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MINIMUM COST DESIGN OF COMPOSITE FLOOR SYSTEMS USING COLD FORMED STEEL DECKING

BY

J. I. NICHOLLS[1] AND A. T. MEROVICH[2]

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Introduction

In the last ten years structural designers have been giving more and more attention to the field of design optimization. Initially, the emphasis was placed on minimum weight design, perhaps as a continuation of previous work done in the aircraft industry. Later however, this emphasis has changed to minimum cost design wherein not only material costs but also fabrication and erection costs are included. Minimum cost is recognized as the significant factor in structural design optimization.

There are three basic optimization procedures, each having specific qualities in reference to the type of problem they are best suited to solve. All three of these will now be discussed in terms of the proposed investigation. These three basic procedures are as follows:

(1) Closed form solution procedures (such as Linear Programming).

(2) Gradient Procedures.

(3) Grid Search Procedures.

In the closed form procedures a direct solution is obtainable provided a set of initial conditions is met. For example, in the Linear Programming algorithm all constraints and the objective function must be linear in the decision variables. All decision variables however are assumed to be continuous functions. This is not a practical limitation. The gradient procedures suffer primarily from the fact that they cannot in general produce an optimal solution which is known to be the global optimum. Various methods of overcoming this limitation have been tried, prime amongst which is the procedure of restarting the procedure at different initial points. While perhaps giving a sense of security relating to a solution developed from several starting points, this by no means defines the global optimum. This technique is simple to program however and a modification of this developed by Goble et al (1)*, (2) allows the incorporation of practical size limitations.

Finally, the grid search technique assures us, by the very nature of the procedure, that the global optimal solution will be developed provided all possible combinations are considered. Obviously, for large problems wherein a large number of trials are to be considered, this can lead to an extensive computational effort. This fact alone has, in the opinion of the authors, been a major reason against its use in the past. With the increase in the efficiency and speed of the digital computer at the present time however this may no longer be a critical factor. Certainly procedures such as critcal path method and dynamic programming which are showing very prominently in the literature at the present time rely on basic algorithms not unlike Grid Search procedures. Further, the methodology of this procedure incorporates a non-continuous spectrum of points for the decision variables. This investigation used the grid search procedure. For the problem considered very short operational times and small associated computer costs were involved in its use. This last point justified its use for the proposed investigation, and is a factor which must be taken into consideration if the practicing engineering profession will be using the end product.

A definition of the problem attempted may now be written as follows:

Using the Grid Search Procedure determine the optimal cost configuration for a composite floor system in a steel framed multi-story building given the initial bay size, the design loading and specific engineering properties of the cold formed decking elements, the rolled beam sizes and the concrete slab.

In this investigation 16 of the most commonly used H.H. Robertson Q-Lock cold formed decking sections were used, and 28 rolled beam sizes were considered as sufficient to develop the necessary load carrying requirements. These sections are listed in Table 1. It should be noted however that this is not a restriction on the program developed. Additional beam sizes and/or different cold formed decking configurations may be used almost directly in the existing program.

Solution Procedure

A computerized procedure has been evolved for the determination of the optimal configuration. This procedure has five basic steps.

1 Define an acceptable framing scheme.

2 Select an admissible cold formed decking element and a concrete slab thickness.

3 (a) Select an admissible rolled beam size for non-composite action.

(b) Select an admissible rolled beam size for composite action.

Table 1

Listing of Cold Formed Decking and Rolled Beam Sections Used in the Computer Investigation

Cold Formed Decking*	Rolled Beams**	
QL- 3 -22	W 12 x 14	W 14 x 30
QL- 3 -20	W 8 x 15	W 16 x 31
QL- 3 -18	W 12 x 16.5	W 14 x 34
QL- 3 -16	W 8 x 17	W 18 x 35
QL-ukx-18/18	W 10 x 17	W 16 x 36
QL-ukx-18/16	W 10 x 19	W 16 x 40
QL-ukx-16/16	W 12 x 19	W 18 x 40
QL-ukx-16/14	W 8 x 20	W 21 x 44
QL-21 -22	W 10 x 21	W 21 x 49
QL-21 -20	W 12 x 22	W 18 x 50
QL-21 -18	W 14 x 22	W 18 x 55
QL-21 -16	W 8 x 24	W 21 x 55
QL-nkx-18/18	W 10 x 25	
QL-nkx-18/16	W 14 x 26	
QL-nkx-16/16	W 16 x 26	
QL-nkx-16/14	W 12 x 27	

* See Reference (4)
** See Reference (7)

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* Numbers in parentheses refer to items in the Reference section.

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4 Determine the required fireproofing for both the cold formed decking and the rolled beam(s) and calculate the cost of the total design.

5 Select the minimum cost of all acceptable design configurations.

A flow chart illustrating these five steps and their interaction is given in Figure 1. The five basic steps will now be discussed individually.

Step 1: Framing scheme selection

The selection of an acceptable framing scheme is made on the basis of providing a span length for the cold formed decking which is within the range of standard lengths commercially produced. The determination of this span length is made by dividing the bay length B by n, where n = 1, 2, ..., until this quotient lies within the range of commercially produced lengths.

Step 2: Cold formed decking and slab thickness selection

This step requires an iterative search to be carried out to determine a cold formed decking/concrete slab thickness combination which would not violate limitations on bending stress, shear stress and deflection, etc. The allowable values for stress and deflection are obtained from trade literature (3), (4). In addition to the computation of acceptable stress and deflection values both shored and unshored spans are considered. When required, shoring is provided only at midspan. This is a practical limitation. A flow chart of this step is given in Figure 2. If no acceptable combination of cold formed decking and concrete slab thickness can be found, the program returns to Step 1 where a new acceptable framing scheme is selected, provided one exists. (See Figure 1)

Step 3: (a) Rolled beam selection/non-composite

All 28 wide flange beam sizes including specific engineering properties pertinent to the stress and deflection calculations were stored in the computer. Flexural stress and midspan deflection were calculated for the selected beams assuming non-composite action. In all cases, the beams were considered to be pinned at each end thus giving maximum flexural stress and maximum deflection at midspan. If a beam is found that has flexural stresses and deflections less than the maximum allowable (6) the program proceeds to Step 4. If no acceptable beam size is found, the program proceeds to Step 3 (b).

Step 3: (b) Rolled Beam Selection/composite

If the cold formed decking type and concrete slab thickness permits composite action to be used with the rolled beam (3) then the program will attempt to find a rolled beam capable of supporting the floor system. The selection of this beam is subject to flexural stress and deflection limitations (6) that are imposed on the behavior of the composite cold formed decking/slab/beam system under live and dead load conditions. If no beams can be found that will satisfy these requirements or, if the cold formed decking and concrete slab thickness do not permit composite action the program returns to Step 2. If however an acceptable beam size is found, the number of shear studs, and their spacing necessary to facilitate composite action is determined by conventional design procedures (6), (7). If the resulting spacing of the shear studs proves to be very large (>72") or very small (<6") the program considers composite action either practically or structurally infeasible. For shear stud spacings greater than 72 inches the program returns to Step 2 since composite action is not economically worth considering. For spacings less than 6 inches the studs are too close and the program returns to Step 2. If an acceptable beam size is found that permits an adequate shear stud spacing the program proceeds to Step 4.

Step 4: Fireproofing Determination and Total Design Cost

In determining the amount of sprayed-on fireproofing that is necessary for a given design to develop a 2 hour fire rating, the program multiplies the bay size by an average fireproofing thickness. This fireproofing thickness has been abstracted from test information (8) which details the exact fireproofing application to obtain a 2 hour fire rating. The fireproofing required by the beam is determined in a similar manner. With the amount of fireproofing determined a complete design has been evolved and only its cost remains unknown. The total cost of the completed design is calculated by summing a series of subcosts each of which represents some aspect of the design. These subcosts include both material costs plus an allowance for labor and erection costs and can be listed as follows:

1. The cost of the cold formed decking
2. The cost of the concrete
3. The cost of the rolled beams
4. The cost of providing temporary mid-span shoring of the decking - if necessary
5. The cost of temperature mesh in the slab
6. The cost of providing composite action between the slab/decking system and the rolled steel beams
7. The cost of providing the necessary fireproofing

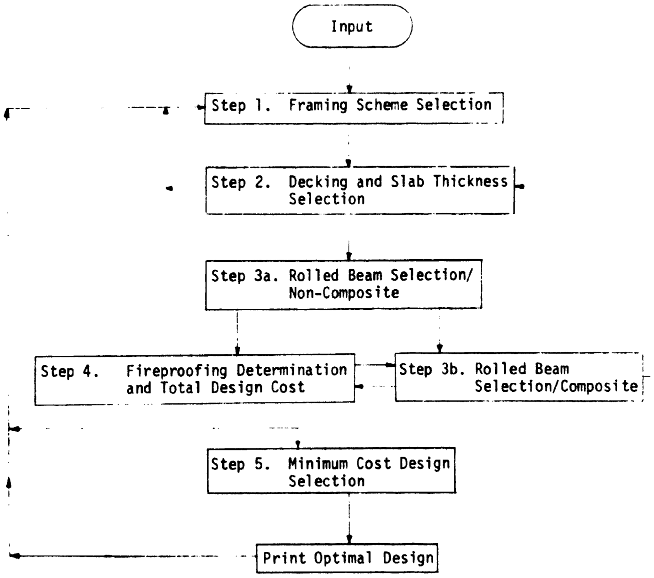

Figure 1

Flow Diagram of Sequencing of the Computer Program

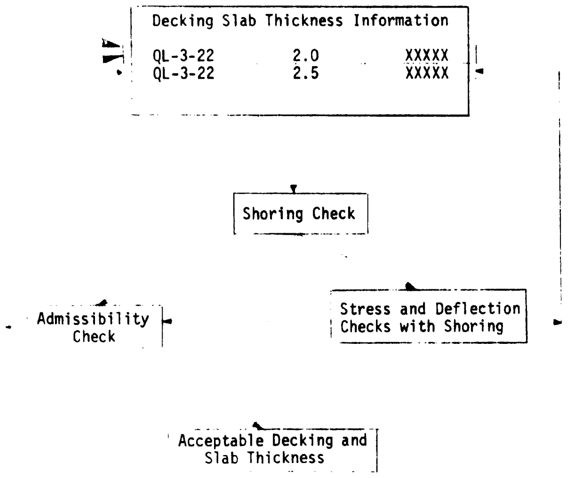

Figure 2

Flow Diagram of Computer Sequencing of Step 1 of the Computer Program

With the total cost determined the program returns to Step 2 to generate another design configuration for the framing scheme under consideration. When all such designs have been generated and costed the program proceeds to Step 5.

Step 5: Minimum Cost Design Selection

At this point all possible acceptable designs have been generated, costed and stored in the computer. To find the required optimal design the individual costs generated in Step 4 are scanned to find the minimum. The program will report this design configuration as an optimal one for the framing scheme being considered. The program will then return to Step 1 and reinitiate the design cycle for another acceptable framing scheme. When the point is reached at which no further acceptable framing schemes can be found the solution of the problem is complete and the program terminates operation.

Results and Discussion

Using material, labor, and erection costs related to the Seattle area a total of 35 designs were run on the program. The parameters which were changed in these computer runs were the bay width and bay length. The live load used was 100 p.s.f. because this floor loading is the most widely used loading for office buildings of the size being considered. The results of these trials have been plotted in Figure 3 where cost contours have been plotted to indicate relative bay size costs for varying A and B values. The designs evolved showed some repetition in certain areas, and these areas are shown shaded in Figure 3. The repeated designs in these shaded areas are defined as follows:

AA - QL-3-22 cold formed decking
4.5 inches of hardrock concrete
Composite action
Beam size varies.

AAX - Same as AA except 3" of hardrock concrete and fireproofing required.

C - QL-21-22 cold formed decking
3.25 inches of light-weight concrete
No composite action
Beam size varies.

CX - Same as C except 4.0 inches of light-weight concrete.

D - QL-21-22 cold formed decking
4.5 inches of hardrock concrete
No composite action
Beam size varies.

NOTE:

(1) Weight of hardrock concrete = 145 lb./cu.ft.
Weight of light-weight concrete = 100 lb./cu.ft.

(2) Shoring was required for all these design selections

(3) No fireproofing of the cold formed decking for designs AA, C and D is required.

Surprisingly for the wide range of A and B considered, the lightest gaged cold formed decking appeared in all designs. Without shoring, the heavier gaged sections would become prevalent. This fact has been substantiated by actual computation wherein shoring costs were increased substantially in order to make its presence prohibitive.

The AA designs are located in the region shown due primarily to the acceptability of composite design for the 1.5 inch cold formed decking in the range of B from 30 feet to 80 feet. In the region of B equal to 20 feet, the acceptable framing schemes forecast maximum spans acceptable to both 1.5 inch and 3.0 inch cold formed decking. Since the 1.5 inch cold formed decking requires less concrete and thus a lighter beam, it thus produces the optimal cost.

The C, CX and D designs are optimal in the regions shown as a result of the framing scheme geometry as well as the relative cost

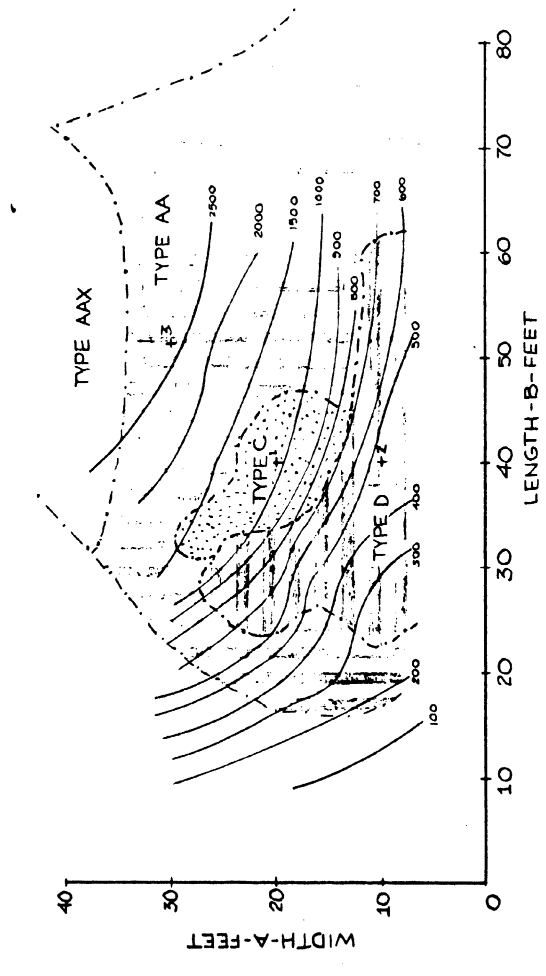

Figure 3

differences in hardrock and light-weight concrete.

For all the designs of Figure 3 shoring was predominant. Assuming shoring to be a nuisance item its cost was increased until in the optimal design no shoring was necessary. In general it was found that cost increases in the order of 6 to 9 times the original shoring cost was required to do this. The three designs chosen for this investigation are numbered in Figure 3, and the initial and final costs are given in Table 2. The final cost shown represents the first optimal design to appear which did not have shoring, and the factor is the proportional increase of the initial shoring cost.

A further investigation was carried out on the three numbered designs. This time the relative costs of light-weight and hardrock concrete were varied. These results are given in Table 3 where L/H is the ratio of light-weight concrete cost to hardrock concrete cost. In all of these cases the cost of the hardrock concrete remained constant and only the light-weight concrete's cost was varied.

Table 2

Comparison of Optimal Design Costs
for Increases in Shoring Costs

Initial Design		Final Design	
Number	Cost	Factor	Cost
1	$1,107.84	6	$1,268.75
2	$ 455.87	9	$1,560.60
3	$2,588.62	6	$3,056.46

Table 3

Comparison of Initial and Final Optimal Design
Costs for Varying Ratios of Lightweight
to Hardrock Concrete Costs

Design Number	Initial Designs		Final Designs					
	L/H = 2.0		L/H = 1.0		L/H = 3.0		L/H = 5.0	
	Type	Cost	Type	Cost	Type	Cost	Type	Cost
1	C	$1,107.84	C	$1,049.88	D	$1,117.07	D	$1,117.07
2	D	$ 455.87	C	$ 446.37	D	$ 454.37	D	$ 454.37
3	AA	$2,588.62	AA	$2,635.47	AA	$2,635.47	AA	$2,635.47

Conclusions

The computer program used to calculate the resulting design selections in this paper can be used by the practicing engineer without difficulty. It is efficient and the average run for a design costs approximately $0.50. The output specifies directly all the necessary details for the optimal design selection for each framing scheme. The engineer thus has the option of selecting any acceptable framing scheme from this output, which is not necessarily the global optimum.

From the information given in the results section, it would appear as though the lightest gage cold formed decking, if acceptable, should be included in the optimal design assuming shoring costs are not prohibitive.

Fireproofing does not appear predominantly in the designs carried out. This would suggest that if a trade-off can be made between fireproofing and concrete thickness the latter would be preferable from a cost standpoint.

The optimal cost design for typical bay sizes incorporates both hardrock and light-weight concrete dependent upon the B/A ratio of the slab. By varying the relative costs of the hardrock to light-weight concrete as shown in Table 3, these designs can be interchanged.

Finally this program although limited to the flooring systems of steel framed buildings, cannot be discounted as being too specific. The total cost optimization of such a structure can possibly be best approached by considering the complexity of the total problem as a series of sub-optimal problems. A program such as that discussed here is a step in this direction.

ACKNOWLEDGEMENTS

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