some of the "behind the scene" factors which are forcing increases in the cost of housing. One of these factors is the building code. In United States cities today there are over 8300 different codes. (10) These codes not only retard standardization, but they also slow acceptance of new materials and methods. Builders are prevented from reaping the savings of mass production and component standardization because of the variations in codes. Union featherbedding and work which involves overlapping union crafts inflate construction costs. Limited success is being experienced toward achieving interchangeability of work among crafts (11) but union-management agreements on a larger scale are needed. These areas of the housing industry must be improved before alternate flooring systems can be developed to their full potential.

"Traditional" Flooring Systems

The timber floor system has long been an accepted component of the American home. Down through the years timber has been plentiful and economical. Timber floors have complemented the remainder of the house, which was composed primarily of wood products and involved the same craftsman, the carpenter, in its construction. The use of timber for the floor permitted modification on the site by the carpenter when problems arose or revisions were desired. Timber makes a flexible flooring system because it is a workable building material.

A common timber floor consists of timber joists, a subfloor, and bridging. (Figure 1) The finished floor and the ceiling of the level below will not be considered since they are common to all the floor systems that will be examined. The timber floor system to be used in this study is considered typical and is based on common practices described in references (12,13,14) and observations of the author.

The timber joists act as beams spanning over the space below. Common joist sizes encountered in residential construction are 2"x8", 2"x10" and 2"x12"; the joist spacing is usually 16 inches center-to-center. The joists are analyzed as independent, simply supported beams subjected to a uniformly distributed load. The uniform load includes a 40 psf live load and dead load consisting of the weight of the subfloor, finished floor, ceiling and joist. The design is normally controlled by bending moment or deflection, which is computed considering the uniform live and dead loads. In most cases, the joists are not actually designed but a joist size that is known to be adequate is merely specified.

The joists span the smaller dimension of the floor area and if necessary, beams running the length of the floor area can be used to support the joists at interior points. This allows the joists to be spliced at the beam and much shorter joists can be used. Normally joists are doubled under cross partitions (a partition running parallel to the joists).

Construction of the floor system begins by securing the sill to the foundation wall through the use of anchor bolts. (Figure 2) (Only the ground level will be discussed.) Next, the rim joist, a frame of joist size lumber that encloses the floor area, is nailed to the sill. The joists are then set in place and nailed to the sill and rim joists. If this does not provide the joists sufficient bearing area, the joists must be extended to the outside edge of the sill and separate blockouts must be placed between the ends of the joists to replace the side rim joists.

The subfloor is commonly 3/4" plywood decking which runs normal to the joists. The decking is secured to the joists with nails. Although the subfloor increases the strength and rigidity of the joists considerably, this beneficial effect is not considered except that is assumed that continuous lateral support is provided to the joists by the subfloor.

"Bridging" consists of lumber that is nailed between joists to produce unit action in the floor system. Solid bridging is joist size lumber and is used at main bearings such as support beams and foundation walls. It also acts as a firestop if a ceiling covers the joists. Herringbone bridging is normally used between main bearings and is spaced such that the distance between bridging never exceeds eight feet.

Alternate Flooring Systems

The first alternate flooring system considered in the study is the conventional concrete slab subfloor supported by open-web steel joists. (Figure 3) Reuseable forms would, no doubt, have to be utilized to reduce forming expenses. This type of flooring system minimizes building material expense while increasing the contractor's investment in forms and equipment. Both lightweight and standard concrete subfloors have been designed.

The second type of subfloor considered in the study uses form decking to replace the forms used in the system described above. (Figure 4) The decking serves only as a form and is not an integral part of the concrete subfloor, therefore, reinforcement steel is required. Where relatively light live loads are encountered, such as in high-rise apartments, a 2½" concrete subfloor poured on form decking supported by open-web steel joists makes a very economical flooring system. (15,16) Again, both lightweight and standard concrete subfloors have been designed.

Although form decking represents a substantial increase in building material costs, it has several advantages. It can normally be installed faster and with less labor than conventional form work. In most cases, the floor layout can be easily and more ecomonically designed such that temporary shoring is not required. The decking also provides a convenient working platform for workmen of other trades.

The flooring systems discussed thus far display one common characteristic. In each design the subfloor adds a varying degree of rigidity to the supporting open-web joist, thereby increasing the strength of the flooring system. If shear connectors are used, the subfloor and the joist act as a unit resulting in composite joist action. Composite joist action is what differentiates the alternate flooring systems that follow from those previously discussed.

The use of composite joist action increases the load carrying ability of the open-web joist. The joists can then be spaced at greater intervals and fewer joists are required. Recent work by Tide and Galambos (17) and by Nall, Harmon, Konpalian and Galambos (18) has resulted in shear connector load values and design procedure based on the elastic method. These studies ininvolved 3/8" stud shear-connectors. The composite joist designs of this study have been based primarily on the findings of these two investigations.

The final flooring systems examined are the concrete slab subfloor and the form decking subfloor both acting compositely with the joist. As before, both lightweight and standard concrete have been considered with each design.

DESIGN PROCEDURE AND RESULTS

Introduction

In an attempt to include all the joist spans commonly encountered in American residences, spans of 8, 12, 16 and 20 feet were included in the study. The design live load was a uniformly distributed load of 40 psf. The dead load consisted of a 15 psf load (finish floor and ceiling) plus the system's sefl-weight.

The joist spacing in each alternate floor system design was a variable determined by joist limitations. Modules of width equal to the joist spacing were then designed for each system. A summary of the flooring systems that were included in the study is presented in Appendix B. Several designs were developed for each combination of span length and type of system.

Appendix B includes the abbreviations for each design which were used throughout the study. The first letter or first two letters are J and/or C. In each design the J means open-web steel joist and the C denotes composite joist design. The next letter or two letters in the abbreviation are either S or FD. An S means the subfloor is a concrete slab type subfloor with reuseable forms used to support it during construction. The letters FD denote that form decking was used in place of reuseable forms. The last letter of each abbreviation tells whether lightweight concrete, L, or standard concrete, S, was used in the flooring system. For example, a non-composite joist design with standard concrete and reuseable forms is denoted by the letters JSS, while CJFDL represents a composite joist design with form decking and lightweight concrete.

Each component of the flooring systems was designed in accordance with the appropriate design standards currently in use. The joist design conformed to the Steel Joist Institute's "Standard Specifications and Load Tables" (19) and the "Steel Construction Manual" (20). The composite joist design included the suggestions of reference 18 as well. All concrete design complied with the "Building Code Requirements for Reinforced Concrete" (21) in addition to references 22, 23, 24 and 25. Timber was designed in accordance with the "Timber Construction Manual" (26).

Design of Flooring Systems

Design of the various flooring systems began with the conventional timber floor. The design load included a uniformly distributed live load of 40 psf and a uniformly distributed dead load of 15 psf (finish floor and ceiling) in addition to the self-weight of the system. The timber joists were spaced at 16 inches center-to-center and analyzed as independent, simply supported beams. The design procedure involved calculating the maximum moment produced at midspan of the joist and then determining the required section modulus based on allowable bending stress. The size of joist necessary to satisfy bending stress requirements was then checked to see if shear, deflection, and bearing limitations did not control the design. For the shorter spans of 8 and 12 feet bending stress controlled while for the longer spans of 16 and 20 feet the joist size was dictated by deflection limitations. The design procedure is displayed in Appendix C. A $\frac{3}{4}$ inch tongue and groove (T&G) plywood subfloor completed the conventional timber flooring system. Results of the design calculations are shown below.

Span	Joist Size	Joist Spacing
8ft	2x6	16in
12	2x8	16
16	2x12	16
20	2x14	16

The first of the alternate flooring systems to be designed was the non-composite joist with concrete subfloor formed with reuseable forms, JSS and JSL. Since the subfloor design was the same whether it was used with composite or non-composite joists it was decided to design the concrete subfloors, SS and SL, independently of the joists. The same design load of 40psf live load and 15psf dead load was used. Subfloors $2\frac{1}{2}$ and 3 inches thick were designed using welded wire fabric (WWF) reinforcement. No attempt was made to drape the reinforcement and thereby increase the "d" value (distance from the top of the concrete slab to the center of the reinforcing steel) at points of maximum moment. The WWF was assumed to be centered in the concrete so that "d" was equal to one half the concrete slab thickness at all points in the subfloor. A minimum joist spacing of 30 inches was arbitrarily adopted for all alternate designs. The concrete subfloor was analyzed as a continuous, one-way slab. The subfloor design was based on an ultimate strength design procedure outlined in the ACI Code. (21) Appendix D presents sample calculations of the subfloor design. When it later became apparent that the steel joist was to be the limiting factor in the flooring system design, the three inch subfloor designs were discarded. Designs for standard and lightweight concrete subfloors of 2½ inch thickness are shown below.

SS			SL		
Design Number	Joist Spacing	Reinforcement*	Design Number	Joist Spacing	Reinforcement*
SS-1	2'-6"-4-8	6x6-6/6 wwf	SL-1	2'-6"-4-11	6x6-6/6 wwf
SS-2	4-8--5-0	6x6-5/5 wwf	SL-2	4-11--5-3	6x6-5/5 wwf
SS-3	5-0--5-3	6x6-4/6 wwf	SL-3	5-3--5-9	6x6-4/6 wwf
SS-4	5-3--6-3	6x6-2/2 wwf	SL-4	5-9--6-7	6x6-2/2 wwf
SS-5	6-3--6-6	6x6-1/1 wwf	SL-5	6-7--7-0	6x6-1/1 wwf
SS-6	6-6--7-0	6x6-0/0 wwf			

*Reinforcement Designations from Reference 22

With the concrete subfloors designed, the steel joists were added to complete the flooring system designs. Both J-series and H-series (19) were initially included in the designs, but later the J-series proved to be uneconomical and their design was discontinued. In an attempt to prevent the alternate flooring systems from exceeding the depth of the conventional timber floor, no joists greater than ten inches deep were considered in the study. This limited the joists to one eight-inch joist, 8H2, and three ten-inch joists, 10H2, 10H3, 10H4. Joist sizes which are available in the desired length were selected and the spacing of the joists was then determined by the allowable total load. (19) Sample calculations for determining joist spacing are shown in Appendix E. In order to limit the joist spacings to practical and easy-to-construct measurements, the spacings were rounded off to quarter of a foot (three inch) increments. The JSS and JSL designs are shown below.

	JSS				JSL		
Span	Joist Size	Spacing	Subfloor	Span	Joist Size	Spacing	Subfloor
8'	8H2	69"	SS-4	8'	8H2	72"	SL-4
12	8H2	33	SS-1	12	8H2	36	SL-1
12	10H2	48	SS-1	12	10H2	54	SL-1
12	10H3	57	SS-2	12	10H3	63	SL-2
12	10H4	63	SS-3	12	10H4	72	SL-4
16	10H4	33	SS-1	16	10H3	30	SL-1
20	*	--	--	16	10H4	36	SL-1
				20	*	--	--

*No joists 10H4 or smaller are adequate

Design of the non-composite joist with form decking flooring systems, JFDS and JFDL, was conducted quite like the JSS and JSL designs. The concrete subfloor, which would be poured on form decking, is identical whether the joist is acting compositely or non-compositely. However, the form decking did require an additional computation. When the concrete is poured for the subfloor, the form decking must carry the wight of the concrete, its selfweight and a nominal construction load of 20 psf. (25) Since the form decking will not be exposed to the elements, uncoated decking was specified for greater economy. (25) A form decking marketed under the tradename, Slabform, was considered typical and the design was based on its specifications. (25) Appendix F presents sample calculations for the maximum joist spacings limited by the decking's construction loading capacity. The actual design of the subfloor and spacing of the steel joists follow the procedure used to design the JSS and JSL flooring systems. The form decking subfloor designs, FDS and FDL, and flooring system designs, JFDS and JFDL, are presented below.

FDS

Design Number	Span	Form Decking	Reinforcement
FDS-1	2'-6"-3-9	28 Gage	6x6-6/6 wwf
FDS-2	3-9--4-6	26 Gage	6x6-6/6 wwf
FDS-3	4-6--5-0	26 Gage	6x6-5/5 wwf
FDS-4	5-0--5-3	26 Gage	6x6-4/6 wwf
FDS-5	5-3--5-9	26 Gage	6x6-2/2 wwf
FDS-6	5-9--6-3	24 Gage	6x6-2/2 wwf
FDS-7	6-3--6-6	24 Gage	6x6-1/1 wwf
FDS-8	6-6--7-0	24 Gage	6x6-0/0 wwf

FDL

Design Number	Span	Form Decking	Reinforcement
FDL-1	2'-6"-4-0	28 Gage	6x6-6/6 wwf
FDL-2	4-0--4-9	26 Gage	6x6-6/6 wwf
FDL-3	4-9--5-3	26 Gage	6x6-5/5 wwf
FDL-4	5-3--5-6	26 Gage	6x6-4/6 wwf
FDL-5	5-6--6-3	26 Gage	6x6-2/2 wwf
FDL-6	6-3--6-6	24 Gage	6x6-2/2 wwf
FDL-7	6-6--7-0	24 Gage	6x6-1/1 wwf

JFDS				JFDL			
Length	Joist Size	Spacing	Subfloor	Length	Joist Size	Spacing	Subfloor
8'	8H2	66"	FDS-5	8'	8H2	72"	FDL-6
12	8H2	30	FDS-1	12	8H2	33	FDL-1
12	10H2	48	FDS-2	12	10H4	54	FDL-2
12	10H3	54	FDS-3	12	10H3	63	FDL-4
12	10H4	63	FDS-5	12	10H4	69	FDL-5
16	10H4	30	FDS-1	16	10H4	33	FDL-1
20	*	-	-	20	*	-	-

*No Joists 10H4 or Smaller Are Adequate

The flooring systems consisting of non-composite joists with composite decking and non-composite joists with cellular decking introduced in the proposal for the research were not designed. It was obvious from the previous designs that the steel joists controlled the joist spacing and strengthening of the subfloor to span greater spacings through composite subfloor design would be of no benefit. The additional expense of cellular decking could not be justified and this design was dropped.

The concrete subfloor formed with reuseable forms and acting compositely with the joist, CJSS and CJSL, was the first composite joist system to be designed. The composite joist design was based on "Standard Specifications and Load Tables" (19) and the research of Nall, Harmon, Konyalian, and Galambos. (18) After the joist spacing was determined by the composite joist design, a subfloor was selected from the previously computed table of SS and SL subfloor designs. Appendix G contains sample design calculations for the CJSS and CJSL flooring systems and the designs are shown below.

CJSS				CJSL			
Length	Joist Size	Spacing	Subfloor	Length	Joist Size	Spacing	Subfloor
8'	8H2	*	-	8'	8H2	*	-
12	8H2	45"	SS-1	12	8H2	51"	SL-1
12	10H2	*	-	12	10H2	*	-
12	10H3	*	-	12	10H3	*	-
12	10H4	*	-	12	10H4	*	-
16	8H2	30"	SS-1	16	8H2	36"	SL-1
16	10H2	36	SS-1	16	10H2	42	SL-1
16	10H3	42	SS-1	16	10H3	48	SL-1
16	10H4	48	SS-1	16	10H4	51	SL-1
20	10H3	30	SS-1	20	10H3	33	SL-1
20	10H4	36	SS-1	20	10H4	42	SL-1

*Spacing Limited by Shear in Joist, Therefore Composite Design Not Economical

The last of the alternate flooring systems to be designed was the form decking subfloor supported by steel joists acting compositely with the subfloor, CJFDS and CJFDL. The design method was similar to that used to design the CJSS and CJSL flooring systems. The results are presented below.

CJFDS				CJFDL			
Length	Joist Size	Spacing	Subfloor	Length	Joist Size	Spacing	Subfloor
8'	8H2	*	-	8'	8H2	*	-
12	8H2	42"	FDS-1	12	8H2	48"	FDL-1
12	10H2	*	-	12	10H2	*	-
12	10H3	*	-	12	10H3	*	-
12	10H4	*	-	12	10H4	*	-
16	8H2	30"	FDS-1	16	8H2	36"	FDL-1
16	10H2	33	FDS-1	16	10H2	39	FDL-1
16	10H3	39	FDS-1	16	10H3	45	FDL-1
16	10H4	45	FDS-1	16	10H4	51	FDL-1
20	10H3	30	FDS-1	20	10H2	30	FDL-1
20	10H4	36	FDS-1	20	10H3	36	FDL-1
				20	10H4	39	FDL-1

Discussion of Designs

Complete design data is tabulated in Appendix H and was the source of the designs presented in the previous sections.

The steel joist was the limiting factor in all designs of alternate flooring systems. The non-composite designs (JSS, JSL, JFDS and JFDL) were governed by shear and deflection in the steel joist. The composite joist designs (CJSS, CJSL, CJFDS and CJFDL) increased the moment of inertia of the cross-section. By using temporary shoring or joist cambering to control joist deflection until composite action occurs, the joist capacity can be increased. However, composite action does not increase the joist's ability to resist shear. The load carrying capacity of a joist limited by shear cannot be increased by designing the joist to act compositely with the concrete subfloor. Therefore, all composite joist designs were governed by shear.

Comparison of Flooring System Costs

In the final analysis, the economy of an alternate flooring system will determine its practicality. This cost study was limited to the cost of the building materials. Labor was not included. Material costs were obtained from a lumber dealer, two concrete ready-mix firms, and a steel supplier, all located in Topeka, Kansas. The Topeka market area was chosen because of its size and proximity. The material prices (effective June 1, 1970) obtained from the suppliers are tabulated in Appendix I. These charges are contractor prices within the greater Topeka area, such that no delivery expenses are included.

Some minor building material costs were omitted from the study. The expense of bridging lumber and nails was not included in the conventional timber floor costs, nor was bridging material and reinforcement chairs included in the alternate design costs. Since the costs were minor, they would effectively cancal each other out when the systems are compared.

The building material cost for each alternate flooring system design, in dollars per square foot of floor area, is presented in Appendix H. The table below is derived from data in Appendix H and shows the relative costs of the alternate designs using the conventional timber floor, with a relative cost of 1.0, as a basis for comparison.

Span \ System	Timber	JSS	JSL	JFDS	JFDL	CJSS	CJSL	CJFDS	CJFDL
8'	1.0	1.44	1.47	2.49	2.83	-	-	-	-
12	1.0	1.17	1.21	2.17	2.17	1.26	1.25	2.09	2.08
16	1.0	1.23	1.22	1.90	1.88	0.99	0.98	1.61	1.61
20	1.0	-	-	-	-	0.97	0.95	1.51	1.50

Discussion of Cost Comparison

As expected, the building material costs of most of the alternate designs were greater than those associated with the conventional timber floor. Only four of the 24 alternate designs have relative cost ratios of less than one. Several factors contribute to the higher material expense of the alternate systems and some improvements can be made in these areas.

The steel joists that are available are somewhat inefficient when used for residential flooring because of the loading and spans. The non-composite joist designs (JSS, JSL, JFDS, and JFDL) were limited by deflection and shear. By increasing the web area and cambering the joist, the load carrying capacity of the joist can be improved with little increase in cost. (Cambering from zero up to 3/8 inch can be specified for joists up to 20 feet in length. The designs of this study assumed no camber.)

The composite joists in the CJSS, CJSL, CJFDS and CJFDL designs were governed by shear. The cross-section's capacity to resist deflection and flexure was increased through the composite action but the shear capacity was not. The steel joists used in these designs are poorly proportioned for composite design. The top chords are large to prevent buckling in the case of non-composite design. With composite design the top chord is laterally supported during and after construction. Therefore, it has only to meet flexure limitations while under construction loadings. Reduction of the top chord could offset the increase in web area resulting in a better proportioned joist at an equivalent price.

Another example of building materials that had to be used even through they were poorly suited for the purpose was the welded wire fabric which was used for the concrete subfloor reinforcement. In several subfloor designs the most economical wwf could not be specified because it was not commonly sold by the steel supplier and the cost could not be furnished. This added to the cost of several subfloor designs unnecessarily. In the event that flooring systems similar to those included in this study are widely accepted such wwf sizes should become available.

Several refinements of the basic JSS design were included in the alternate designs. Among these was the use of lightweight concrete. Lightweight concrete appears to be economically and structurally well suited for use in residential flooring systems. In most designs the material costs of lightweight concrete designs were equivalent to standard concrete designs and in some instances, the lightweight design actually had lower material costs. Structurally the lightweight concrete subfloors are adequate and joist spacing is still limited by the joist. Further savings should occur during construction due to the reduced deadweight.

The use of form decking caused the material costs for these designs to increase far above the material costs for comparable designs using reuseable forms. This high initial expense may be justified during construction by savings due to reduced construction time and lower labor costs. Also the contractor can forego the expense of reuseable form rental or ownership.

Composite joist design appears to be well suited for use in residential flooring systems. With a minimal increase in material and labor costs composite joist action allowed greater joist spacing and increased floor area. Composite joist action resulted in more economical designs and allowed the spanning of lengths which non-composite designs could not accomodate.

DISCUSSION OF OTHER FACTORS

Construction Equipment

Use of the alternate flooring systems will cause only a minor change in the contractor's equipment. Construction of the non-composite alternate systems (JSS, JSL, JFDS, and JFDL) requires no investment in special equipment other than forms. Joists, form decking and bridging can be secured with mechanical connectors. Welding equipment is not necessary; however faster and in the long run possibly cheaper erection may result from using a welder. Lifting equipment is not required either. The largest joist weighs only 122 pounds and the maximum form decking section weighs less than 110 pounds. Both of these components can be handled easily by two men.

Composite action systems (CJSS, CJSL, CJFDS, and CJFDL) will require the use of a stud welding gun. For the size and quantity of studs that will be welded, only a small stud welder would be necessary. A stud welder is not a major investment and it can normally be powered by a conventional portable welder.

Pouring of the concrete subfloors presents no equipment problem to the contractor. On the average job the subfloor area should be easily accessible and only limited dragging of the concrete will be required. The concrete subfloor should pour and finish as easily as a basement floor or driveway slab.

Construction Details

The alternate designs developed in this study will introduce many changes in construction details. Some of these details may result in savings over the conventional flooring system and others will increase the cost of the alternate designs. Whatever their effect an attempt has been made to foresee these changes in order to qualitatively compare the flooring systems.

In order to maintain the same ceiling height in the basement rooms foundation walls will, in some cases, have to be constructed taller than is the case with conventional flooring. For example the JSS and JSL designs would require foundations 9 inches taller than for a conventional timber floor. However, this is offset in some cases by the fact that plumbing, wiring and ductwork running normal to the joist can be easily placed through the open-web joist and need not be suspended below the joist. (Figure 5 Appendix A)

Joists must be secured to the foundation wall to prevent lateral movement and uplift. This can be accomplished by a bracket anchored in the foundation wall at the time of its construction. These brackets would be spaced approximately at the joist spacing and fine adjustment of the spacing could be made before the joists are permanently fastened. Once secured the end of the joist and the bracket can be encased in concrete when the subfloor is poured. (Figure 5)

Anchor bolts for securing wall baseplates may be placed in the foundation wall when it is poured and be made long enough to extend above the subfloor. The subfloor can then be poured around the anchor bolts later.

Sleeves for electrical wiring, plumbing and other utilities can be installed before the subfloor is poured. When forms are used to pour the subfloor placing the sleeves is all that is necessary. If form decking is used, a hole must be drilled through the deck after the concrete has had time to harden. However, as was noted above, wiring and ductwork can be placed through the open-web joist without drilling holes as is required with timber joist.

Bridging for steel joists must be installed such that the distance between points of lateral support of the bottom chord does not exceed eight feet. Subfloors using form decking must have the bridging installed before the subfloor is poured. If reuseable forms are used to construct the subfloor, the forms themselves act as bridging and permanent bridging can be installed as the forms are removed. By removing individual rows of forms while leaving the adjoining rows the permanent bridging can be installed without endangering the integrity of the system.

Fire Resistance

One of the major requirements of a residential flooring system over and above the basic structural demands is that of fire resistance. In the event of fire the flooring system must continue to function safely in order that people and property can be removed from danger. Dependent upon the type of ceiling installed below the floor system, fire resistance ratings of one and one half and two hours can be obtained. Test results published by the National Board of Fire Underwriters and the Underwriters Laboratories, Inc. (19) list the following fire ratings,

One and One Half Hour Fire Resistance
Top Slab: 2" reinforced concrete
Ceiling: 5/8" UL listed gypsum board

Two Hour Fire Resistance
Top Slab: 2" reinforced concrete
Ceiling: 5/8" UL listed acoustical tile

These ratings are comparable to conventional timber floor ratings (14) and can be improved by utilizing a ceiling of one inch gypsum-vermiculite plaster on expanded lath up to five hours. The alternate flooring systems should enjoy good fire ratings and low fire insurance expenses.

CONCLUSIONS

Several conclusions can be formulated from this investigation. These conclusions are limited to the assumptions of the study and the material costs used to compile the flooring cost information. With proper considerations of local material costs these results should be of value in other areas.

Currently the alternate designs included in this study are not economically competitive. Although material costs in many of the designs are equivalent, higher labor expenses will increase the cost of the alternate systems above that of the conventional flooring system.

Concrete subfloor of 2½ inch thickness proved to be adequate. Joist spacing was governed by joist limitations in all cases.

The open-web steel joists available for use in residential flooring are not well suited for this purpose. The joists which were used are the four smallest joists that are manufactured in the steel joist series. Proper proportionment would result in better utilization of the joist material with shear, flexure and deflection limits being reached simultaneously.

For spans of more than 12 feet composite joist action becomes economical and is necessary to span the longest lengths included in the study.

Lightweight concrete is more economical than standard concrete in most of the alternate designs, and because of its reduced deadweight, it should be used when possible. The prices of lightweight and standard weight concrete used in this investigation were $18.50 and $15.50. Changes in these prices could offset the economic advantage that lightweight concrete showed in this study.

RECOMMENDATIONS FOR FURTHER STUDY

During the course of this research several facets of the residential flooring system problem, which require more individual study, have become apparent. Additional research, with resulting information in these areas, could improve the effectiveness of all residential flooring systems, conventional and alternate designs.

A study of reproportioned and cambered joists for use in non-composite designs could be conducted. Non-composite designs in this study were most often governed by shear and deflection, not flexure. By increasing the web and cambering the joist, a much better proportioned joist could be obtained.

Reproportionment of joists for composite action also warrants further study. In the case of available joists, the top chord is unnecessarily large and the web is undersized. A substantial increase in load carrying capacity could make production of such reproportioned joists economically feasible.

Experimental work with thinner concrete slabs could make reductions in material costs and floor system dead weight possible. This would result in more economical flooring systems.

A comparison of labor costs needs to be conducted. Such a study may require actual construction of alternate flooring systems to determine the time and labor problems involved.

Research in the area of fire resistance should be persued to determine the relative safety of the various flooring systems. If systems do not satisfy safety requirements, then methods to improve them should be developed and tested. Sound absorption characteristics should also be evaluated.

ACKNOWLEDGEMENTS

The author expresses his gratitude to Dr. Peter B. Cooper for his time, assistance and encouragement during the course of this investigation.

The helpful suggestions of Dr. Jack B. Blackburn, Professor Vernon H. Rosebraugh, Dr. Robert R. Snell, Dr. Stuart Swartz and Professor Eugene Thorsen are sincerely appreciated.

Special thanks should go to Mrs. Patty Vigneron, Civil Engineering Secretary, for her assistance with the extensive correspondence involved in the study.

REFERENCES

1) "Savings from Systems Will Come Slowly", Engineering News-Record, Vol. 183, No. 20, Nov. 13, 1969, pp. 14-15.

2) "Crisis: Lumber Sizes May Shrink", Domestic Engineer, Vol. 214, No. 3, Sept., 1969, pp. 51,57.

3) "2x4 Defined", Engineering News-Record, Vol. 183, No. 24, Dec. 11, 1969, pp. 27.

4) "Will Operation Breakthrough Break Down?", Domestic Engineer, Vol. 214, No. 5, Nov., 1969, pp. 47-48.

5) "The Housing Crisis: What's Romney's Approach?", Domestic Engineer, Vol. 213, No. 5, May, 1969, pp. 87-88.

6) "Can a Breakthrough Break Through?", Architectural and Engineering News, Vol. 11, No. 12, Dec., 1969, pp. 38-41.

7) "Operation Breakthrough", Constructor, Vol. 51, No. 9, Sept., 1969, pp. 24-29.

8) Williams, D. N., "Low-Cost Housing Is Homeless Waif", Iron Age, Vol. 204, No. 11, Sept. 11, 1969, pp. 63-66.

9) "Congress Speeds System Use", Engineering News-Record, Vol. 183, No. 18, Oct. 30, 1969, pp. 97-99.

10) "Why Housing Costs Are Going Through the Roof", Time, Oct. 31, 1969, pp. 82.

11) "Three Unions Sign Prefab Pact", Engineering News-Record, Vol. 183, No. 20, Nov. 13, 1969, pp. 14.

12) Edwards, H. Griffith, Specifications, D. Van Nostrand Co., Inc., Princeton, N. J., 1961.

13) Wilson, J. Douglas, Practical House Carpentry, McGraw-Hill Book Co., Inc., New York, 1957.

14) Scofield, V. Fleming, O'Brien, W. H., "Modern Timber Engineering", Southern Pine Association, New Orleans, 1963.

15) Design of High Rise Steel Framed Buildings, American Iron and Steel Institute, New York.

16) Tall, L., Beedle, L. S., Galambos, T. V., eds., "Structural Steel Design", The Ronald Press Co., New York, 1964.

17) Tide and Galambos, "Composite Open-Web Steel Joists", Research Report No. 4, Structural Division, Washington University, St. Louis, Missouri, Feb., 1968.

18) Nall, Harmon, Konyalian, and Galambos, "Experiments on Composite Open-Web Steel Joists", Research Report No. 13, Structural Division, Washington University, St. Louis, Missouri, Jan. 1970.

19) Standard Specifications and Load Tables, Steel Joist Institute, Washington, D. C., Jan., 1970.

20) Steel Construction Manual, American Institute of Steel Construction, Inc., New York, 1967.

21) Building Code Requirements for Reinforced Concrete, American Institute, Detroit, Michigan, June, 1963.

22) Manual of Standard Practice, Concrete Reinforcing Steel Institute, 19th Edition, 2nd Printing, Chicago, Illinois, 1968.

23) Structural Lightweight Concrete, Portland Cement Association Bulletin ST82.

24) "Guide for Structural Lightweight Aggregate Concrete", Journal of the American Concrete Institute, Aug., 1967.

25) Concrete Formwork, Permanent Forms, Bethlehem Steel, Feb., 1969.

26) Timber Construction Manual, American Institute of Timber Construction, John Wiley and Sons, Inc., New York, 1966.

Appendix: A Figures

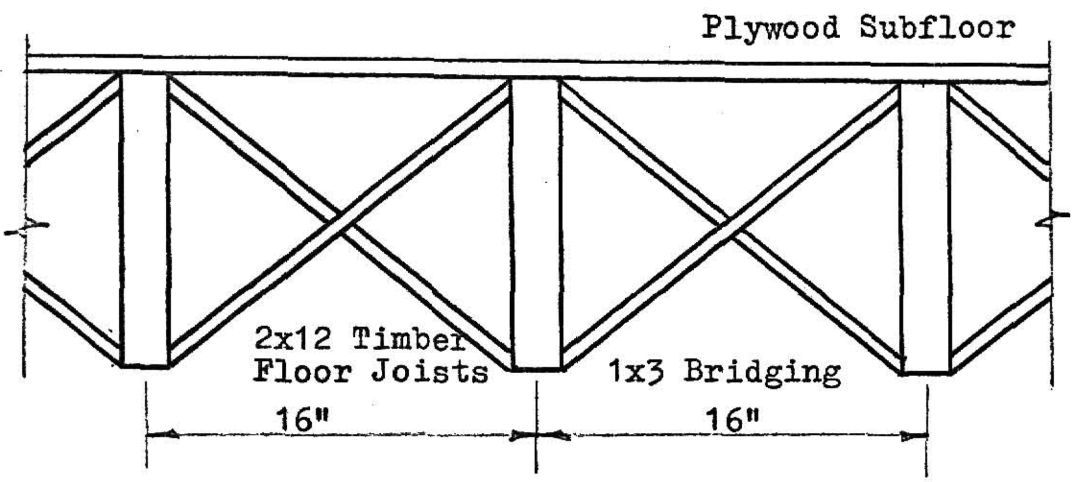

Figure 1

Typical Timber Joist Floor System Cross Section

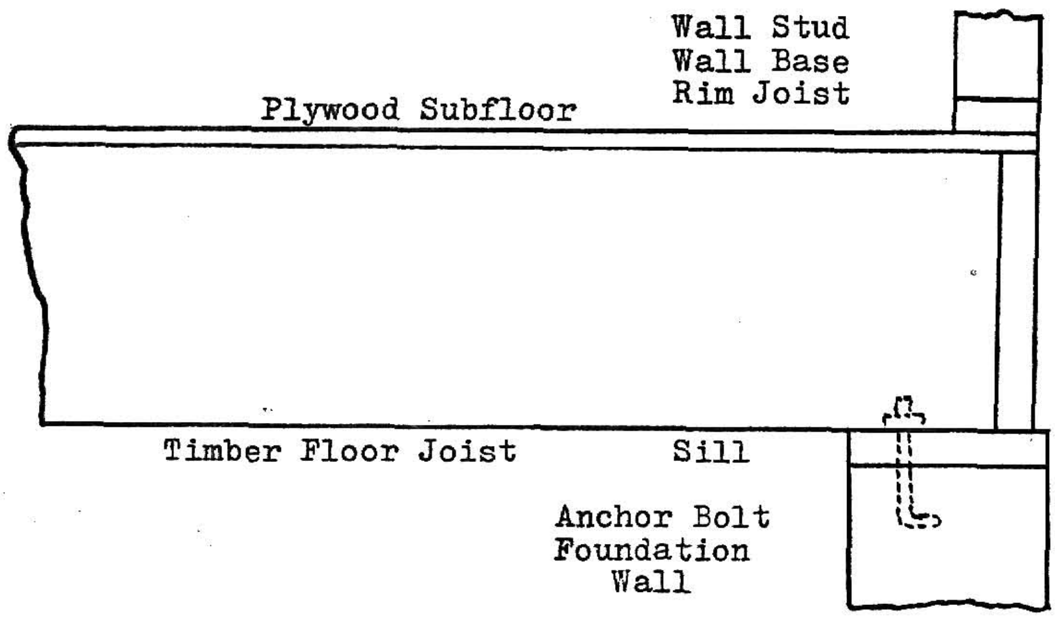

Figure 2

Typical Details for Timber Frame Construction

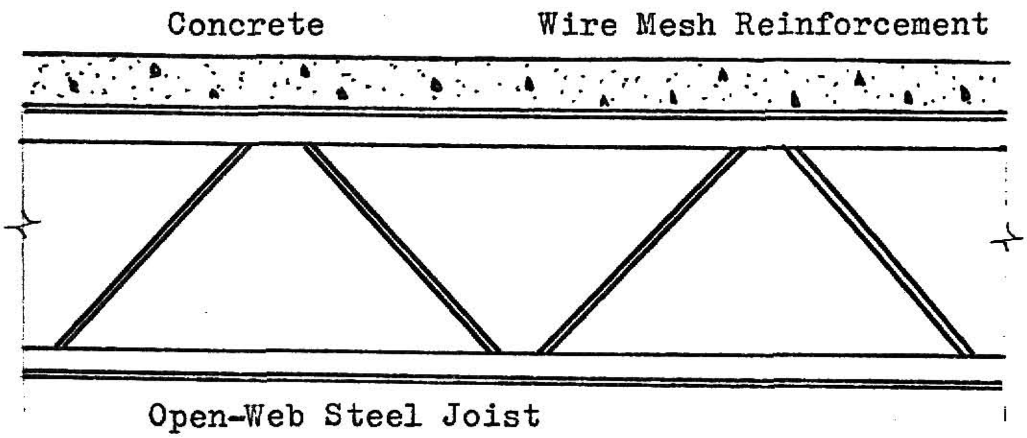

Figure 3

Typical Concrete Subfloor Using Reuseable Forms

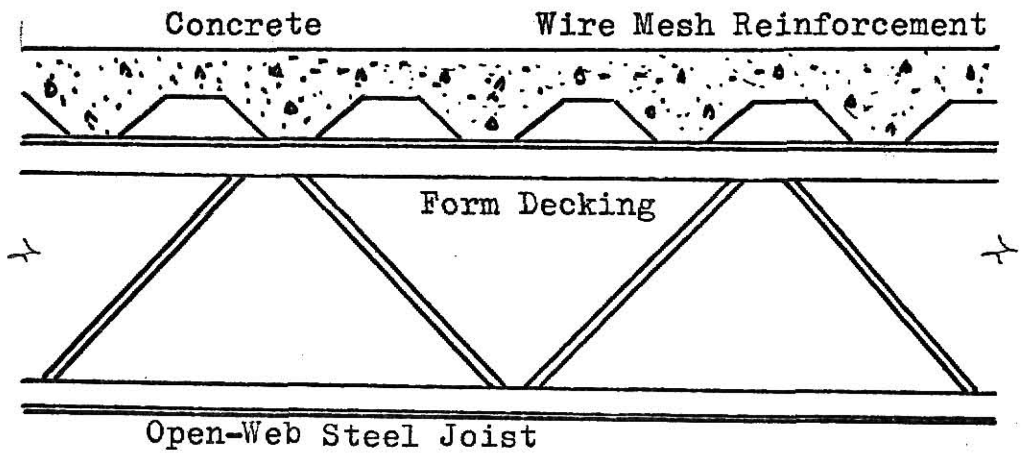

Figure 4

Typical Form Decking System Cross Section

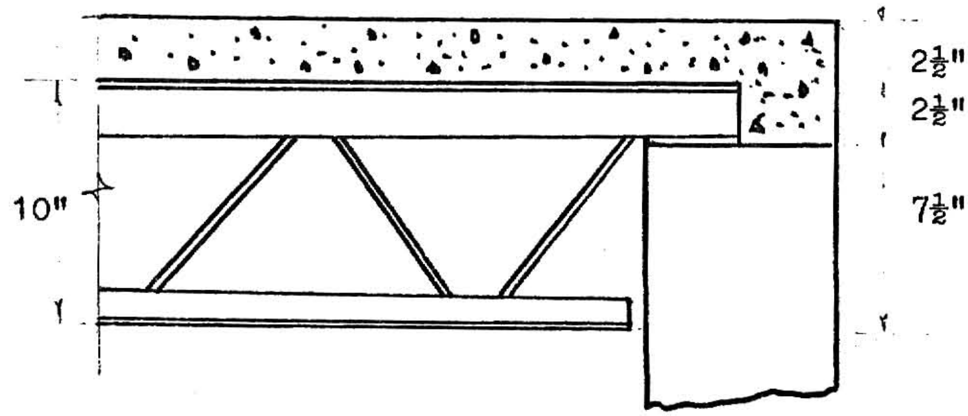

Figure 5

Joist-Foundation Wall Construction

Appendix B: Flooring System Designs

System	Spans (ft) 8	12	16	20
Timber	x	x	x	x
Non-composite Joist				
JSS	x	x	x	-
JSL	x	x	x	-
JFDS	x	x	x	-
JFDL	x	x	x	-
Composite Joist				
CJSS	-	x	x	x
CJSL	-	x	x	x
CJFDS	-	x	x	x
CJFDL	-	x	x	x

Appendix C: Timber Floor Design Calculations

Construction grade Douglas Fir lumber was considered typical for joists in the timber floor systems. Douglas Fir possesses the following properties. (26)

Allowable Unit Stresses
- Extreme fiber in bending, F_b=1500psi
- Tension parallel to grain, F_t=1500psi
- Horizontal shear, F_v=120psi
- Compression perpendicular to grain, F'_c=390psi
- Compression parallel to grain, F_c=1200psi

Modulus of elasticity, E_s=1.76x10^6psi

Unit weight @20% M.C., u=32pcf

The working load includes a uniformly distributed live load of 40psf and a dead load of 15psf (finish floor and ceiling) in addition to the selfweight of the flooring system.

For the 12ft. length the bending moment at midspan, M', is

$$M'=\frac{wl^2}{8} = \frac{76.3(12')^2}{8}(12"/_{'}) = 16.45 \text{ k-in.}$$

Where w= 40.0 + 15.0 + 2.25(plywood subfloor) = 57.25(16/12) = 76.3 #/, The required section modulus, S

$$S = \frac{M'}{F_b} = \frac{16.45}{1.5} = 10.97 \text{ in}^3$$

Try 2x8 joist, S = 15.23 in^3. Also A=12.19 in^2 and I=57.13 in^4. Joist weight, w_j,

$$w_j = (32 \text{ pcf})(12.19)(\frac{1}{12"/_{'}})^2 = 2.7 \#/_{'}$$

$$M = \frac{76.3+2.7}{76.3}(16.45 \text{ k-in}) = 17.05 \text{ k-in.}$$

$$F_b = \frac{M}{S} = \frac{17.05}{15.23} = 1.12 \text{ ksi} < 1.5 \text{ ksi}$$ Flexure OK

Allowable midspan deflection, D

$$D = \frac{l}{360} = \frac{144''}{360} = 0.40''$$

$$d = \frac{5}{384}\frac{wl^4}{EI} = \frac{5}{384}\frac{(79.0)(12')(144'')^3}{(1.76x10^6)(57.13)} = 0.367 \text{ in.}$$

$d = 0.367 < D = 0.40$ in. Deflection OK

Allowable shear stress, F_v

$$f = \frac{3}{2}\frac{V}{A} \qquad V = \frac{wl}{2} = 79.0(6.0) = 474.0$$

$$f = (1.5)\frac{(474)}{12.2} = 58.3 \text{ psi}$$

$f = 58.3 < F_v = 120$ psi Shear OK

Allowable bearing stress, F'_c

$$f'_c = \frac{V}{A}$$

Assuming a 2x6 sill, bearing area = (1-5/8)(5-1/2) =

8.93 sq. in.

$f'_c = \frac{474}{8.93} = 53.0 < F'_c = 390$ psi Bearing OK

For 12' length use 2x8 joists.

Terms:

l = length of joist
M' = midspan moment excluding weight of joist
w = load carried by timber joist, pounds per foot
M = midspan moment including weight of joist
s = sectional modulus of joist
A = cross sectional area of joist
I = moment of inertia of joist
V = shear force acting on joist
d = midspan deflection
D = allowable midspan deflection, l/360

Appendix: D Concrete Subfloor Design

Design loadings,

Live load = 40 psf

Dead load = 15 + $(\frac{2\frac{1}{2}}{12})$(150pcf) = 46.25 psf.

Applying the ultimate strength design factors,

40(1.8) + 46.3(1.5) = 141.4 psf

Considering a 1 foot strip normal to the joists,

w = 141.4 #/' = 11.8 #/"

Design constants include,

f'_c = 3000psi f_y = 60,000psi b = 12" d = t/2 = 1.25"

For span, s = 30"

$M = 0.1wl^2 = 0.1\ (11.8)(30)^2 = 1.06$ k-in.

$A_s = \frac{M}{\phi f_s(d-\frac{a}{2})}$ $\phi = 0.90$ and assuming a=0.03

$A_s = \frac{1.06}{0.9(60)(1.25-\frac{0.03}{2})} = 0.0159$ sq. in./ft.

$a = \frac{A_s f_s}{0.85 f'_c b} = \frac{A_s(60)}{0.85(3)(12)} = \frac{A_s}{0.51} = \frac{0.0159}{0.51} = 0.0312\ 0.03$

$A_s = 0.0159$ sq. in./ft.

$A_{st} = 0.0018(2.5)(12) = 0.054$ sq.in./ft.

$A_s < A_{st}$ therefore use $A_s = A_{st}$ use 6x6-6/6wwf

$A_s = A_{st} = 0.058$ sq. in./ft.

$p = \frac{0.058}{(1.25)(12)} = 0.00387$

$$p_{max} = 0.75p_b = 0.75\text{x}0.85k'\frac{f'_c}{f_y}\frac{87}{f_y+87}$$

$$= 0.75(0.85)^2\frac{3}{60}\frac{87}{147} = 0.0160$$

$p << p_{max}$

For A_s = 0.058 sq. in./ft.

$$M_u = \phi p f_y b d^2(1-0.59p\frac{f_y}{f'_c})$$

$$= 0.9(0.00387)(60)(12)(1.25)^2(1-0.59\text{x}0.0038\text{x}20)$$

$$= 373 \text{ k-in.}$$

$M_u = 0.1wl^2$ therefore,

$$l = (M_u/0.1w)^{\frac{1}{2}} = (3.73/0.1\text{x}11.8)^{\frac{1}{2}} = 56.2''$$

For joist spacings up to 56 inches 6x6-6/6wwf is adequate reinforcement.

For explanation of terms see Reference 21.

Appendix: E Non-Composite Joist System Design Calculations

For 2½" concrete subfloor,

Live load = 40psf

Subfloor = 31.25

Finish floor
and ceiling = 15

w_s = 86.25 psf

For a 8H2 joist 12 feet long (19),

w = 246#/, (limited by deflection)

w_{joist} = 4.2#/,

$$s = \frac{w-w_j}{w_s} = \frac{246-4.2}{86.25} = 2.8' = 33.6"$$

Design:

8H2 joists @ 33" with 2½" concrete subfloor reinforced with 6x6-6/6wwf.

Appendix: F Form Decking Subfloor Design Calculations

For small joist spacings 28 Gage Standard Slabform was used. Due to the corrugation pattern a $2\frac{1}{2}$" concrete cover above the top of the corrugation was used.

Construction loading (25),

Concrete = 35.7psf

Form decking = 0.8

Construction load = 20

Total = 56.5psf For a 1 foot strip, w=56.5#/'

For 28-Gage Slabform with s = 45"

w = 62.2 62.2(0.934) = 58.1#/'

(6.6% reduction due to continuous form decking)

$58.1 > 56.5$ OK

The concrete subfloor design is identical to the design procedure of Appendix D. With 6x6-6/6wwf reinforcement 28-Gage decking can be used to span joists at spacings up to 45 inches. (Limited by construction loading.)

For a 8H2 joist 12' in length,

$$s = \frac{241.8}{91.5} = 2.64' = 31.7''$$

Design:

8H2 joists @ 30" with 28-Gage Slabform and 6x6-6/6wwf reinforcement.

Appendix G: Composite Joist Design Calculations (18,19)

Construction loading,

Concrete = 31.25psf

Construction load = <u>20.0</u>

Total = 51.25psf

Working load,

Concrete subfloor = 31.25psf

Finish floor and ceiling = 15

Live load = <u>40.0</u>

Total = 86.25psf

For a 8H2 joist 12 feet in length,

$w = 333$ (shear) $w = 246$ (deflection) $w_{joist} = 4.2$

s limitations,

Shear: $s = \frac{333-4.2}{86.25} = 3.81' = 45.8''$

Construction load: $s = \frac{246-4.2}{51.25} = 4.71' = 56.5''$

b, effective width,

b 1/4 = 36", or b 16t = 40", or b s

Assume b = 36" $b' = b/n = \frac{36}{9} = 4.0$

$I_s = 11.0 in^4$ $y_s = 4.27$

$$y_c = \frac{\Sigma \bar{y} A}{\Sigma A}$$

Assuming $y_c' = 1.2''$

$$y_c = 8.0 + 2.5 - 0.234 - 1.2 =$$

$$= \frac{4.0(1.2)(8.0+2.5-0.234-0.6) + 0.46(8.0-0.234-0.36)}{4.0(1.2) + 0.46 + 0.345}$$

$9.07'' = 9.07''$

$y_c' = 1.20''$ and $y_c = 9.07''$

$$I_c = I_s + A_s(y_c - y_s)^2 + (1/3)b'(y_c')^3$$

$$= 11.0 + 0.805(9.07-4.27)^2 + (1/3)(4)(1.2)^3$$

$$= 31.8 \text{in}^4$$

Assuming s = 45" (Limited by shear)

$$M_l = 0.04(\tfrac{45}{12})(12')^2(12''/_{'})/8 = 32.4 \text{ k-in.}$$

$$M_d = \frac{0.04625}{0.04}(32.4) + 0.0042(12')^2(12''/_{'})/8 = 38.4 \text{ k-in.}$$

Stress in bottom chord,

$$\frac{M_l y_c}{I_c} + \frac{M_d y_s}{I_s} \quad 0.6F_y$$

$$\frac{32.4(9.07)}{31.8} + \frac{38.4(4.27)}{11.0} = 24.15 \quad 30.0 \text{ ksi} \qquad \text{OK}$$

Concrete stress,

$$f = \frac{M_l y_c'}{nI_c} = \frac{32.4(1.2)}{9(31.8)} = 136\text{psi} \quad 1350\text{psi} \qquad \text{OK}$$

Slab force,

$$F_s = \frac{by_c'f}{2} = \frac{36(1.2)(136)}{2} = 2.93 \text{ k}$$

Shear connectors,

$$N = \frac{F_s}{2.6} = \frac{2.93}{2.6} = 1.13$$

Use 2 shear connectors per shear span, 4 total.

Design:

8H2 joists @ 45" with 4-2"x3/8"ϕ stud shear connectors with SS-1 subfloor.

Appendix: H Flooring Designs and Costs

Length	Size	Joist Floor Area	Cost	Subfloor Cost	Total Cost
ft		sq ft	$/sq ft	$/sq ft	$/sq ft
8	2x6	10.67	0.113	0.148	0.261
12	2x8	16.0	0.153	0.148	0.301
16	2x12	21.3	0.252	0.148	0.400
20	2x14	26.7	0.306	0.148	0.454

Timber Designs and Costs

Design No.	Span (S)	Reinf.	Concrete Cost	Reinf. Cost	Total Subfloor Cost
	ft-in	wwf	$/sq ft	$/sq ft	$/sq ft
Standard Weight Concrete					
SS-1	2-6--4-8	6x6-6/6	0.120	0.042	0.162
SS-2	4-8--5-0	6x6-5/5	0.120	0.049	0.169
SS-3	5-0--5-3	6x6-4/6	0.120	0.050	0.170
SS-4	5-3--6-3	6x6-2/2	0.120	0.077	0.197
SS-5	6-3--6-6	6x6-1/1	0.120	0.089	0.209
SS-6	6-6--6-9	6x6-0/0	0.120	0.105	0.225
Lightweight Concrete					
SL-1	2-6--4-11	6x6-6/6	0.143	0.042	0.185
SL-2	4-11--5-3	6x6-5/5	0.143	0.049	0.192
SL-3	5-3--5-9	6x6-4/6	0.143	0.050	0.193
SL-4	5-9--6-7	6x6-2/2	0.143	0.077	0.220
SL-5	6-7--7-1	6x6-1/1	0.143	0.089	0.232

Concrete Subfloor Designs and Costs

Length ft	Size	Spacing in	Joist Limitation	Floor Area sq ft	Cost $/sqft	Subfloor Design No.	Subfloor Cost $/sqft	Total Cost $/sqft
Standard Weight Concrete								
8	8H2	69	Shear	46.0	0.178	SS-4	0.197	0.375
12	8H2	33	Deflection	33.0	0.290	SS-1	0.162	0.452
12	10H2	48	Shear	48.0	0.200	SS-1	0.162	0.362
12	10H3	57	Shear	57.0	0.191	SS-2	0.169	0.353
12	10H4	63	Shear	63.0	0.199	SS-3	0.170	0.369
16	10H4	33	Deflection	44.0	0.331	SS-1	0.162	0.493
20	*	-	-	-	-	-	-	-
Lightweight Concrete								
8	8H2	75	Shear	50.0	0.164	SL-4	0.220	0.384
12	8H2	36	Deflection	36.0	0.266	SL-1	0.185	0.451
12	10H2	54	Shear	54.0	0.178	SL-1	0.185	0.363
12	10H3	63	Shear	63.0	0.173	SL-2	0.192	0.365
12	10H4	72	Shear	72.0	0.174	SL-4	0.220	0.394
16	10H3	30	Deflection	40.0	0.334	SL-1	0.185	0.519
16	10H4	36	Deflection	48.0	0.303	SL-1	0.185	0.488
20	*	-	-	-	-	-	-	-

* No joist 10H4 or smaller is adequate.

JSS and JSL Designs and Costs

Design No.	Span (s) ft-in	Form Decking	Cost $/sqft	Reinforcement	Cost $/sqft	Concrete Cost $/sqft	Subfloor Cost $/sqft
Standard Weight Concrete							
FDS-1	2-6--3-9	Standard	0.216	6x6-6/6wwf	0.042	0.137	0.395
FDS-2	3-9--4-6	Heavy-Duty	0.291	6x6-6/6wwf	0.042	0.120	0.453
FDS-3	4-6--5-0	Heavy-Duty	0.291	6x6-5/5wwf	0.049	0.120	0.460
FDS-4	5-0--5-3	Heavy-Duty	0.291	6x6-4/6wwf	0.050	0.120	0.461
FDS-5	5-3--5-9	Heavy-Duty	0.291	6x6-2/2wwf	0.077	0.120	0.488
FDS-6	5-9--6-3	Extra-Heavy	0.383	6x6-2/2wwf	0.077	0.120	0.580
FDS-7	6-3--6-6	Extra-Heavy	0.383	6x6-1/1wwf	0.089	0.120	0.592
FDS-8	6-6--7-0	Extra-Heavy	0.383	6x6-0/0wwf	0.105	0.120	0.608
Lightweight Concrete							
FDL-1	2-6--4-0	Standard	0.216	6x6-6/6wwf	0.042	0.163	0.421
FDL-2	4-0--4-9	Heavy-Duty	0.291	6x6-6/6wwf	0.042	0.143	0.476
FDL-3	4-9--5-3	Heavy-Duty	0.291	6x6-5/5wwf	0.049	0.143	0.483
FDL-4	5-3--5-6	Heavy-Duty	0.291	6x6-4/6wwf	0.050	0.143	0.484
FDL-5	5-6--6-3	Heavy-Duty	0.291	6x6-2/2wwf	0.077	0.143	0.511
FDL-6	6-3--6-6	Extra-Heavy	0.383	6x6-2/2wwf	0.077	0.143	0.603
FDL-7	6-6--7-0	Extra-Heavy	0.383	6x6-1/1wwf	0.089	0.143	0.615

Form Decking Subfloor Designs and Costs

Length ft	Size	Limitation	Joist Spacing in	Floor Area sq ft	Cost $/sqft	Subfloor Design No.	Subfloor Cost $/sqft	Total Cost $/sqft
Standard Weight Concrete								
8	8H2	Shear	66	44.0	0.186	FDS-5	0.488	0.674
12	8H2	Deflection	30	30.0	0.318	FDS-1	0.395	0.713
12	10H2	Shear	48	48.0	0.201	FDS-2	0.453	0.654
12	10H3	Shear	54	54.0	0.201	FDS-3	0.460	0.661
12	10H4	Shear	63	63.0	0.199	FDS-5	0.488	0.687
16	10H4	Deflection	30	40.0	0.364	FDS-1	0.395	0.759
20	*	-	-	-	-	-	-	-
Lightweight Concrete								
8	8H2	Shear	75	50.0	0.164	FDL-6	0.603	0.767
12	8H2	Deflection	33	33.0	0.289	FDL-1	0.421	0.710
12	10H2	Shear	54	54.0	0.178	FDL-2	0.476	0.654
12	10H3	Shear	63	63.0	0.173	FDL-4	0.484	0.657
12	10H4	Shear	69	69.0	0.182	FDL-5	0.511	0.693
16	10H4	Deflection	33	44.0	0.331	FDL-1	0.421	0.752
20	*	-	-	-	-	-	-	-

* No joist 10H4 or smaller is adequate to permit joist spacing 30"

JFDS and JFDL Designs and Costs

Length ft	Size	Spacing in	Limit.	Joist Floor Area sq ft	Cost $/sqft	Shear Conn.	Cost $/sqft	Subfloor Design No.	Subfloor Cost $/sqft	Total Cost $/sqft
Standard Weight Concrete										
8	8H2	*	-	-	-	-	-	-	-	-
12	8H2	45	Shear	45.0	0.212	4	0.006	SS-1	0.162	0.380
12	10H2	*	-	-	-	-	-	-	-	-
12	10H3	*	-	-	-	-	-	-	-	-
12	10H4	*	-	-	-	-	-	-	-	-
16	8H2	33	Shear	44.0	0.255	10	0.014	SS-1	0.162	0.431
16	10H2	36	Shear	48.0	0.234	8	0.011	SS-1	0.162	0.407
16	10H3	42	Shear	56.0	0.238	6	0.007	SS-1	0.162	0.407
16	10H4	48	Shear	64.0	0.227	6	0.006	SS-1	0.162	0.395
20	10H3	33	Shear	55.0	0.265	12	0.014	SS-1	0.162	0.441
20	10H2	36	Shear	60.0	0.275	12	0.013	SS-1	0.162	0.450
Lightweight Concrete										
8	8H2	*	-	-	-	-	-	-	-	-
12	8H2	51	Shear	51.0	0.187	4	0.005	SL-1	0.185	0.377
12	10H2	*	-	-	-	-	-	-	-	-
12	10H3	*	-	-	-	-	-	-	-	-
12	10H4	*	-	-	-	-	-	-	-	-
16	8H2	36	Shear	48.0	0.234	10	0.013	SL-1	0.185	0.432
16	10H2	42	Shear	56.0	0.201	4	0.005	SL-1	0.185	0.391
16	10H3	48	Shear	64.0	0.209	6	0.006	SL-1	0.185	0.400
16	10H4	51	Shear	68.0	0.214	6	0.006	SL-1	0.185	0.405
20	10H3	36	Shear	60.0	0.244	12	0.013	SL-1	0.185	0.442
20	10H4	42	Shear	70.0	0.235	12	0.011	SL-1	0.185	0.432

* Limited by shear in joist, span same as non-composite design.

CJSS and CJSL Designs and Costs

Length ft	Size	Spacing in	Limit.	Joist Floor Area sq ft	Cost $/sqft	Shear Conn.	Cost $/sqft	Subfloor Design No.	Subfloor Cost $/sqft	Total Cost $/sqft
Standard Weight Concrete										
8	8H2	*	-	-	-	-	-	-	-	-
12	8H2	42	Shear	42.0	0.227	4	0.008	FDS-1	0.395	0.630
12	10H2	*	-	-	-	-	-	-	-	-
12	10H3	*	-	-	-	-	-	-	-	-
12	10H4	*	-	-	-	-	-	-	-	-
16	8H2	30	Shear	40.0	0.281	8	0.016	FDS-1	0.395	0.692
16	10H2	33	Shear	44.0	0.256	4	0.007	FDS-1	0.395	0.658
16	10H3	39	Shear	52.0	0.257	4	0.006	FDS-1	0.395	0.658
16	10H4	45	Shear	60.0	0.242	6	0.008	FDS-1	0.395	0.645
20	10H3	30	Shear	50.0	0.292	12	0.019	FDS-1	0.395	0.706
20	10H4	36	Shear	60.0	0.275	12	0.016	FDS-1	0.395	0.686
Lightweight Concrete										
8	8H2	*	-	-	-	-	-	-	-	-
12	8H2	48	Shear	48.0	0.199	4	0.007	FDL-1	0.421	0.627
12	10H2	*	-	-	-	-	-	-	-	-
12	10H3	*	-	-	-	-	-	-	-	-
12	10H4	*	-	-	-	-	-	-	-	-
16	8H2	36	Shear	48.0	0.234	8	0.013	FDL-1	0.421	0.668
16	10H2	39	Shear	52.0	0.216	4	0.006	FDL-1	0.421	0.643
16	10H3	45	Shear	60.0	0.222	6	0.008	FDL-1	0.421	0.645
16	10H4	51	Shear	68.0	0.214	6	0.007	FDL-2	0.476	0.697
20	10H2	30	Shear	50.0	0.259	10	0.016	FDL-1	0.421	0.696
20	10H3	36	Shear	60.0	0.243	12	0.015	FDL-1	0.421	0.680
20	10H4	39	Shear	65.0	0.253	12	0.015	FDL-1	0.421	0.689

* Limited by shear in joist, span same as non-composite design.

CJFDS and CJFDL Designs and Costs

Appendix: I Building Materials Costs

Timber

Joist Lumber

2x6	Construction KD	@$0.15/Bd-ft
2x8	Construction KD	@$0.1525/Bd-ft
2x12	Construction KD	@$0.1675/Bd-ft
2x14	Construction KD	@$0.175/Bd-ft

Subfloor Plywood

3/4" 4x8 T&G "C" Cross Band
Underlayment Plywood @$0.1975/Bd-ft

Alternate Systems

Steel Joist

Designation	Costs of Lengths of			
	8ft	12ft	16ft	20ft
8H2	$8.18	9.56	11.23	-
10H2	-	9.63	11.25	12.96
10H3	-	10.88	13.36	14.60
10H4	-	12.55	14.56	16.48

Welded Wire Fabric

Designation	Cost per Roll (750 ft^2)
6 6-0/0	$78.68
6x6-1/1	66.82
6x6-2/2	57.38
6x6-3/3	49.95
6x6-4/4	43.05
6x6-4/6	37.12
6x6-5/5	36.82
6x6-6/6	31.42

Steel Form Decking

Designation*	Cost per Square (100 ft^2)
Standard Slabform (28 Gage)	$21.62
Heavy-Duty Slabform (26 Gage)	29.12
Extra Heavy-Duty (24 Gage	38.25

* Bethlehem Slabform or equivalent (25)

Shear Connectors

Designation	Cost per 100
3/8" ø Stud 2" Length	$6.40
3/8" ø Stud 2½" Length	7.90

Concrete

Designation	Cost per Cubic Yard
Standard Concrete 3000 psi	$15.50
Lightweight Concrete Haydite 3000 psi	18.50

A Study of Residential Flooring Systems

by

James Keith Carlat

B. S., Kansas State University, 1969

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1970

ABSTRACT

This thesis describes a study of residential flooring systems. It begins with an examination of the conventional timber joist flooring system commonly used in the American home today. The research continued with the design of several alternate flooring systems of concrete and steel construction. The conventional timber floor and the alternate flooring systems were then compared. Building material costs were collected and compared along with other pertinent aspects of the flooring systems such as labor requirements, construction details and equipment, and fire resistance.

The study included joist lengths of 8, 12, 16, and 20 feet. These lengths cover the range of joist spans in the average residence. The conventional timber joist system was designed with the common joist spacing of 16 inches on center with 3/4 inch T&G plywood for a subfloor. The alternate flooring systems included in the study were adaptations of flooring systems with open-web steel joists and concrete subfloors, currently used in high-rise apartments, office buildings and similar structures. These systems were designed to meet current design criteria.

Comparison of the systems showed that in several instances building material costs were equivalent. However, in mosts cases higher construction costs would increase the cost of the alternate systems above that of the conventional flooring system.

The study revealed that the limiting factor in the alternate system designs was the steel joist. Reproportionment of the steel joists could result in alternate systems that are economically competitive.