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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Today's building facilities are becoming more complex and costly. The profitability of the processes carried on within such facilities is directly affected by both their capital and operating costs. To assist in designing efficient buildings, considerable work has been focused to date on developing sophisticated analysis and design tools for the various subsystems which comprise a total building system (e.g. foundation, structure, mechanical, electrical, etc.) Some attention has also been directed toward the optimal design of these systems. For example, a great deal of work has been performed in the area of structural optimization, with system weight or weight related cost being selected as the performance criterion.

What is missing, however, is a practical methodology to assist the designer in selecting the most appropriate alternative for each subsystem and in coordinating the design of the various subsystems in a way which minimizes project cost. Further, in many cases, insufficient information is available to assist the designer in assessing the cost implications of his design.

With respect to the foregoing needs, two goals were selected for achievement in this thesis. They are:

(i) To develop a practical computerized design aid for the design of the foundation, structural and enclosure subsystems of light industrial type buildings in such a way as to permit tradeoffs to be made between these subsystems in order to optimize overall system performance; and

(ii) to demonstrate the importance of careful formulation of the performance measure used for determining the optimal configuration of the system.

Light industrial facilities have been selected as a vehicle for developing a computerized design aid because of their economic importance and relative simplicity.

1.2 THE DESIGN PROBLEM

The design problem examined herein is illustrated in Figure 1.1. Attention is focused on the design of the foundation, structural bent and roof system with allowance being made for the cost of the cladding system. Not considered at present are the mechanical and lighting systems, the designs of which can have important implications for both the enclosure and structural bent systems. Inclusion of these systems in the design package is left to a future study. The design problem, as treated in this thesis, is described below under several headings which pertain to the function of the building type being designed, the information required in the design process, decisions to be made, the manner in which they are made, and so forth.

i) Function:

Function refers to the purpose for which the building is being designed. For the problem at hand, it was assumed that large column free spaces were required to facilitate the processes to be carried on within the building. Thus, the structural system must eliminate the need for interior columns. Further, in order to enhance the profitability of the processes housed within, the building should be designed and constructed so that capital and operating costs are minimized.

ii) Environment:

Environment relates to the external conditions which the facility must exclude or carry (loads caused by weather, including gravity and lateral loads, heat loads, etc.) and the internal conditions in terms of temperature, humidity, etc. which must be maintained inside the facility. These conditions have an important bearing on the design, construction, operation, maintenance and depreciation of each of the subsystems comprising the facility. For this study, external influences were determined as per the National Building Code (21).

iii) Configuration:

Configuration relates both to the manner in which the various subsystems are interconnected as well as to the layout of each subsystem. Overall systemand subsystem configurations are described in terms of topology and geometry variables. For this study, the configuration of the total system was expressed in terms of three variables: bent spacing, number of panels per truss and truss depth to span ratio. Given values for these variables, the number of bents, foundations, purlins and joists can be readily determined. Subsystem configuration is expressed in terms of member sizes, spacing, etc. For the bent design, trusses were assumed to have equal panel spacing. Footings were assumed to be square. Purlins were assumed to be placed at panel points only.

iv) Codes:

The design of each subsystem must satisfy the relevant code. For this study, structural loads and load combinations were determined as per the National Building Code. The structural bent and roof system were designed in accordance with CSA Standard S16-1969. Footing design was performed in accordance with the National Building Code and ACI318-71 Building Code. Other codes which influence overall system configuration include municipal codes and zoning regulations which set limits on height, setback, floor area ratio, noise level, demand on services, etc. Such code provisions were not considered in this study.

v) Performance Criteria:

Performance criteria relate to the manner in which subsystem and overall system effectiveness are measured. Of several criteria possible for assessing system performance, three crucially important ones relate to financial return, cost and time. Capital cost was singled out as the most important single criterion for this study. Life cycle cost would only have been applicable if mechanical system design had been included, assuming that questions of future renovations and/or expansion can be ignored.

For a cost criterion to be useful in helping the designer to determine the most effective system and subsystem configuration, it must reflect the range of economic inputs required and the manner in which these inputs are determined. Expressions for capital cost for each subsystem were determined in this study which reflect the inputs of labour, equipment, material and overhead, as well as contractor profit. Explicit recognition was given to handling costs which are a function of the number of components to be constructed as well as to costs related to material quantities. In general, the capital cost C_i for the ith subsystem may be written as

$$C_i = \text{PROFIT}_i + \text{OVERHEAD}_i + \text{LABOUR}_i + \text{EQUIPMENT}_i + \text{MATERIAL}_i \qquad (1.1)$$

Expression 1.1 reflects the manner in which fabrication and construction costs are determined by contractors. For this study, profit and overhead have been computed as a fraction of direct costs, yielding the following expression for C_i:

$$C_i = (1 + M_i)(1 + O_i)[\text{LABOUR}_i + \text{EQUIPMENT}_i + \text{MATERIAL}_i] \qquad (1.2)$$

where M_i is the fraction of direct cost and overhead charged for profit and office overhead and O_i is the fraction of direct cost charged for field and/or shop overhead.

Normal design office practice is to compute system cost by multiplying the various material quantities required by their respective unit costs and then summing up to obtain total system cost. These unit costs are normally derived from previous experience on projects of a similar nature and include the inputs of labour and equipment as well as materials. While such an approach is useful for estimating an overall budget, it does not reflect the manner in which a project is costed by a contractor nor does it accurately account for the costs which are a function of the number of components to be installed or erected. It is shown in this study that depending on which cost model form is used, different design configurations are selected as being optimal in terms of capital cost. Further, it is shown that the sensitivity of labour input to changes in system configuration is considerably greater than material quantity sensitivity, thus highlighting the need for proper formulation of the cost model.

vi) Alternatives:

Normally the designers of each subsystem have a range of feasible alternatives from which they can choose. For example, for a building of the type considered herein, feasible alternatives for the structural system include gable-frames, arches, a space truss, etc. For this study, attention was restricted to one alternative for each subsystem. A square spread footing was selected as the main foundation element. For the structural system, a steel bent consisting of a welded parallel chord pratt truss and wide flange columns was selected. Double angle members were selected as web members and tees were used for chords. Even panel spacing was assumed with loads being applied to the panel points. G40.21, grade 44W steel was used for all members. A roof system comprised of purlins, joists and steel Q decking was used. When purlin spacing was less than the maximum allowable span for the decking, joists were eliminated. Open web short and long span manufactured joists were used for joists and purlins, respectively. A steel cladding system was adopted for the walls.

vii) Interaction:

In order to effect meaningful tradeoffs between subsystem designs, subsystem interaction must be properly modeled. Interaction or interface variables for the subsystem alternatives considered herein correspond to bent spacing or number of bays, number of panels and truss depth to span ratio. Subsystem interaction for the problem at hand takes the form of loads transmitted for one subsystem to another (i.e. roof system to bent system and bent system to foundation system). These loads are a function of the interface variables. Costs which reflect the number of components in each subsystem are also a function of these variables.

viii) Construction:

The fabrication and/or construction operations implied by each subsystem design have an important bearing on project cost. Knowledge of these operations along with the appropriate production rates is essential for the formulation of cost models which can predict total system costs accurately. An effort was made in this study to model the operations involved in the construction of the foundation, bent and roof systems adopted for this study and to obtain actual production rates. This information has been incorporated into the cost models developed.

ix) Operation and Maintenance:

These items refer to the operating and maintenance characteristics of each subsystem including costs, the relationship of these characteristics to design configuration and the influence of economic conditions on future costs. No consideration was given to these items in this study. They will be taken into account when mechanical system design is incorporated into the design aid.

x) Design Algorithms:

Design algorithms refers to the set of analysis and design techniques used for specifying subsystem characteristics. For this study, footings were designed using a standard trial and error design routine, an elastic design philosophy was used for the structural bent design with forces and deflections being determined by the stiffness method and members sized according to a fully stressed design criterion and the roof members were designed using look-up tables based on manufacturer's data.

xi) Optimization:

Cost minimization was selected as the objective function. Because of the size and nature of the problem, it was decomposed into subproblems consisting of the foundation, structural bent and roof systems. Given values of the interface variables, subsystem designs were optimized. Coordination of the design process was achieved by use of a master optimization problem which determined values for the interface variables. A direct search procedure, Box's Complex Method, was used for the master program, a "satisfying" criterion was used for foundation design, a fully stressed design criterion for the bent design and an exhaustive search procedure for the roof system design.

1.3 LITERATURE REVIEW

Previous work which pertains to the problem examined in this thesis is briefly described below.

Lee and Knapton (13) investigated the minimum cost of portal framed buildings, based on plastic design. Number of bays, frame spacing, eave height, roof pitch, building length and building width were considered as independent variables. These variables were subject to constraints on site limitation, area and building volume. The cost criterion was composed of the sum of the individual material and fabrication costs for the structural steelwork, purlins and cladding. Erection costs and non weight related fabrication charges were not considered. Emphasis was placed on obtaining workable designs. The search through the feasible design space for the least cost structure was accomplished using the nonlinear variable metric simplex method.

Morris (19) outlined in conceptual terms a methodology for building systems synthesis. He discussed optimization procedures, performance criteria and constraint relationships. He suggested that many of the subsystems normally omitted in optimization studies, such as wall and HVAC, play an important role in determining total building cost. While the importance of considering subsystem interaction was stressed, no mechanisms were described for coordinating the design of the various building subsystems.

Miller, Moses and Yeung (18) set out a systematic approach for building design optimization. Minimum cost design for each subsystem were determined, given values for the interaction variables. Optimum system design was then performed using dynamic programming. The methodology presented was an interesting one possessing considerable potential. However, it is not immediately clear how it can be extended to cope with the more general design problem where multiple load cases must be considered.

Lipson and Russell (17) investigated labour and fabrication cost independent of material cost for a structural roof system model to examine the effect of topology cost on the optimum configuration. The main decision variables considered were truss spacing, truss depth to span ratio and number of panels. Member sizes were determined according to fully stressed design criterion. Values for the main decision variables were determined using Box's Complex Method. The work described herein is a direct extension of this previous work.

Bradley, Brown and Feeney (5) studied the cost optimization of factory structures using geometric programming. Their investigation centers around those elements that provide the greatest variation in cost due to different structural forms and various available material products. The elements considered in their model were the structural frame, columns, purlins, wall components, eave beams and flashing and major area-dependent components such as weatherproofing and insulation. The objective function for the study was to minimize cost. The constraints considered were of both a structural and a practical nature. The optimization procedure considered a range of structural systems as well as the geometry and member sizes for each system.

1.4 THESIS OVERVIEW

The design and costing of the foundation system is considered in Chapter 2. Also examined is the variation in foundation cost and material quantities as a function of the interface variables. Chapters 3 and 4 are identical in nature to Chapter 2 except that the structural bent system and roof system are examined, respectively. System performance as a function of the interface variables is examined in Chapter 5. Performance is considered in terms of weight, weight related cost and a general cost model. Also examined in this chapter is an optimization scheme for determining values for the interface variables and coordinating subsystem design. The effectiveness of the optimization procedure is examined in detail and results are given for an example problem. Conclusions and recommendations for future work are presented in Chapter 6.

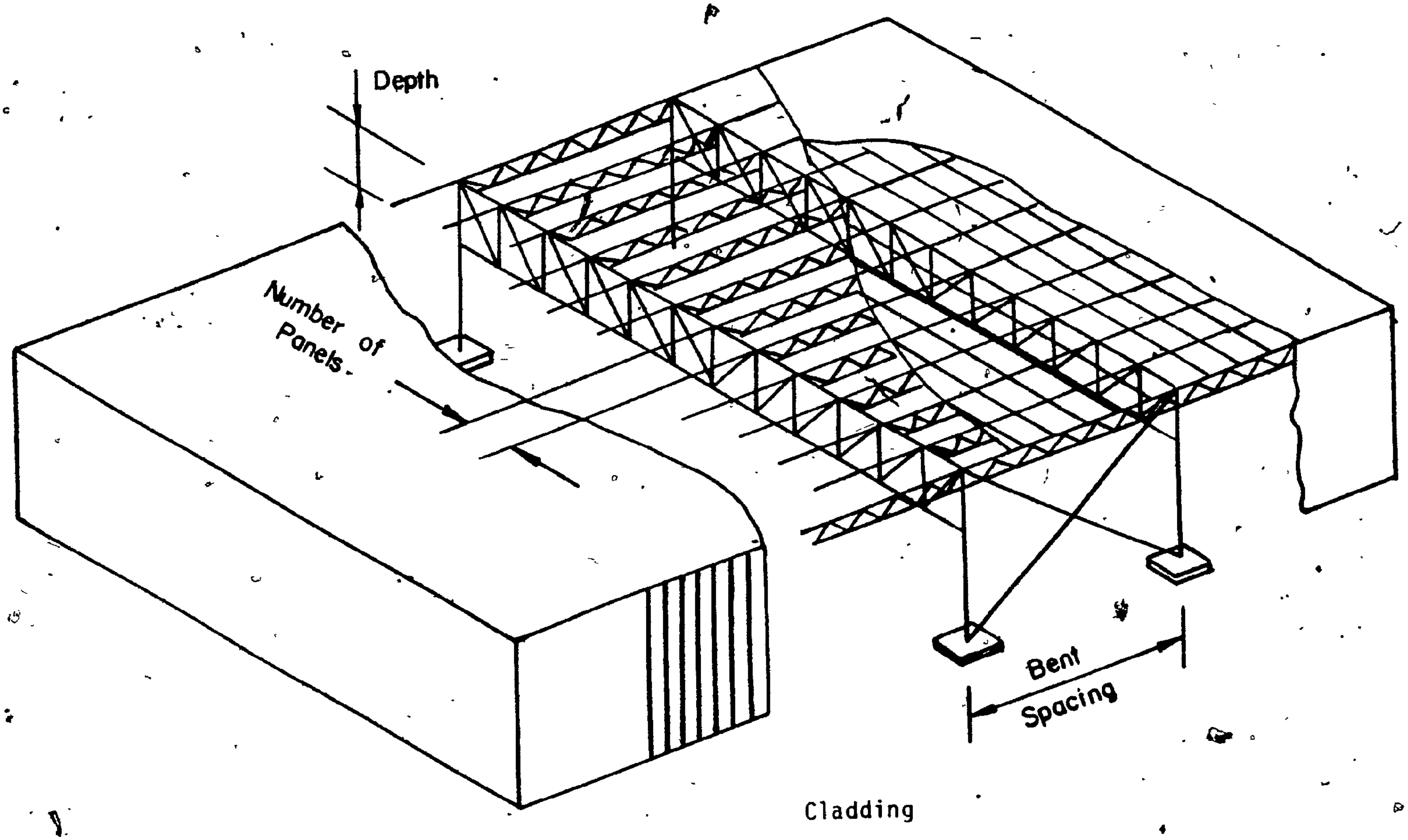


FIGURE I.I- SCHEMATIC OF THESIS DESIGN PROBLEM

CHAPTER 2

FOUNDATION SYSTEM

2.1 INTRODUCTION

The design and costing of the foundation system for the design problem described in Chapter 1 are examined herein. The objectives of this chapter are:

(i) To describe the foundation system adopted for this study and the algorithm used for its design;

(ii) To formulate cost models for the foundation system which reflect the design decision variables of number of bays, number of panels and depth to span ratio and which account for material, labour and equipment charges;

(iii) To examine the significance of the cost trade offs between material, labour and equipment charges; and

(iv) To examine the sensitivity of both foundation system material quantities and cost to changes in design configuration.

2.2 FOUNDATION SYSTEM DESIGN

Figure 2.1 depicts various alternative foundation systems that could be used for an industrial building of the type described in Chapter 1. Three elements other than cost which must be considered in selecting the most appropriate foundation type relate to:

(a) Site conditions, which include bearing capacity of the soil, soil settlement characteristics, location of ground water table, size of the site and proximity of building to adjacent properties and buildings;

(b) Structural considerations, which include the size of the building and its loads and their distribution and the building tolerance for differential and total settlement; and

(c) Codes which set limits on allowable bearing pressure, differential and total settlement, frost penetration, etc.

For the problem at hand, soil of good bearing capacity has been assumed and problems associated with settlement, groundwater table and adjacent buildings were assumed not to exist.

Of the three key structural decision variables, number of bays, number of panels and depth to span ratio, the first has the greatest impact on the foundation design problem. This is because the number of foundation elements is a function of number of bays, and their size which is a function of the load transmitted is in turn, also a function of the same variable. The other two variables have a secondary effect on the design of the foundation as they influence the magnitude of the dead load transmitted to the foundation. The vertical and lateral loads applied to each foundation element are also influenced by the horizontal live loads acting on the structure, and these loads are in part a function of the truss depth to span ratio.

For this study, the foundation system has been designed in accordance with the National Building Code of Canada (21). For the building type considered herein, its geometry in terms of distance between column supports and the range of column loads considered are such that individual footings constitute the most appropriate foundation element. Further, because of code provisions relating to frost penetration, a pedestal footing (Figure 2.1(c)) has been assumed for this study. It is left to a later study to develop a library of foundation types which will permit the design of foundation elements to satisfy a wider range of loading types and soil conditions.

Figure 2.2 depicts the geometry of the footing and shows the relevant material quantities as a function of footing size. The footing has been assumed to be square and the dimensions of the pedestal are taken to be equal to the column base plate plus 2 inches, with the base plate being designed in accordance with the National Building Code. For analysis and design purposes, the column to footing connection is assumed to be pin connected.

Although allowance for forming of the footing has been made in the computer program developed, for purposes of this study it was assumed that the soil was sufficiently stiff that the sides of the excavation would remain vertical and could be used as a natural form.

The basic footing design algorithm was adopted from Bowles (3) and is based on the ACI 318-71 Building Code. This algorithm requires values for the following parameters:

(a) Footing material properties which include allowable compressive strength of concrete f'_c and the yield strength of reinforcing steel f_y (taken as 3 ksi and 60 ksi, respectively, for this study);

(b) Allowable soil bearing pressure, (taken as 4 ksf for this study);

(c) Size of the column base plate; and

(d) Magnitude of the loads transmitted from the superstructure (see Chapter 3 for the load cases considered).

Items (c) and (d) are functions of the three key decision variables and the values for these parameters are transmitted to the foundation system design routine upon completion of the superstructure design.

The key attributes of the footing are computed as follows:

(a) Lateral dimensions of footing:

$$B = \frac{DL+LL}{q_a}$$

where

q_a = allowable soil bearing pressure;
DL = dead load; and
LL = live load.

The value of B is rounded up to the nearest quarter foot as a practical field construction consideration.

(b) Ultimate soil pressure (q_u) to find the footing thickness:

$$q_u = \frac{P_{ult}}{B^2}$$

where

$$P_{ult} = 1.4DL + 1.7LL$$

(c) Footing thickness d for diagonal tension:

$$d^2(V_c + q_u/4) + w(V_c + q_u/2)d = \frac{(B - w^2)}{4} q_u$$

where

$$V_c = 2 \phi\sqrt{f'_c}$$

= wide-beam shear stress - ACI 318-71 code;

f'_c = 3000 psi according to ACI 318-71, art 8.1

w = column width; and

ϕ = workmanship factor for uncertainties.

(d) Fraction of footing cross-sectional area for steel bending (ρ).

Bending moment at the critical section of the footing

$$M_u = q_u * L^2/2$$

where

L = cantilever length (see Figure 2.2)

and knowing M_u, area of steel, A_s can be computed from

$$M_u = \phi A_s f_y (d - \frac{a}{2})$$

where

M_u = ultimate moment at the critical section due to ultimate soil bearing pressure;

f_y = yield strength of the steel; and

a = equivalent depth of compression zone and

$$0.002 \leq \rho = A_s/bd \leq 0.0160 \text{ (for } f_y = 60{,}000 \text{ psi)}$$

where

ρ = percentage of steel at a cross section of a flexural member.

(e) Check for bond:

$$L_d = 0.04\ A_b f_y/\sqrt{f'_c}$$

where

L_d = required embedment depth for rebars; and

A_b = area of any steel reinforcing bar.

2.3 FOUNDATION MATERIAL QUANTITIES AS A FUNCTION OF SUPERSTRUCTURE CONFIGURAION

To determine the sensitivity of foundation material quantities to variations in values of key design parameters and variables, several computer runs with the foundation model were made. Figure 2.3 depicts the variation of individual footing concrete quantity versus total design load for various soil bearing capacities. Figures 2.4 through 2.8 depict various footing material quantities versus truss spacing for a building having overall plan dimensions of 100 x 520 feet. Both individual footing quantities and total footing quantities are shown in these figures. The influence of variations in truss D/S ratio and number of panels is minimal on these quantities and thus results are shown only for a D/S ratio of 0.08 and number of panels equal to 8. Truss spacings examined correspond to 26, 20, 16, 13 and 10 bays and the number of footings required is computed as 2(N + 1) where N is the number of bays.

Observations that can be made based on examination of Figures 2.3 through 2.8 include:

(i) Material quantities increase nonlinearly with increasing load (Figure 2.3). For example, with q = 6 ksf, the quantity of concrete required for a footing with a load of 100 kips is 0.69 cy while for a load of 200 kips the concrete quantity is 1.7 cy. This increase in footing material is offset by the decrease in number of footings with increased truss spacing.

(ii) While all material quantities per footing increase with truss spacing, on a total material basis, the minimum total material quantities occur for a truss spacing of 26 feet (42 footings).

(iii) The variation in total material quantities in some cases is quite large over the range of truss spacings examined, with the total variation in each quantity examined being: excavation 10.2%; forming 101.8%; reinforcement 44.1%; concrete 34.2%; and backfill 7.6%.

(vi) The material quantities for a 20 foot truss spacing are close in magnitude to those of the 26 foot truss spacing, with the percentage differences in various quantities for these spacings being: excavation 1.6%; forming 28.7%; reinforcement 20.5%; concrete 5.2%; and backfill 0.3%. Thus, if foundation costs are estimated on the basis of material quantities, these two alternative truss spacings will yield similar foundation cost results. If individual foundation set up costs are included, however, (Section 2.4) these cost differences will become more pronounced.

2.4 FOUNDATION COST MODELS

Two cost models were examined for the foundation system. The first of these follows conventional engineering design office estimating practice and is based on material quantities. This approach also forms the basis for published cost guides such as MEANS (6), DODGE (10) and others. This approach suffers from the fact that the number of elements to be constructed does not form an integral part of the estimating procedure. For example, while the quantity of concrete is computed based on the amount required for one footing multiplied by, say, 100 footings, resulting in, for example, 200 cy of concrete, the pricing of this quantity installed makes no distinction between 1 footing consuming all 200 cy or 100 footings consuming 2 cy each. Clearly, their is a significant difference in labour costs associated with these two cases and, in fact, there is some difference in material costs because of wastage considerations. While the application of judgement factors could offset, at least partially, this deficiency, such factors require considerable construction experience not available to the typical design engineer.

The second approach is based on modeling the actual sequence of construction operations required for the foundation system, and as such, directly accounts for the number of elements to be constructed.

A major problem with this approach, however, is a lack of reliable data pertaining to job site production rates, crew sizes and relocation times.

2.4.1 Material Quantity Related Cost Model

The cost of the foundation system based on the material quantities involved is written as follows:

$$\text{COST OF FOOTINGS} = (1+M)(1+O_H)[\text{COST OF LAYOUT + COST OF EXCAVATION + COST OF FORMING + COST OF REINFORCING + COST OF ANCHOR BOLTS + COST OF CONCRETE + COST OF STRIPPING AND GROUTING + COST OF BACKFILL}] \quad (2\text{-}1)$$

where

M = fraction of direct costs required for profit, office overhead and contingency

and

O_H = fraction of direct costs required for site overhead.

Except for the COST OF LAYOUT and COST OF STRIPPING AND GROUTING, each of the terms in expression (2-1) may be written as

$$\text{Cost of } x = \text{NUMBER OF FOOTINGS*MATERIAL QUANTITY PER FOOTING*UNIT COST OF MATERIAL} \quad (2\text{-}2)$$

where UNIT COST OF MATERIAL includes material purchase, including sales tax (if appropriate) and installation. Table 2.1 summarizes relevant cost data from two published cost guides. All figures have been adjusted to reflect Montreal rates. The COST OF LAYOUT and COST OF STRIPPING AND GROUTING have been estimated on the same basis as used for the general cost model described in section 2.4.2.

2.4.2 General Cost Model

The general cost model is written in the following form:

$$\text{COST OF FOOTINGS} = (1+M)(1+O_H)[\text{COST OF MATERIAL + COST OF LABOUR + COST OF EQUIPMENT}] \tag{2-3}$$

The material cost component of equation 2-3 may be expanded as follows:

$$\text{COST OF MATERIAL} = \text{COST OF FORMWORK + COST OF STEEL + COST OF CONCRETE + COST OF ANCHOR BOLTS + COST OF BACKFILL} \tag{2-4}$$

All material costs are considered FOB site and include both federal and provincial taxes.

In order to assess labour and equipment costs accurately, it is necessary to determine the sequence of operations required for the construction of a typical column footing. A typical sequence, derived in consultation with a former general contractor, is depicted in Figure 2.9. Each operation in this sequence may involve one or more of the resources of men, machines and materials, and these resources can be expressed in terms of the performance criteria of time and cost.

With respect to the time required for the execution of each operation in the construction sequence, a model of the form shown in Figure 2.10

was adopted as most representative. For each operation, a certain time commitment is required independent of the amount of material to be placed, due to relocation of men and equipment, set up, etc. and the balance of the time required is a function of the material quantity to be placed. It is this fixed time component for the various operations required for the construction of each footing which is ignored in the material related cost model.

By breaking the construction sequence down into the elemental operations shown in figure 2.9, it is possible to collect data regarding the time required for each operation and the crew composition. For purposes of this study, times were established based on discussions with a former general contractor. It is left to a future study to observe actual field observations to verify the values assumed in this study for production rates and fixed time components.

Table 2.2 summarizes the time required for each of the operations shown in Figure 2.9. Also listed in this table are the crew requirements for each operation. Table 2.3 is a rate table and lists current wage rates for each labour and equipment type. Table 2.4 lists the material costs used in this study. Using the information in Tables 2.2 and 2.3, expressions for the COST OF LABOUR AND COST OF EQUIPMENT may be readily written as follows:

$$\text{COST OF LABOUR} = N^* \sum_{i=1}^{m} T_i CL_i \qquad (2\text{-}5)$$

where

N = number of footings;

T_i = time required to complete the i-th construction operation for each footing;

CL_i = cost per unit time for the labour crew for the i-th construction operation.

$$\text{COST OF EQUIPMENT} = N * \sum_{i=1}^{m} T_i CE_i \qquad (2\text{-}6)$$

where CE_i = cost per unit time for the equipment required for the i-th construction operation.

2.5 FOUNDATION COSTS

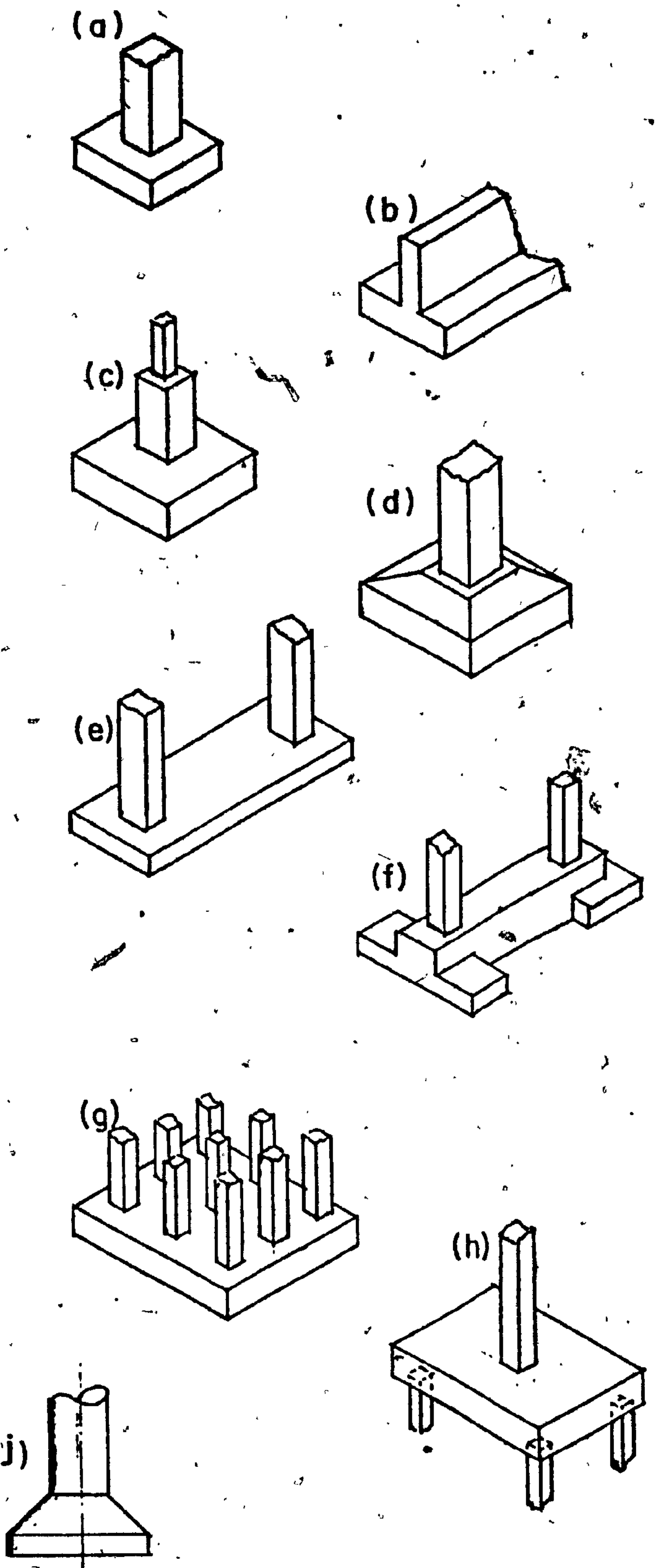
Table 2.5 and Figures 2.11 and 2.12 summarize the results obtained for the foundation design of a warehouse type building having dimensions of 100' x 520'. The following observations are made with respect to these results:

(i) Foundation system cost decreases with increasing truss spacing and decreasing number of footings for both cost model types. Minimum cost for both models occur for a truss spacing of 52.0 feet (22 footings). Consequently, both cost models yield the same design decision for minimum cost.

(ii) The variation in total cost over the range of truss spacing examined is 41.4% for the general cost model and 26.3% for the material quantity related cost model. As expected, the general cost model is more sensitive to variations in design configuration than the material quantity related model.

(iii) This sensitivity is best explained by examining the breakdown in foundation costs for various truss spacing (Figure 2.12). The greater the number of footings, the more impact the fixed costs associated with each construction operation have on a total cost, and hence the greater the difference in cost between the two cost models (50.1% for 20 foot spacing versus 26.6% for 52 foot spacing).

(iv) While, in general, material quantities are minimum for the 26 foot spacing, because cost of layout and cost of stripping and grouting are based on number of footings for the material quantity related cost model, this model yields minimum cost for the maximum truss spacing considered.



(a) Simple Spread Footing

(b) Wall Footing

(c) Stepped or Pedestal Footing

(d) Sloped Footing

(e) Combined Footing

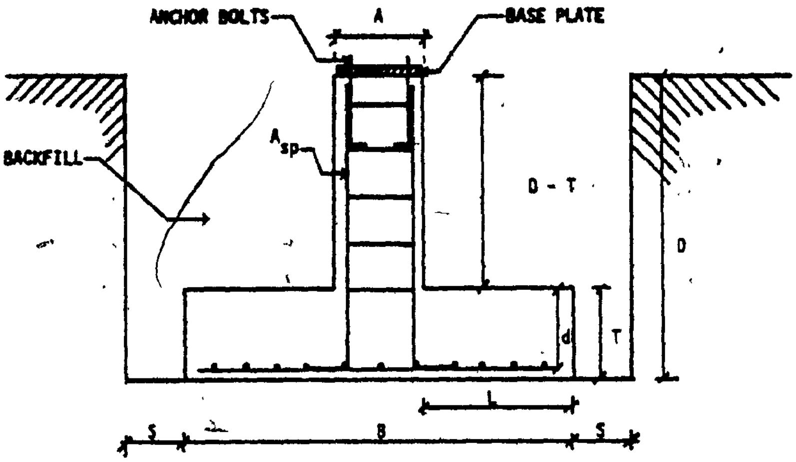
(f) Strap Footing

(g) Mat or Raft Foundation

(h) Pile Cap Foundation

(j) Drilled Belled Pier

FIGURE 2·1 VARIOUS ALTERNATIVES FOR FOUNDATION SYSTEMS



D = Depth of excavation below grade, as set by Code provisions for frost penetration
T = Thickness of footing
= d + 3, where d is the effective depth of footing and 3" is the minimum concrete cover for the steel, as required by the Code.
B = Width of square footing
A = Width of square pedestal
A_{sp} = Area of steel in pedestal
S = Excavated side of footing
L = Cantilever length
= (B-A)/2

Footing material quantities are computed as follows:

VOLEXC = $D(B+2S)^2$
FTCON = $T\ B^2$
FTFWK = 4BT
WFST = $\rho(A_{s1}\ B + A_{s2} B)$
PCON = $(D-T)A^2$
PFWK = $4(D-T)A$
WPST = $\rho\ D\ A_{sp}$
VOLFIL = VOLEXC - FTCON - PCON

where

VOLEXC = Volume of excavation
FTCON = Quantity of concrete for footing
FTFWK = Footing formwork quantity
WFST = Weight of steel for footing
PCON = Quantity of concrete for pedestal
PFWK = Pedestal formwork quantity
WPST = Weight of steel for pedestal
VOLFIL = Volume of backfill
ρ = Unit weight of steel
A_{s1}, A_{s2} = Area of steel required for footing side 1 and 2

FIGURE 2.2: GEOMETRY OF THE FOOTING

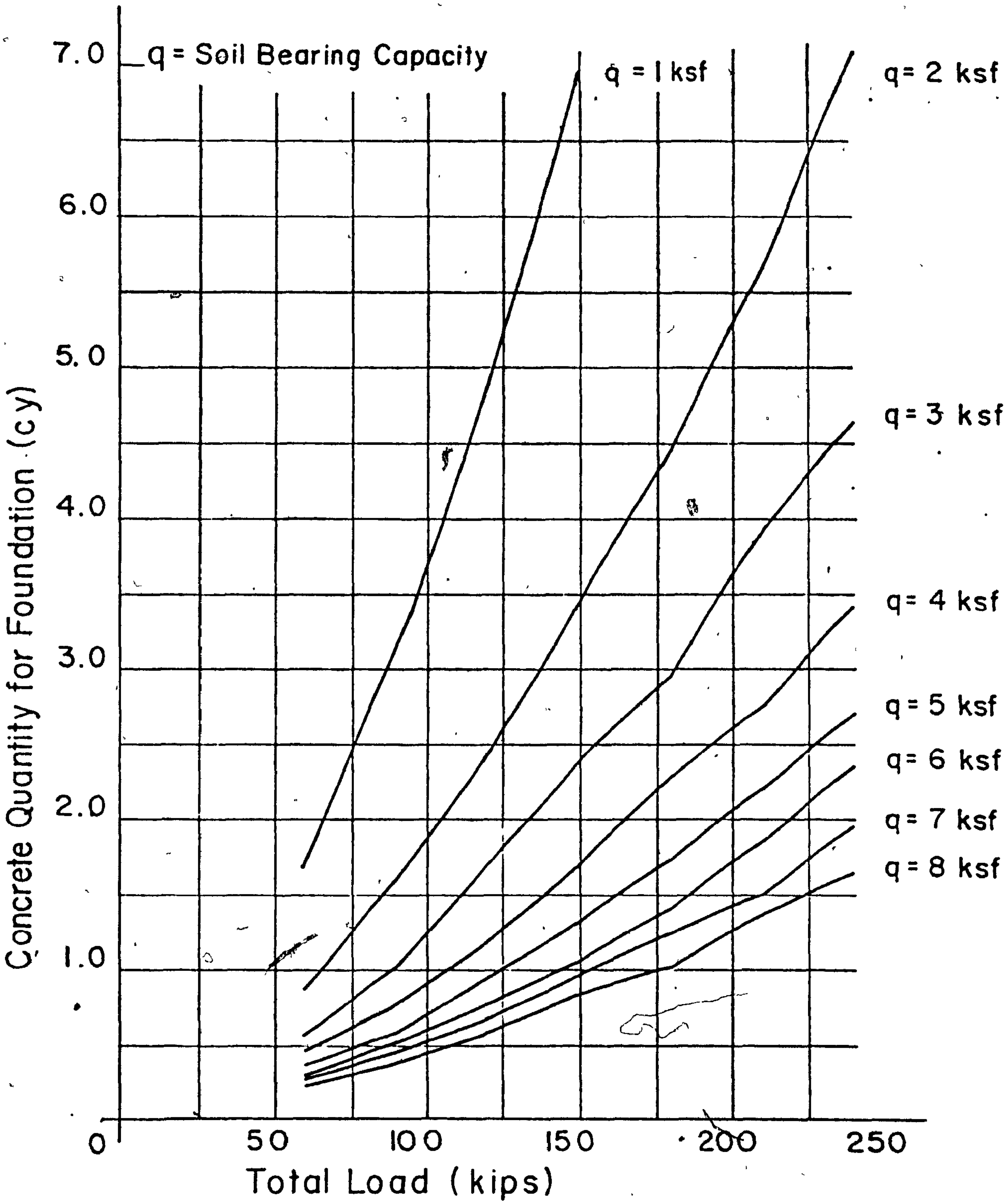


FIG. 2·3 VARIATION OF CONCRETE QUANTITY WITH LOAD AND BEARING CAPACITY

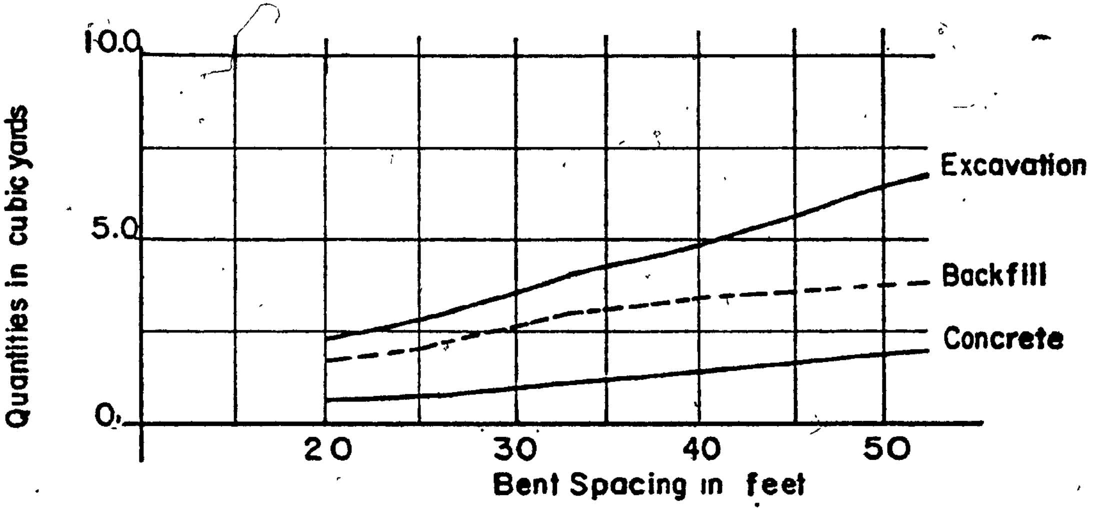


FIG. 2·4 VARIATION OF MATERIAL QUANTITIES FOR INDIVIDUAL FOOTING

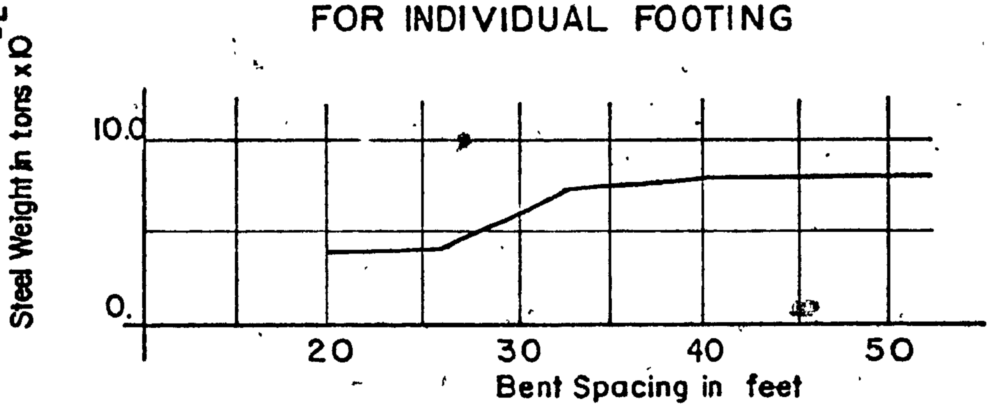


FIG. 2·5 VARIATION OF STEEL WEIGHT FOR INDIVIDUAL FOOTING

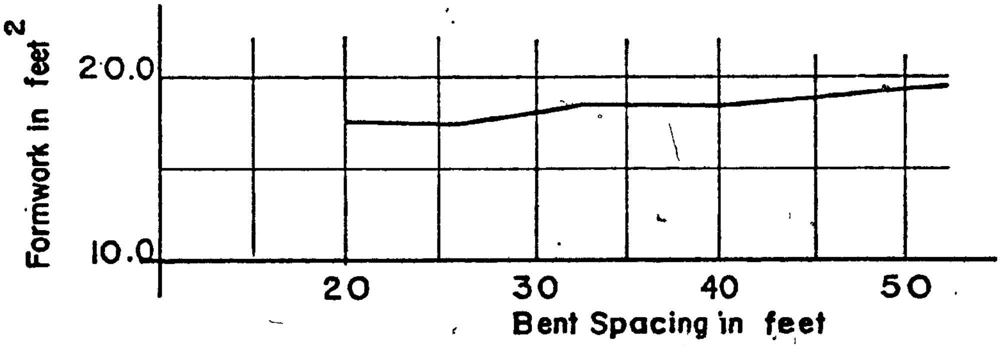


FIG. 2·6 VARIATION OF FORMWORK FOR INDIVIDUAL FOOTING

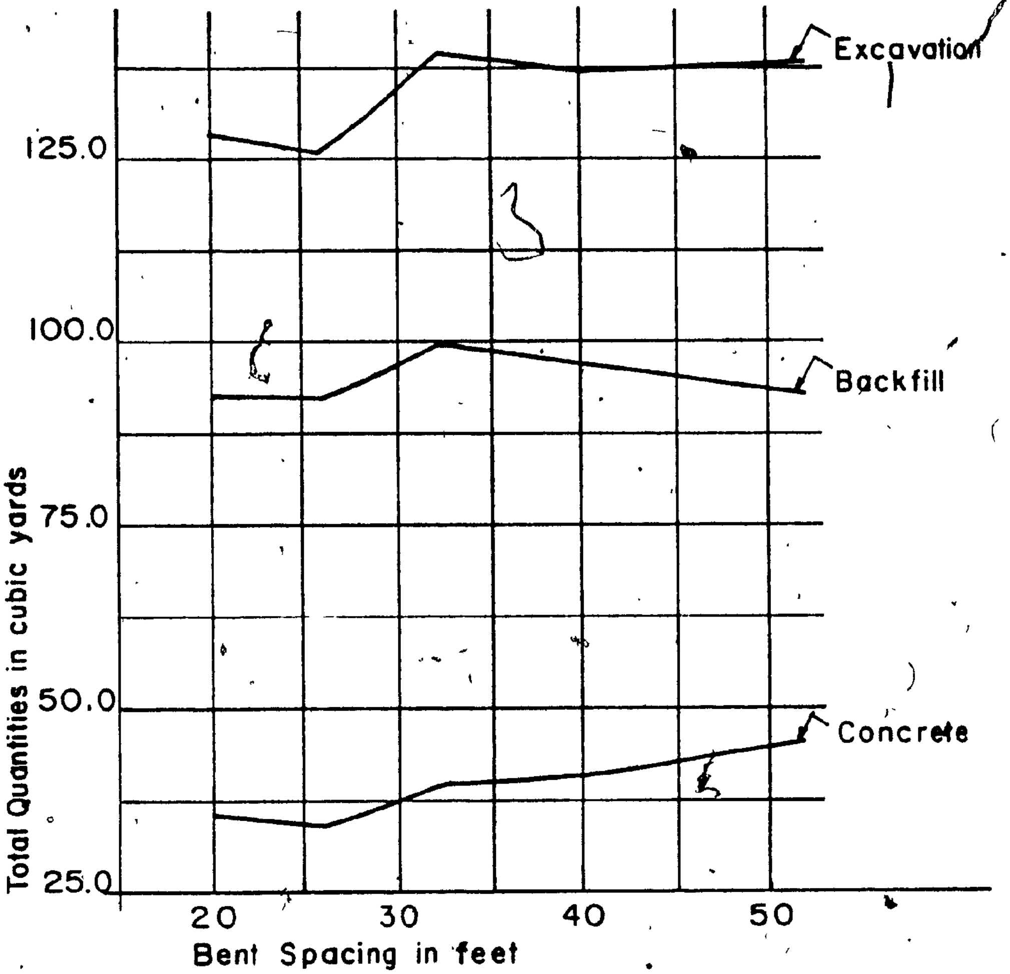


FIG. 2·7 VARIATION OF TOTAL MATERIAL QUANTITIES FOR FOUNDATION SYSTEM

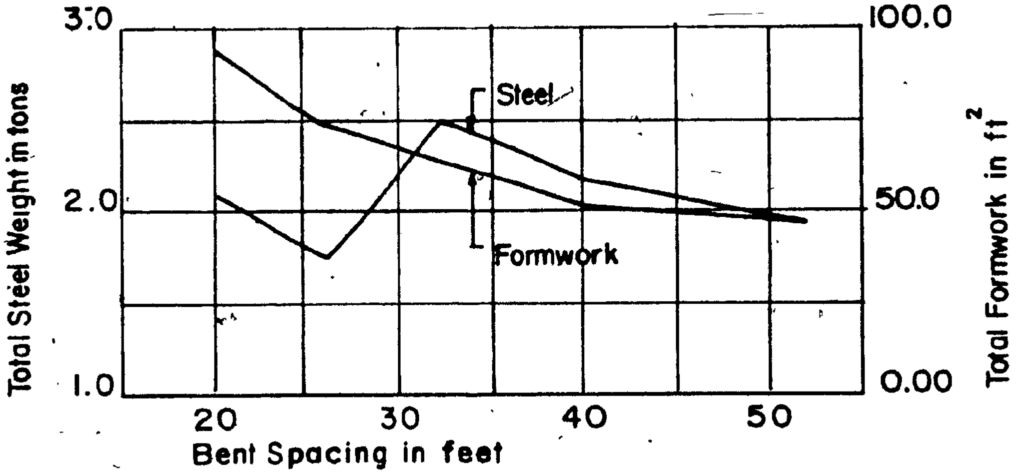


FIG. 2·8 VARIATION OF TOTAL STEEL & FORMWORK QUANTITIES FOR FOUNDATION SYSTEM

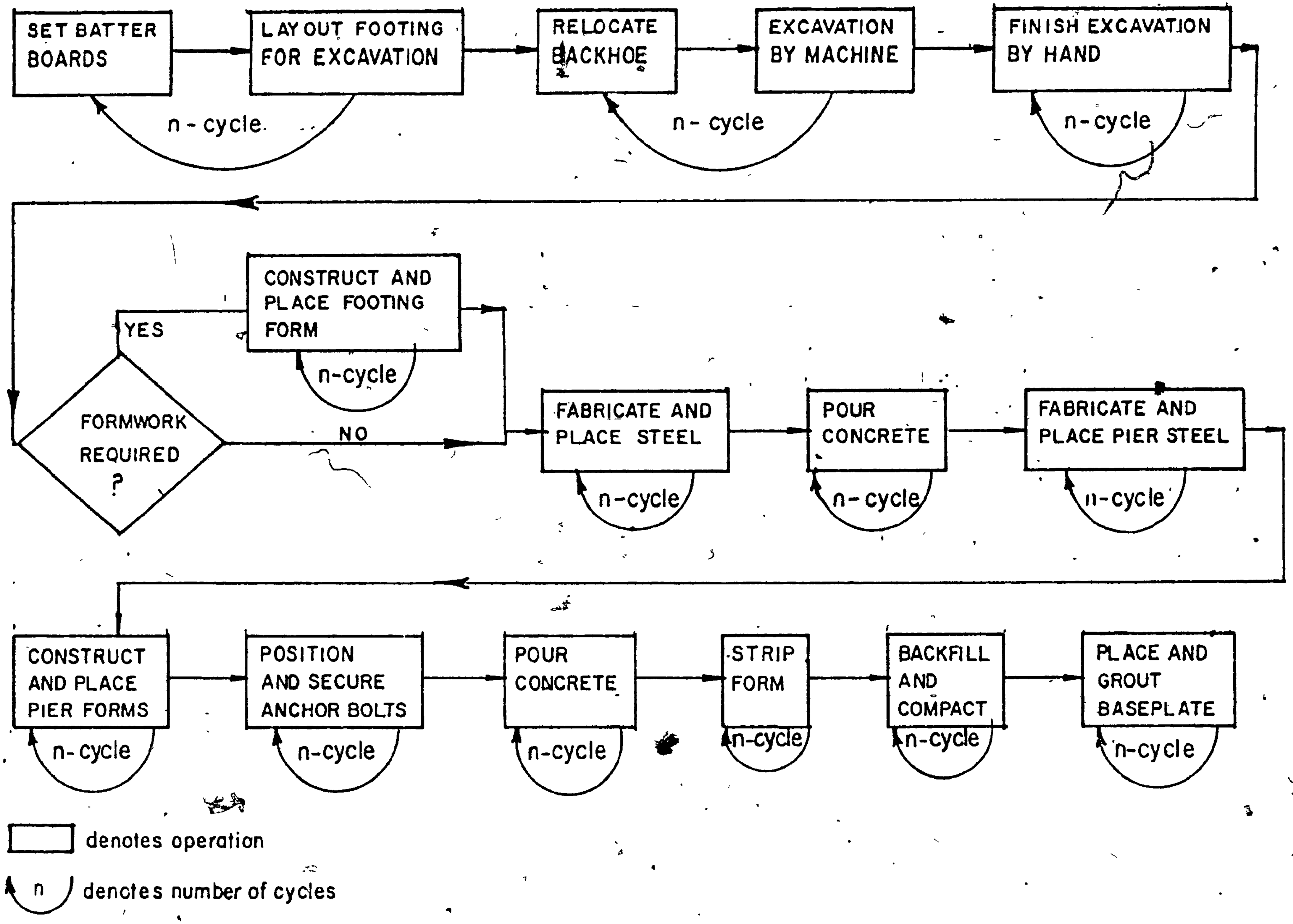
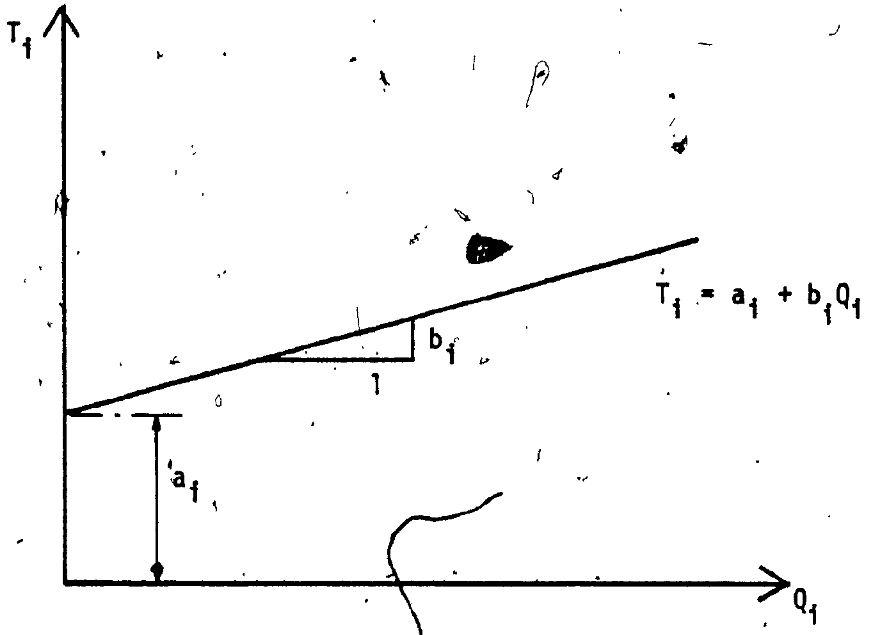


FIG. 2.9 SEQUENCE OF OPERATIONS FOR FOOTING CONSTRUCTION



T_i = time required to complete operation i per footing

a_i = fixed time component for operation i

b_i = production rate for operation i

Q_i = quantity of work or material to be performed for operation i

FIGURE 2.10: TIME MODEL FOR FOOTING CONSTRUCTION OPERATIONS

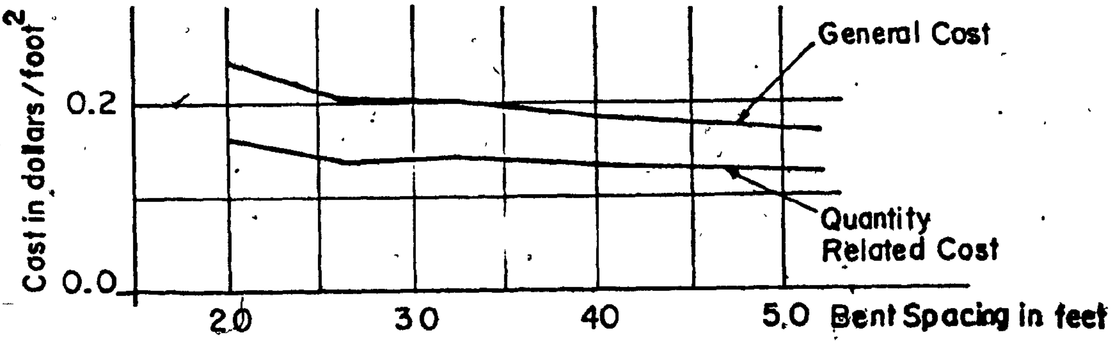
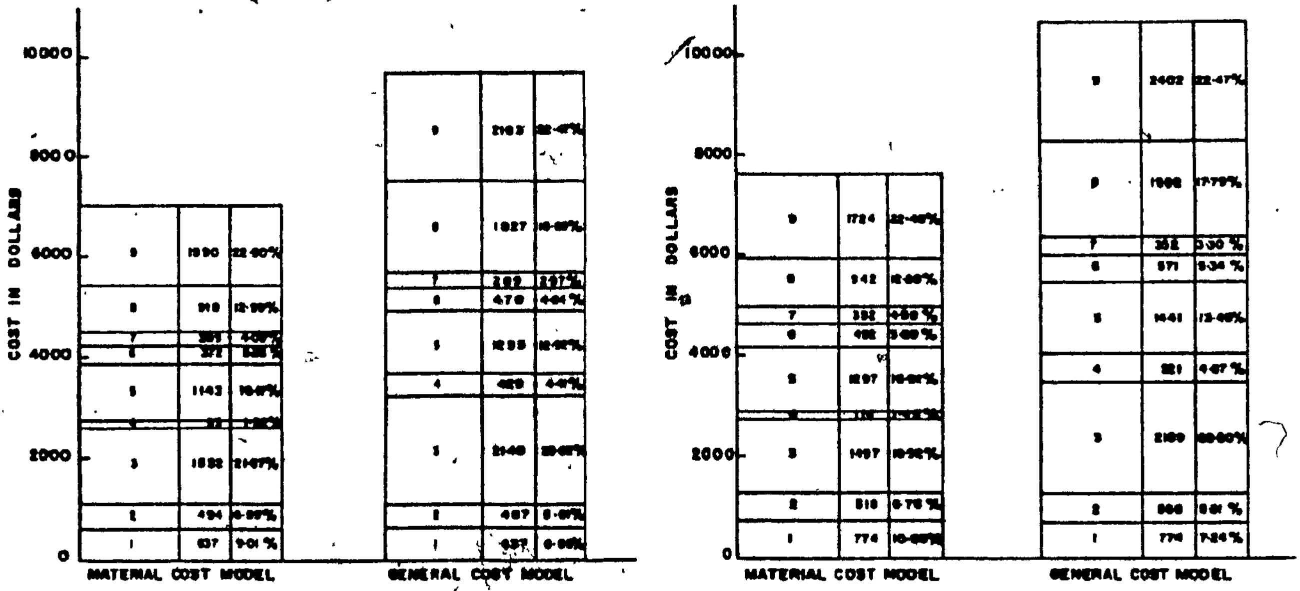
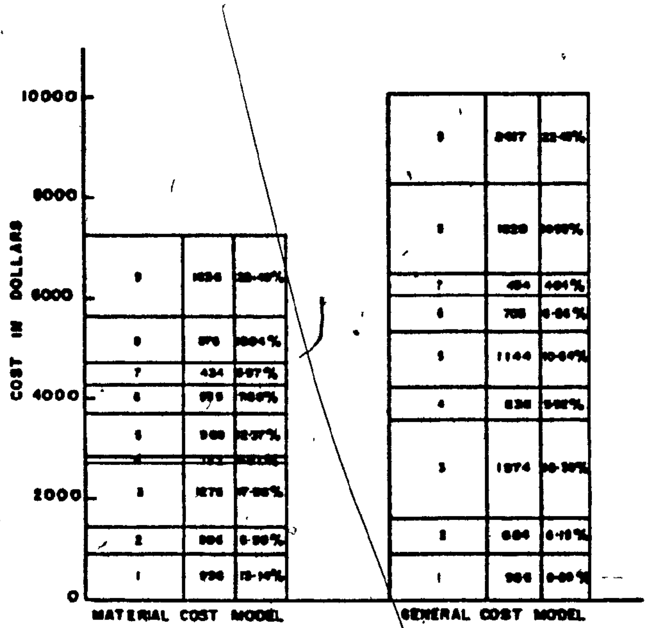


FIG. 2·11 VARIATION OF FOUNDATION COST WITH DESIGN CONFIGURATION



(a) BREAK DOWN OF FOOTING COST FOR 40 FOOT BENT SPACING (28 FOOTINGS).

(b) BREAK DOWN OF FOOTING COST FOR 32·5 FOOT BENT SPACING (34 FOOTINGS).



(c) BREAK DOWN OF FOOTING COST FOR 26 FOOT BENT SPACING (42 FOOTINGS).

KEY

1 = LAYOUT
2 = EXCAVATION
3 = CONCRETE
4 = FORM WORK
5 = STEEL
6 = ANCHOR BOLTS
7 = STRIPPING & GROUTING
8 = BACKFILL
9 = OVERHEAD, CONTINGENCY AND PROFIT ETC.

FIGURE 2-12 BREAK DOWN OF FOUNDATION COSTS VERSUS DESIGN CONFIGURATION

ITEM	SOURCE			
	YARDSTICKS FOR COSTING(30)(1)		MEANS (8)	
	UNIT	$/UNIT	UNIT	$/UNIT
Excavation(2)				
Machine	cy	2.95	cy	2.41
Hand(3)	cy	12.75	cy	14.60
Forming(4)	SF	1.80	SF	1.79
Reinforcing	LB	0.26	LB	0.32
Anchor Bolts (7)		-	EA	6.82
Concrete (5)	cy	37.80	cy	45.02
Backfill (6)	cy	9.50	cy	7.09

(1) Unit prices include all materials, labour to install, transportation, equipment costs, and site overhead and profit for work which is normally undertaken by subcontractors. The unit prices also include federal and provincial sales taxes where applicable.

(2) Assume medium soil, backhoe excavation. Hauling cost not included.

(3) For purposes of calculation, 1/4 yard of hand finishing and excavation for footing assumed.

(4) Applies to pedestal only. Sides of excavation used as form for main footing.

(5) Includes supply and placing of 3000 psi concrete. Concrete placed by direct chute.

(6) Includes supply and compaction of pit run gravel with maximum of 10 mile haul.

(7) Anchor bolts assumed to be 3/4" by 12" long. Installed by 2 carpenters.

(8) Figures quoted include original subcontractors overhead and profit.

TABLE 2.1: FOUNDATION COST DATA FOR MATERIAL QUANTITY RELATED COST MODEL

OPERATION	FIXED TIME COMPONENT a (HRS)	PRODUCTION RATE		CREW COMPOSITION
		b	UNIT	
Set Batter Boards	0.50			Site superintendent + carpenter
Layout Footing for Excavation	0.33			Carpenter + Gradesman
Relocate Backhoe	0.25			Backhoe Operator + Gradesman
Excavation by Machine		.025	HR/CY	Backhoe Operator + Gradesman
Finish Excavation by Hand	0.50			Labourer
Footing Formwork				
Construct		0.03	HR/FT^2	2 Carpenters
Place	0.50	0.01	HR/FT^2	2 Carpenters
Footing Steel				
Fabricate	0.166	1.5	HR/TON	1 Ironworker
Place	0.166	5.5	HR/TON	
Pour Concrete	0.25	0.5	HR/TON	2 Labourers
Pier Steel				
Fabricate	0.166	1.5	HR/TON	1 Ironworker
Place	0.166	5.5	HR/TON	
Pier Formwork				
Construct		0.03	HR/FT^2	2 Carpenters
Place	0.50	0.01	HR/FT^2	
Position and Secure Anchor Bolts	0.50/bolt			Carpenter
Pour Pier Cement	0.25	2	HR/cy	2 Labourers
Strip Forms	0.25	0.005	HR/FT^2	2 Labourers
Backfill and Compact	0.25	0.4	HR/cy	2 Labourers
Grouting of Base Place	0.50			Labourer

TABLE 2.2: TIME MODEL PARAMETER VALUES FOR FOOTING CONSTRUCTION OPERATIONS

LABOUR TYPE	UNIT	RATE $	REMARKS
Superintendent	HR.	17.88	Unit rates include all fringe benefits
Carpenter	HR.	12.36	
Ironworker	HR.	11.74	
Labourer	HR.	10.15	
Gradesman	HR.	10.54	
Backhoe & Operator	HR.	22.51	

TABLE 2.3: RATE TABLE

MATERIAL	COST	UNIT	REMARKS
Formwork	0.215	FT^2	Unit cost excludes provincial tax
Reinforcing Steel	360.0	TON	
Concrete	33.60	cy	
Backfill	8.62	cy	
Anchor Bolts	2.05	BOLT	

TABLE 2.4: MATERIAL COST

Bent Spacing	No. of Bays	No. of Footings	QUANTITIES					Quantities Related Cost $/ft	General Cost $/ft	DL + LL kips	Pier Size	Footing Size
			Steel Tons/ft (Tons)	Concrete cy/ft (cy)	Excavation cy/ft (cy)	Backfill cy/ft (cy)	Formwork SFT/ft (cy)					
20.0	26	54	0.000040 (2.086)	0.00068 (35.56)	0.00246 (128.00)	0.00178 (92.44)	0.00182 (94.50)	0.1620	0.2432	14.06 + 48.20	16" x 16"	4' x 4' x 9"
26.0	20	42	0.000033 (1.731)	0.00065 (33.81)	0.00242 (126.00)	0.00177 (92.19)	0.00141 (73.44)	0.1399	0.2067	17.67 + 62.66	16" x 16"	4.5' x 4.5' x 9.5"
32.5	16	34	0.000048 (2.495)	0.00076 (39.61)	0.00267 (138.83)	0.00191 (99.23)	0.00121 (63.00)	0.1475	0.2056	21.74 + 78.32	17" x 17"	5.25' x 5.25' x 11"
40.0	13	28	0.000042 (2.198)	0.00078 (40.53)	0.00264 (137.14)	0.00186 (96.62)	0.00100 (51.79)	0.1359	0.1869	26.51 + 96.40	17" x 17"	5.75' x 5.75' x 12"
52.0	10	22	0.000037 (1.937)	0.00087 (45.36)	0.00265 (137.70)	0.00178 (92.35)	0.00090 (46.83)	0.1283	0.1724	34.14 + 125.32	18" x 18"	6.5' x 6.5' x 14"

TABLE 2.5: FOUNDATION MATERIAL QUANTITIES AND COSTS FOR VARIOUS DESIGN CONFIGURATIONS

CHAPTER 3

STRUCTURAL BENT SYSTEM

3.1 INTRODUCTION

The design and costing of the structural bent system for the design problem described in Chapter 1 are examined herein.

The objectives of this chapter are:

(i) To describe the structural bent system adopted for this study and the algorithm used for its design;

(ii) To formulate cost models for the structural bent system which reflect the design decision variables of number of bays, number of panels and depth to span ratio and which account for material, labour and equipment charges;

(iii) To examine the significance of the cost tradeoffs between material, labour and equipment costs; and

(iv) To examine the sensitivity of both structural bent system weight and cost to changes in design configuration.

3.2 STRUCTURAL BENT SYSTEM

3.2.1 Description of Bent System

Attention was focussed on a parallel chord pratt truss connected to wide flange columns as the main structural element. Decision variables were taken as truss spacing (number of bays), truss depth to span ratio and number of panels, with all panels being of equal length. The bent system was assumed to be fabricated from G40.21, grade 44W steel. Chords were assumed to be continuous and of constant area and were fabricated from Tees. Back to back double angles were used as web members. All connections were assumed to be welded except for field chord splices and column connections which were assumed to be bolted. Symmetry in terms of web member sizes was imposed. Web member sizes were allowed to vary from panel to panel.

A short study was undertaken to assess the merits of reducing the number of different web member sizes required, thus reducing handling costs. Four designs were prepared (Appendix I) and sent out to a local fabricator for costing. Costing was done on the assumption that 20 trusses were required for each design. Two of these designs were made for trusses of 150' - 0" span and 10 and 14 panels respectively. The chords were specified as having constant area, all diagonal web members were identical in cross sectional area and all vertical web members had identical cross sectional area. The other two designs had similar physical configuration but chord areas were permitted to vary and web members, although symmetrical about the truss midpoint, varied from panel to panel. As seen from the results of this study presented in Table 3.1, the reduction in manhours per ton achieved by minimizing the number of different members sizes is negligible in comparison to the increased material quantities required and the concomitant increase in manhours. Discussions with another fabricator confirmed this conclusion. Thus this study constituted the basis for allowing web member sizes to vary.

During the course of the study, discussions with fabrictors indicated that some thought should be given in future studies to:

(i) allowing chord member area to vary thus increasing the number of chord splices. A definite tradeoff exists between chord material cost and cost of splices. Reference (20) indicates how such a tradeoff may be affected;

(ii) Using double angles in a star configuration as web members. At least two benefits can be derived from this configuration, namely increased radius of gyration leading to increased allowable compressive stresses (14) and simplifications in making welded connections; and

(iii) Using bolted connections instead of welded connections, thus saving labour input (8), (9).

3.2.2 Load Combinations Considered

All members were sized to satisfy the forces arising from consideration of six load combinations as specified by the National Building Code (NBC) of Canada. The combinations are:

(i) DL

(ii) DL + LL

(iii) DL + WL

(iv) DL + EQ

(v) 0.75 (DL + LL + WL)

(vi) 0.75 (DL + LL + EQ)

Where DL = dead load WL = wind load

LL = live load EQ = earthquake load

Dead load was computed as:

$$DL = \text{WEIGHT OF STRUCTURAL BENT + ROOF SYSTEM WEIGHT + ROOF COVERING WEIGHT} \quad (3.1)$$

An allowance of 8 lbs. was made for the roof covering.

Live load consisted of the snow load and was computed as

$$S = C_s * g \quad (3.2)$$

where

S = design snow load in psf

g = ground snow load in psf

C_s = snow load coefficient.

As stated in the National Building Code, values for C_s and g for the Montreal region are 0.8 and 58 respectively. The snow load was assumed to be distributed uniformly over the entire roof area.

The pressure or suction exerted by the wind was computed in accordance with NBC as follows:

$$p = q * C_e * C_g * C_p \quad (3.3)$$

where

p = the design external pressure acting statically and in a direction normal to the surface either as a pressure or as a suction.

q = the reference velocity pressure

C_e = the exposure factor

C_g = the gust effect factor

C_p = the external pressure coefficient

The value of "q" for the Montreal area as stated in the NBC, is 7.8 lbs.ft^2 and has a return frequency of once every thirty years. In computing values for C_e, C_g, and C_p, consideration must be given to the location, height, length and shape of the building as specified in the NBC.

The design loading due to earthquake motion was computed as follows:

$$V = A*S*K*I*F*W$$

where

V = design lateral seismic force

A = assigned horizontal design ground acceleration ratio (0.04 - for the Montreal region)

S = seismic response factor for the structure

K = numerical coefficient that reflects the material and type of construction, damping, ductility and/or energy absorptive capacity of the structure.

I = importance factor of the structure

F = foundation factor

W = dead load including 25 percent of the design snow load specified.

3.2.3 Analysis and Design

An existing general purpose analysis and design package formed the basis for the structural bent system design. Routines were written which generate automatically the joint data as a function of number of panels and depth to span ratio and the load combinations as required by the code, with loads being applied to the panel points. The structure is analysed using the stiffness approach. The Choleski decomposition method is used for solving the stiffness equation. The manner in which the truss is modeled is depicted in Figure 3.1. Chord member design takes into account the secondary moment which result from the truss deflection. Results from the analysis program were verified by reanalyzing a test structure with a proven program.

The design aspect of the program is based on CSA Standard S16-1969. A fully stressed design procedure is used. The structure is analyzed and designed at least twice. The first iteration assumes a value for structure self weight. On the second and subsequent iterations, if required, structure self weight from the previous iteration is used in determining dead loads. After each design cycle, members are grouped according to instructions provided by the user. As stated previously, chords were assumed to be of constant cross section and web members were made symmetrical about the truss midpoint.

3.3 STRUCTURAL BENT SYSTEM WEIGHT

The manner in which component weights (columns, chords, webs) vary with changing configuration is shown in Figures 3.2 through 3.6. More results on total weight variation are presented in Section 3.5 . Figure 3.2 depicts the variation in bent system component weight versus truss spacing for several different depth to span ratios, Figures 3.3 and 3.4 depict weight variation versus depth to span ratio for several different panel configurations and two truss spacings and Figures 3.5 and 3.6 examine weight variation as a function of number of panels for different depth to span ratios and truss spacings. As seen from these plots, for constant depth to span ratio, total bent steel tonnage is relatively insensitive to changes in bent spacing and number of panels. Greatest sensitivity in total weight is exhibited for changes in depth to span ratio. In examining Figures 3.5 and 3.6 it should be noted that the roof system configuration and thus dead weight, changes. For 8 and 10 panels, the system consists of purlins, joists and decking, while for 12 through 16 panels only purlins and decking are required. Twenty gauge decking is needed for 12 panel case while 22 gauge decking is used for all other panel configurations. The lack of smoothness in these plots is accounted for by the discrete member spectrum used for design.

3.4 STRUCTURAL BENT SYSTEM COST MODELS

Two cost models were examined for the structural bent system. The first of these is weight related and is based on the method developed by the Canadian Institute of Steel Construction (1), (24). The second model, denoted as the general cost model, reflects the manner in which a structure is costed by steel fabricators and erectors. Attention is focussed on labour as well as material costs.

3.4.1 Weight Related Cost Model

Following the procedure set out by CISC (1), the cost for the bent system may be written as:

$$\text{COST} = \text{COST INDEX} * \sum_{i=1}^{NM} \text{NET WEIGHT}_i * \text{CONNECTION FACTOR}_i * \text{COST FACTOR}_i \qquad (3.5)$$

where

NET WEIGHT = total weight of all members of type i, with the length of each member being equal to the center distance between joints.

CONNECTION FACTOR = factor to increase the net weight for the ith member type to make provision for the material required (e.g. bolts or welds) to connect truss members to supporting ones.

COST FACTOR = this factor accounts for the class and type of member, any change from CSA G40.21 type 44W Steel, and a charge for wide flange shapes.

COST INDEX = the current cost base of steel work in G40.21 type 44W Steel, which accounts for the type of construction, location, current market conditions, size of building etc. It includes all material and labour costs, shop and site overhead, profit, etc. The cost index is continuously updated by CISC based on data obtained from its members.

NM = number of different member types - e.g. WF, Tees, double angles, etc.

Table 3.2 contains value for connection factors and cost factors for various member types (1). Thus, the weight related cost model for the bent system, which includes both fabrication and erection, may be written as:

$$\begin{aligned} \text{COST OF BENT SYSTEM} &= \text{COST OF COLUMNS} + \text{COST OF TRUSSES} \\ &= (C_{CON}C_{COST}W_{COL} + WEB_{CON}WEB_{COST}W_{WEB} \\ &\quad + CHORD_{CON}CHORD_{COST}W_{CHORD})^{*}\ INDEX \end{aligned} \tag{3.6}$$

where

C_{CON} = connection factor for columns;

C_{COST} = cost factor for columns;

W_{COL} = total weight of columns (tons);

WEB_{CON} = connection factor for webs;

WEB_{COST} = cost factor for webs;

W_{WEB} = total weight of webs (tons);

$CHORD_{CON}$ = connection factor for chords;

$CHORD_{COST}$ = cost factor for chords;

W_{CHORD} = total weight of chords (tons); and

INDEX = CISCC cost index value.

3.4.2 General Cost Model

Before being able to set down a general expression for structural bent system cost, it is first necessary to describe the sequence of operations required for the fabrication and erection of the structure. This is then followed by the development of appropriate cost expressions.

3.4.2.1 Fabrication and Erection Operations for Structural Bent Systems

Figure 3.7 depicts in general terms the sequence of operations required for fabrication and erection of the structural bents. The elements of this figure are described briefly below.

Purchase of Material and Delivery to Yard

The unit price of structural steel members is a function of their shape, size, yieldpoint and quantity. In general, unit costs decrease with increased tonnage and increased member size. Canadian mills contacted were reluctant to disclose their pricing structure because of current discounting practices. Appendix II sets out the pricing structure of a major American supplier. A similar structure exists for Canadian mills. While the cost variations as a function of member type, size and quantity are small on a per pound basis, on an overall structure basis they can be significant. The pricing structure adopted by mills can provide the basis for tradeoffs in the design process. For example, it is cheaper materialwise to use heavier members. However, in the fabrication phase, it is cheaper to use lighter members because they can be handled by hand without the assistance of an overhead crane. Similarly, based on extras charged for small quantities, some benefits could be derived by grouping members, thus minimizing the extras associated with the purchase of small quantities of one member size.

Drawing Office

Drawing office costs are mainly a function of number of members and joint complexity. These factors are in turn a function of the decision variables, number of panels, depth to span ratio and truss spacing. For the type of structure considered herein, figures quoted by fabricators ranged from 30 to 35 hours for shop drawing preparation. This estimate is relatively insensitive to changes in design configuration.

Fabrication

The sequence of steps required for fabrication of the structural bents is depicted in Figure 3.8. The relationship between these steps and independent and dependent variables is shown in Figure 3.9.

In general, the time required to execute an operation is dependent on the number of pieces and their size. For example, light members require less time because they can be manhandled, whereas heavy pieces require the use of cranes. Welding time is a function of the number of welds, their length and thickness. Heavy welds require several passes and require considerably more time than light welds. Thus welding time per truss joint for large bent spacings is considerably higher than for small bent spacing.

In order to assess the time required for the sequence of steps depicted in Figure 3.8 (exclusive of cleaning and painting), as a function of the key decision variables, nine designs (AppendixIII) were prepared and given to a large fabricator for costing. A building having dimensions of 150' - 0" x 900' - 0" by 15' - 0" clear height provided the basis for these designs. Because of the varying nature of labour and overhead costs with time, the fabricator was requested to provide the costing in terms of manhours, and to provide a breakdown of these manhours in terms of the operations performed.

An excellent response was received from this fabricator and the results are summarized in Table 3.3. Manhours shown in this table reflect manhours per bent. Efforts are currently being made to increase this data base by having another series of designs costed by a different fabricator. These results will be reported at a later date.

An attempt was made to develop general expressions for manhours as a function of the key decision variables or functions of them. The time required for column preparation and bent cleaning and painting was separated out from the time required for other fabrication operations because of their invariant nature. As shown in Table 3.3, the time required for column preparation is 3.5 manhours/column, and is independent of column size and weight. Cleaning and painting time was set at 16 manhours/bent. Because the number of chord splices per truss did not vary, an expression for chord splice manhours was developed independently of an expression for other fabrication operations. Manhour estimating relationships were then developed using the SPSS statistical package (23). Regressions were performed for manhours exclusive of splice time (column 21, Table 3.3) against various functions of the independent variables. The following expression for individual truss fabrication manhours was found to give the best fit to the data.

Manhours per truss exclusive of chord splice =

$$MHT = 64.17 + 2.35*NPANL + 0.0189*TRWT^3 \tag{3.7}$$

where

NPANL = number of panels (Column 2, Table 3.3)
TRWT = truss weight in tons (Column 9, Table 3.3)

The expression for chord splice time per truss is:

$$MHS = NSP*(2.20 + 0.0341*CHORDWT^2) \tag{3.8}$$

where

MHS = manhours per splice
NSP = number of chord splices/truss (column 6, Table 3.3)
CHORDWT = total chord weight (tons) (column 10, Table 3.3)

SPSS summary tables for the above regressions are given in Table 3.4. Predicted values fo MHT and MHS based on equations 3.7 and 3.8 are presented in columns 21 and 22 of Table 3.3 respectively.

Using the foregoing relationships and the time estimates for column preparation and bent cleaning and painting, the following expression may be written for the total manhours (TMHR) required in the fabrication phase:

$$\begin{aligned} \text{TMHR} &= \text{NUMBER OF BENTS*}(\text{TRUSS FABRICATION} \\ &\quad + \text{TRUSS CHORD SPLICES} + \text{COLUMN} \\ &\quad \text{PREPARATION} + \text{BENT CLEANING AND} \\ &\quad \text{PAINTING}) \\ &= (\text{NBAY}+1)*(87.17 + 2.35*\text{NPANL} + 0.0189*\text{TRWT}^3 \\ &\quad + \text{NSP}*(2.20 + 0.0341*\text{CHORDWT}^2)) \end{aligned} \tag{3.9}$$

With respect to estimating the quantity of paint required, information provided by a fabricator indicated that a gallon of primer covers approximately 400 square feet of surface area, or, as a rule of thumb, 1.2 gallons per ton. Hourly production by a painter using a spray gun is estimated at 1.5 tons of steel.

Transportation to the Site

The cost of transportation of the bent system to the site is a function of distance to be travelled and the variables of shape, size, weight and number of pieces which describe the structural system. Trusses of large span and depth to span ratio can result in very costly transportation charges because of the need for special escorts for oversized members. By using field splices, and possibly bolted connections the sizes of structural elements can be reduced, thus reducing transportation charges. A tradeoff exists between these charges and splice costs (both field and shop). This trade-off problem is not considered herein. Transportation costs were taken at $15/ton for this study, and represent current rates for normal size components shipped to a destination within a 10 mile radius of the fabrication shop.

Field Erection

The sequence of operations required for the erection of the structural bent system is illustrated in Figure 3.10. Normally, two crews and one foreman would be assigned for the field erection of the type of structure considered herein. Each crew consists of one pusher, one welder and three steel erectors. Based on discussions with an erector, for this same structure type, a satisfactory equipment spread would consist of 1 - 50 ton 80 foot boom crane and 1 - 30 ton 100 foot boom crane. The hourly rate per crane includes the wages of the operator and an oiler.

The erection of a column, including unloading, shimming, plumbing and bolting takes one crew one hour to complete and requires the use of one crane for this hour. The erection of the truss, including unloading and assembly (3 hours) lifting (1 hour) and bolting (1 hour) takes one crew five hours to complete and requires the use of two cranes for two and a half hours each. Thus, the erection of one bent requires a total of 35 manhours and 7 crane hours and total erection time is linearly related to the number of bents. This time estimate does not include an allowance for bracing which will be considered in a later study.

3.4.2.2 Form of the General Cost Model

Based on the discussion in subsection 3.4.2.1, the cost of the structural bent system may be written as:

COST OF STRUCTURAL BENT SYSTEM = COST OF MATERIAL + COST OF DRAWING OFFICE + COST OF FABRICATION + COST OF TRANSPORTATION + COST OF ERECTION (3.10)

Material cost may be expressed as:

COST OF MATERIAL = COST OF COLUMN MATERIAL + COST OF TRUSS MATERIAL + COST OF MATERIAL FOR CONNECTIONS + COST OF PAINT (3.11)

where

COST OF COLUMN MATERIAL = UNIT COST OF COLUMN MATERIAL*TOTAL WEIGHT OF COLUMN MATERIAL (3.12)

COST OF TRUSS MATERIAL = $\sum_{i=1}^{n}$ (UNIT COST OF TRUSS MATERIAL OF ith SIZE * WEIGHT OF ith SIZE) (3.13)

where

n = number of different sizes used for truss members

COST OF MATERIAL FOR CONNECTIONS = UNIT COST OF MATERIAL FOR CONNECTIONS * WEIGHT OF MATERIAL FOR CONNECTIONS. (3.14)

UNIT COST OF ANY SHAPE AND/OR SIZE = (BASE PRICE + EXTRA PRICE)* (UNIT WEIGHT OF RESPECTIVE SHAPE AND/OR SIZE) (3.15)

Weight of connection material is estimated as 5.85% of total truss weight. The overhead factor O_M covers the cost of handling materials from the yard to the shop and is estimated on the basis of forecasted tonnage to be handled for the year. O_M was assumed to be the same as the field overhead factor for this study.

The cost of the drawing office is computed as:

COST OF DRAWING OFFICE = TIME REQUIRED FOR THE DRAWING*UNIT COST OF DRAWING OFFICE (3.16)

The cost of fabrication is computed as:

$$\text{COST OF FABRICATION} = (1 + M)(1+O_S)\text{*TOTAL MANHOURS*COST PER MANHOUR} \quad (3.17)$$

where TOTAL MANHOURS is computed using equation 3.9.

The transportation cost is written as:

COST OF TRANSPORTATION = UNIT COST OF TRANSPORATION*TOTAL WEIGHT TO BE TRANSPORTED*(1 + M) (3.18)

The erection cost is written:

$$\text{COST OF ERECTION} = (1 + M)(1 + O_F)[\text{LABOUR COST} + \text{EQUIPMENT COST}] \quad (3.19)$$

where

LABOUR COST = (NBAY + 1)[MANHOURS PER BENT][COST PER MANHOUR) (3.20)

EQUIPMENT COST = (NBAY + 1) [CRANE SPREAD HOURS PER BENT][COST PER HOUR FOR CRANE SPREAD] (3.21)

3.5 COST MODEL RESULTS

Based on the example building previously described, results were generated for a lattice of the three independent configuration variables considered. Results are summarized in Figures 3.11 through 3.15 for system weight, system cost based on the weight related cost model and system cost based on the general cost model. Figure 3.16 depicts a breakdown of bent costs versus truss spacing for the general cost model. The data used for these plots are presented in Appendix V.

The following observations may be noted based on an examination of these figures:

1. The minimum cost configuration for each cost model is identical (i.e. DSR = 0.12, NPANL = 8 and TSP = 52 feet).
2. Both cost models yield comparable absolute costs for high bent-spacings (32.5 feet and above) but markedly different results for small truss spacings. This discrepancy is accounted for by the fact that the general cost model considers both handling costs as well as material related costs, and the former are maximized for low truss spacings. As seen from Figure 3.16, there is a significant variation of both fabrication and erection labour and equipment cost with bent spacing and only minor variation of material cost with bent spacing. Thus, results based on the general cost model reflect much greater sensitivity to the variable truss spacing than those derived from the weight related cost model.
3. For both cost models, greater sensitivity in the results was exhibited for changes in depth to span ratio as opposed to number of panels.

4. For the configuration of TSP = 52, NPANL = 8 and DSR = 0.06, the largest tee section available is required for the bottom chord. When NPANL is increased to 10, the secondary moments in the chord are increased resulting in increased flexural stresses. The increased allowable compressive stress due to the smaller l/r ratio for the 10 panel versus the 8 panel case is not sufficient to offset these increased bending stresses, and thus no tee section is available for this design. Hence, no design point is shown for the 10 panel configuration in Figure 3.12.
5. Although the weight per bent goes up for the 52 foot bent spacing versus the 47.27 foot spacing, because the number of bents is decreased by one, total bent weight is decreased. For example, for the NPANL equal to 8 and DSR equal to 0.06 and 0.12, individual bent weight increased by 6.13 percent and 0.51 percent, respectively, while total bent weight decreased by 2.72 percent and 7.87 percent respectively.

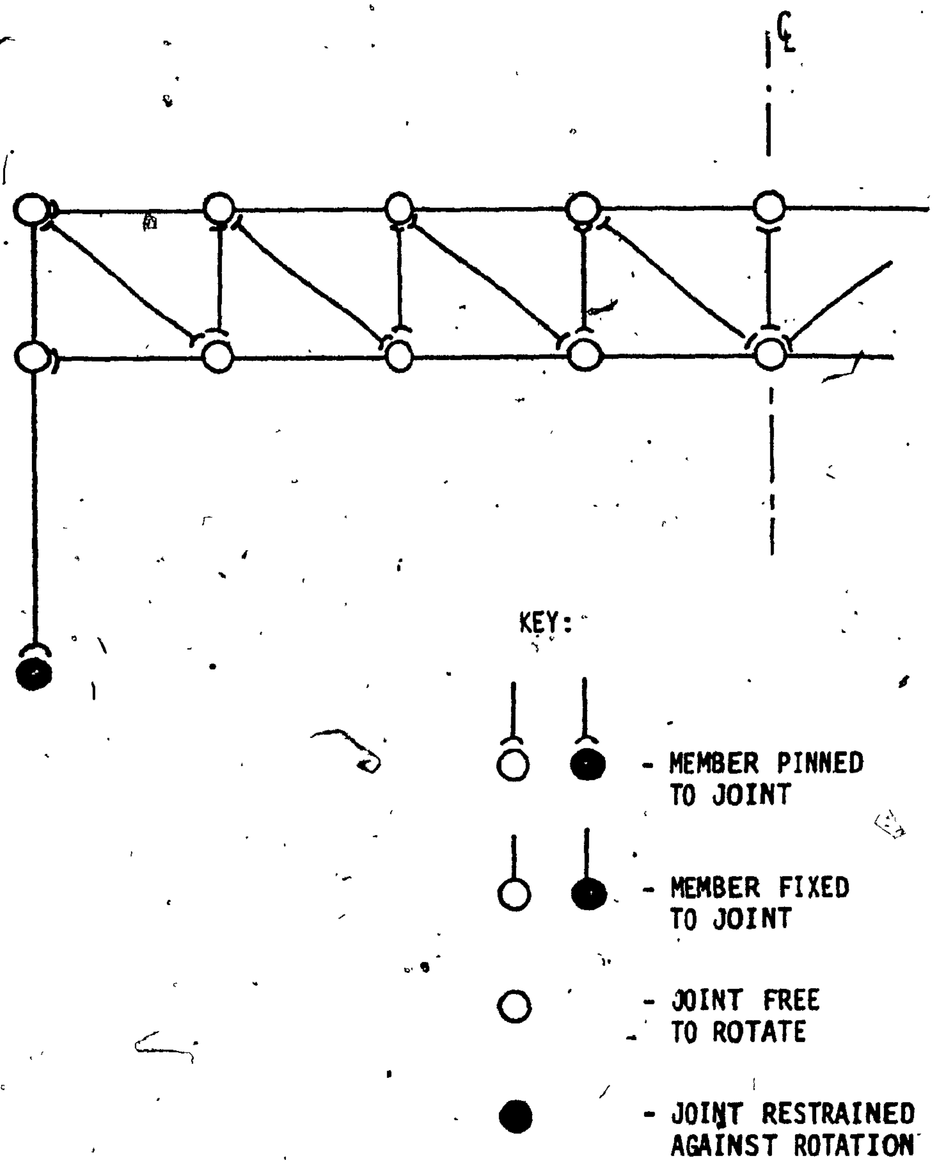
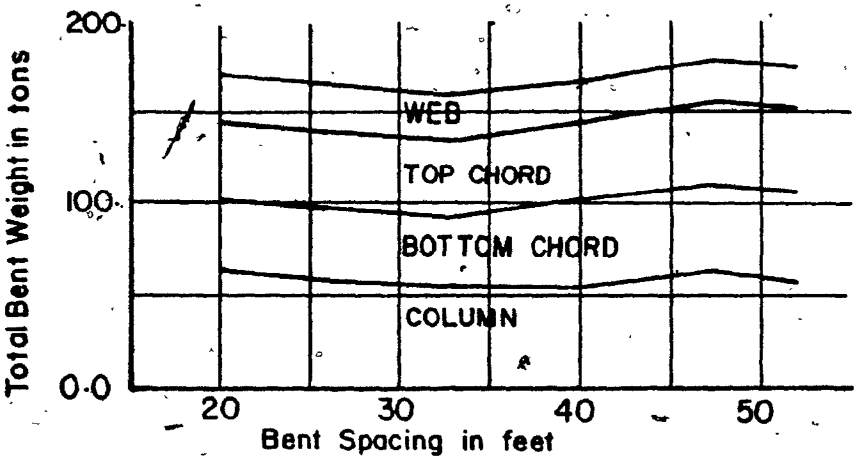
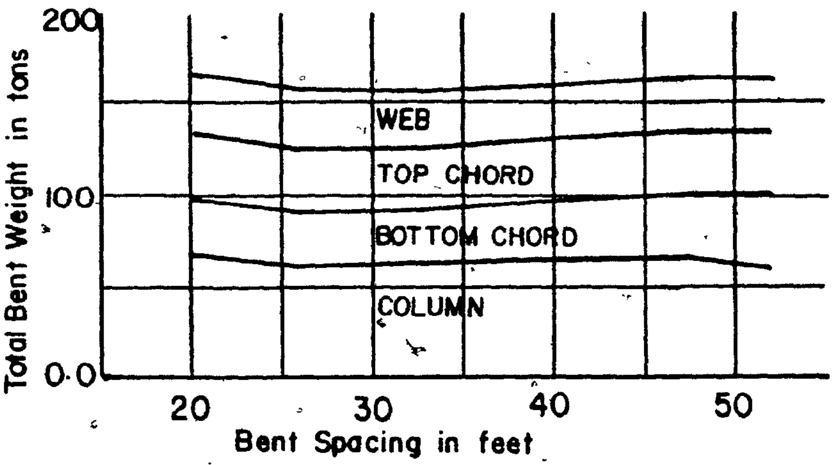


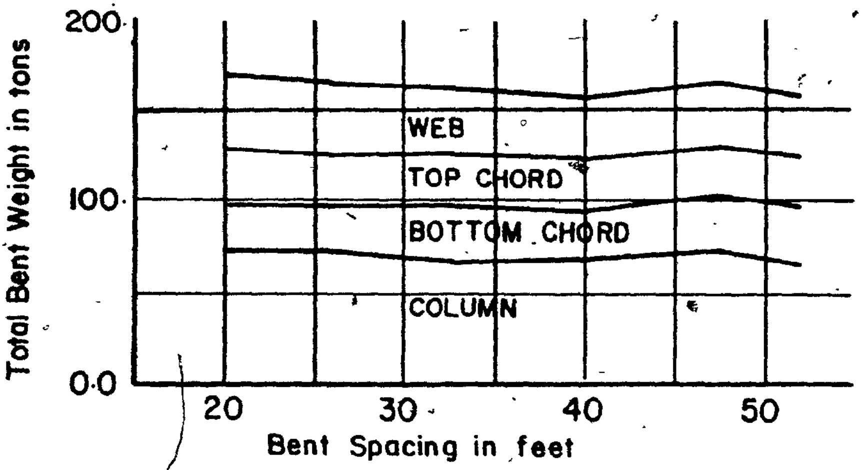
FIGURE 3.1: MODELING OF MEMBER JOINT CONNECTIVITY FOR ANALYSIS



(a) D/S RATIO 0.08



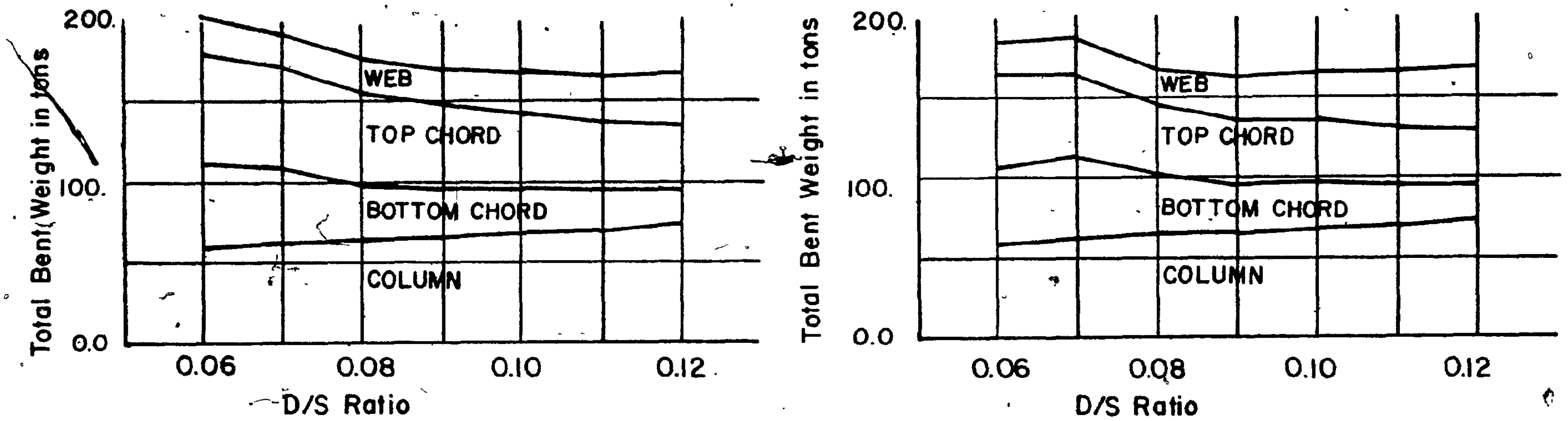
(b) D/S RATIO 0.10



(c) D/S RATIO 0.12

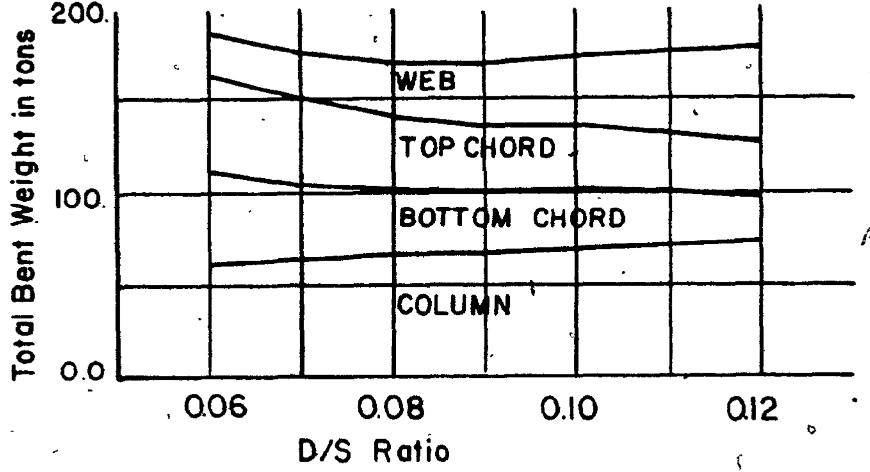
(number of truss panel = 12)

Fig.3.2 - VARIATION OF STRUCTURAL BENT SYSTEM WEIGHT



(a) NUMBER OF TRUSS PANEL 8

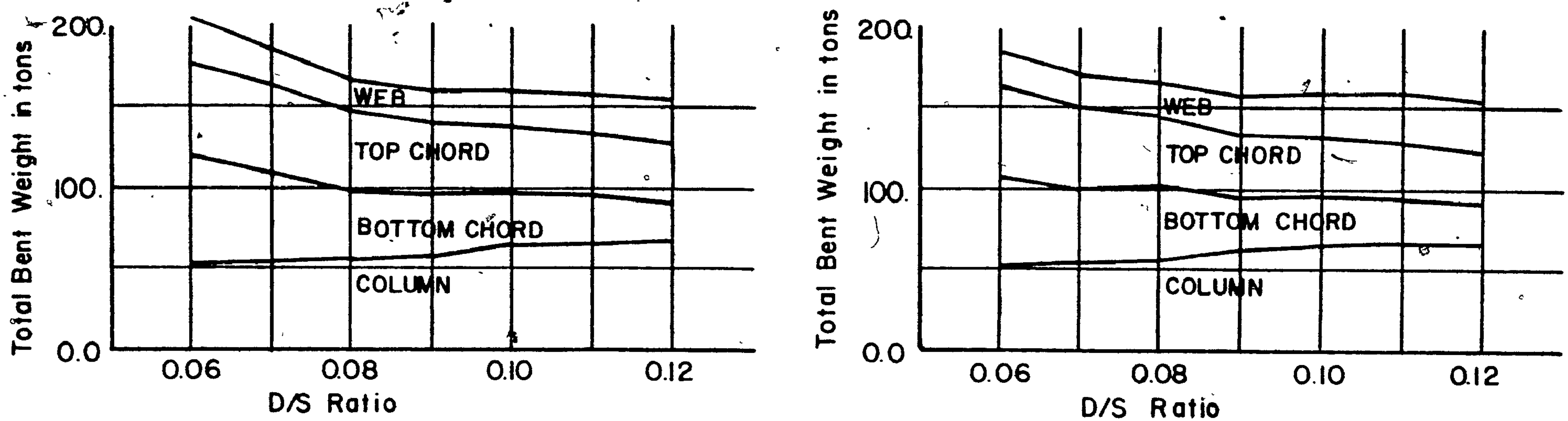
(b) NUMBER OF TRUSS PANEL 12



(c) NUMBER OF TRUSS PANEL 16

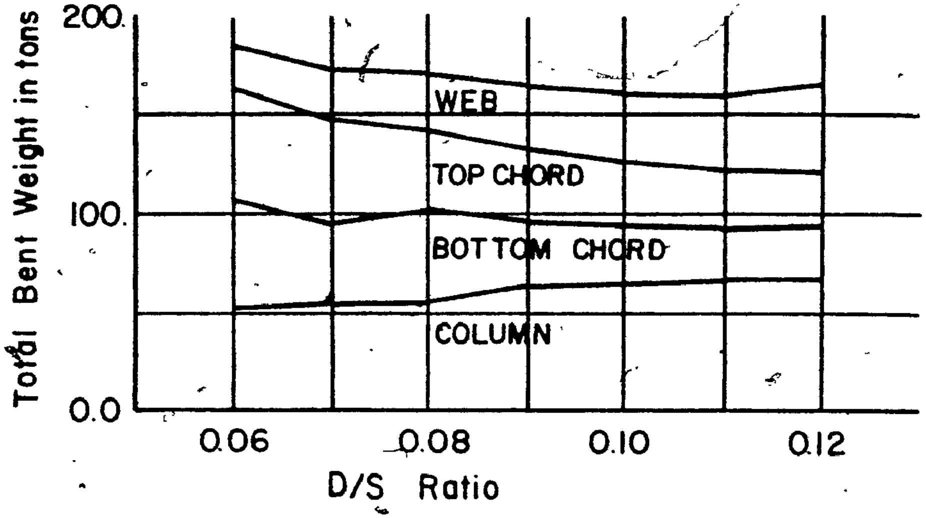
(bent spacing 20.00 feet)

Fig. 3.3 - VARIATION OF STRUCTURAL BENT SYSTEM WEIGHT



(a) NUMBER OF TRUSS PANEL 8

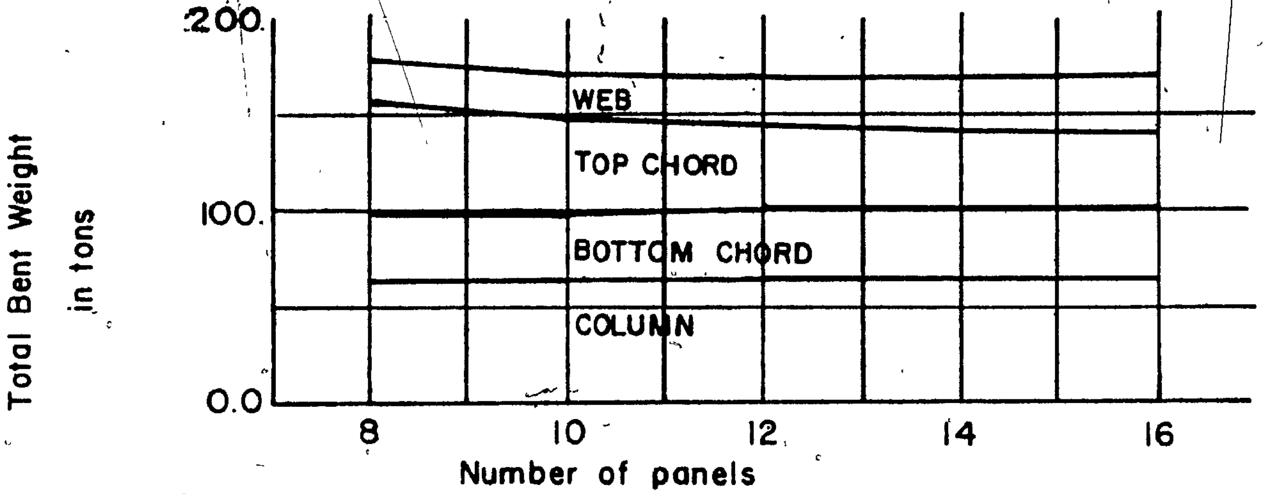
(b) NUMBER OF TRUSS PANEL 12



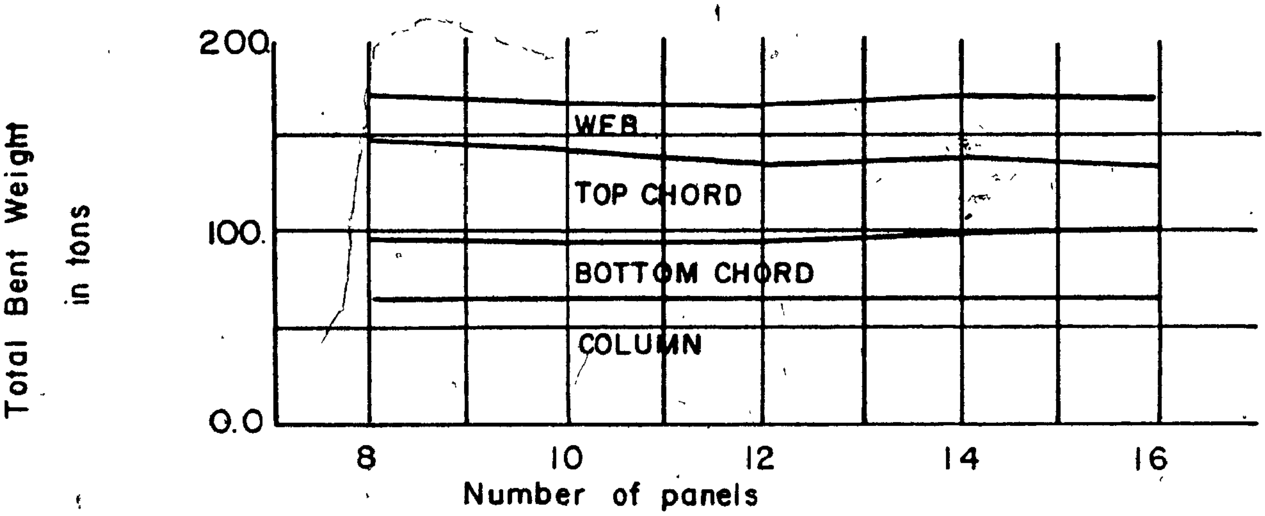
(c) NUMBER OF TRUSS PANEL 16

(bent spacing 40.00 feet)

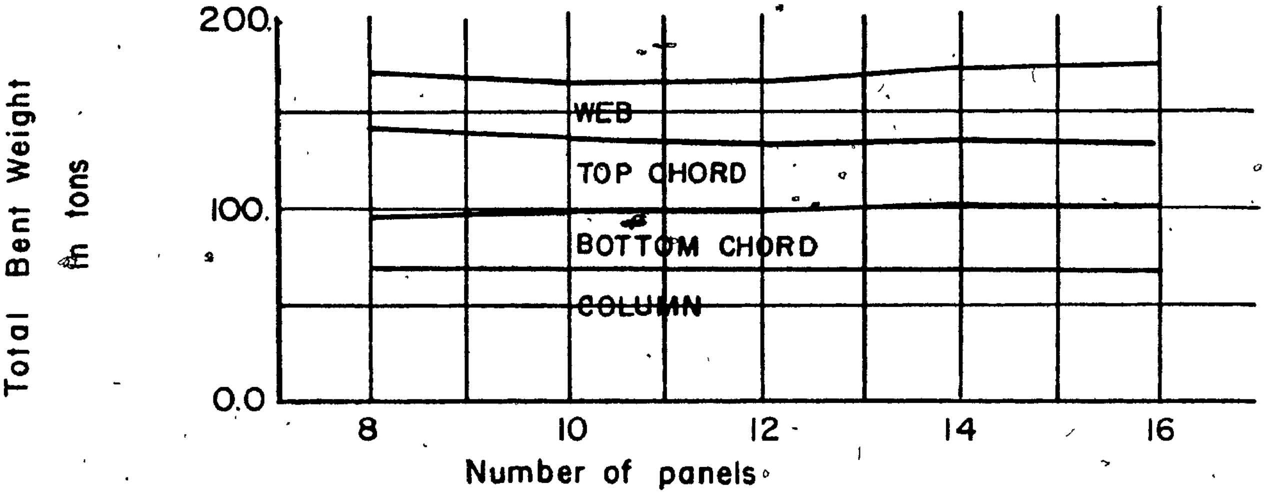
Fig. 3.4 - VARIATION OF STRUCTURAL BENT SYSTEM WEIGHT



(a) D/S RATIO 0.08



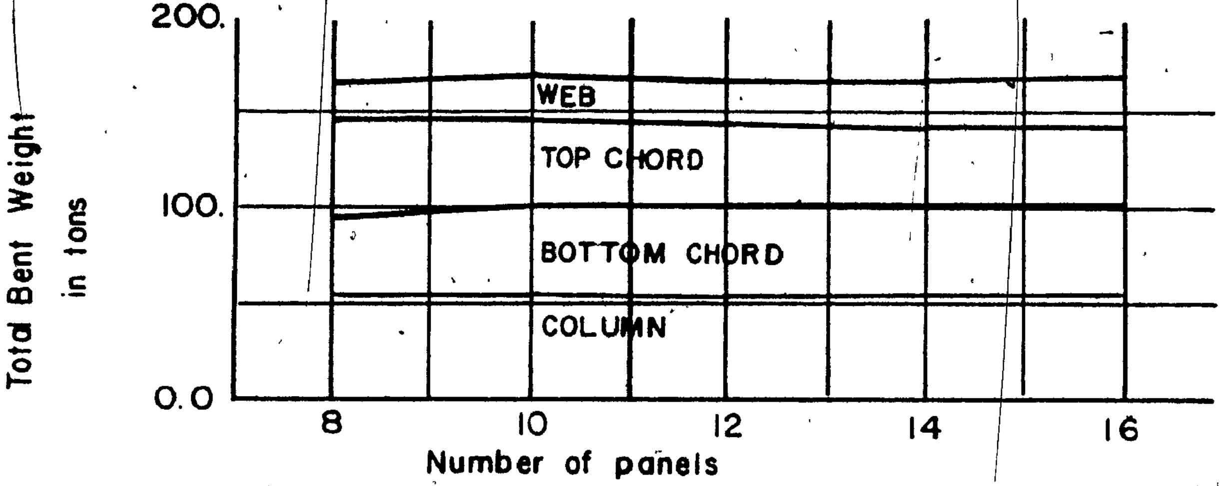
(b) D/S RATIO 0.09



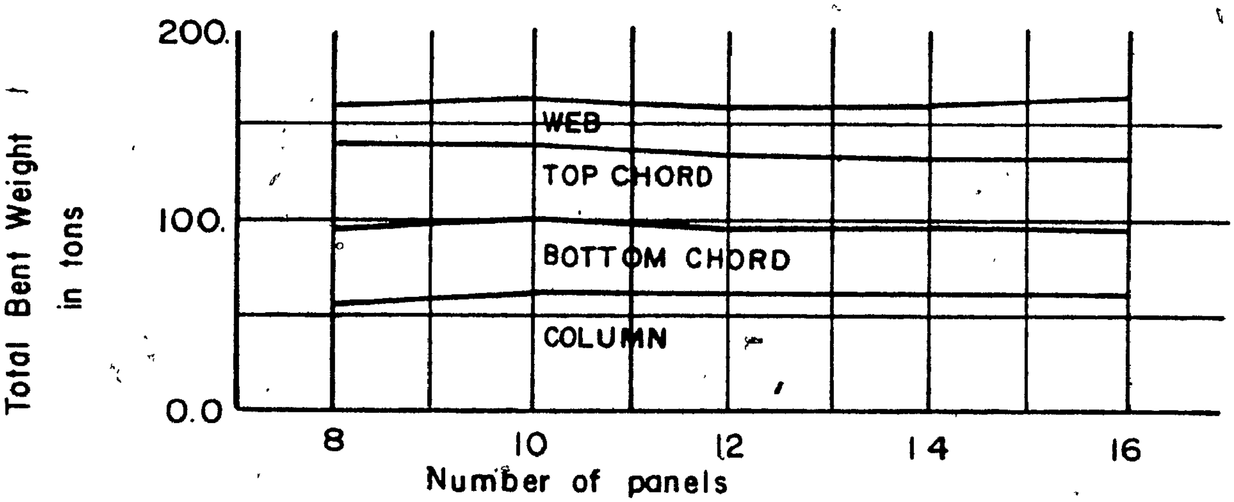
(c) D/S RATIO 0.10

(bent spacing 20.00 feet)

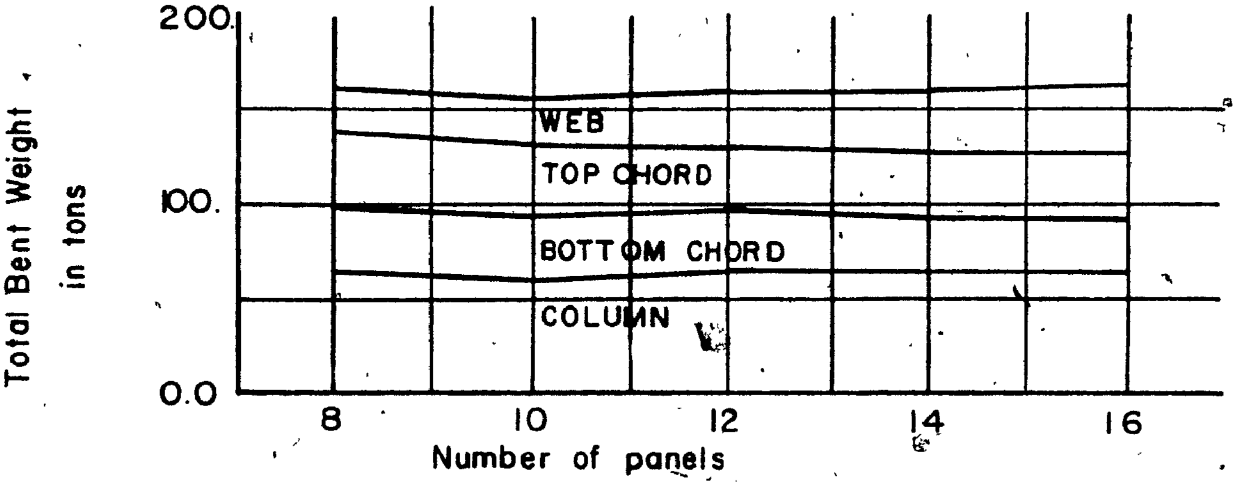
Fig. 3.5 - BREAKDOWN OF STRUCTURAL BENT WEIGHT



(a) D/S RATIO 0.08



(b) D/S RATIO 0.09



(c) D/S RATIO 0.10

(bent spacing 40.00 feet)

Fig. 3.6- BREAKDOWN OF STRUCTURAL BENT SYSTEM

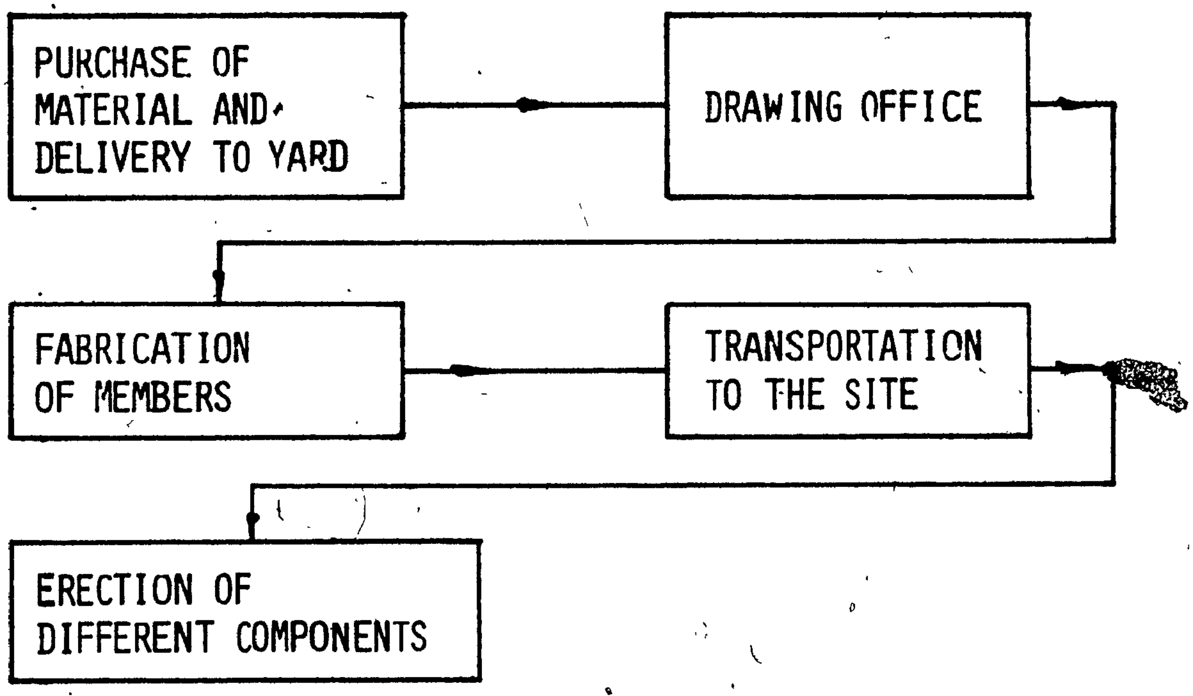


FIGURE 3.7: SEQUENCE OF OPERATIONS FOR STRUCTURAL BENT SYSTEM

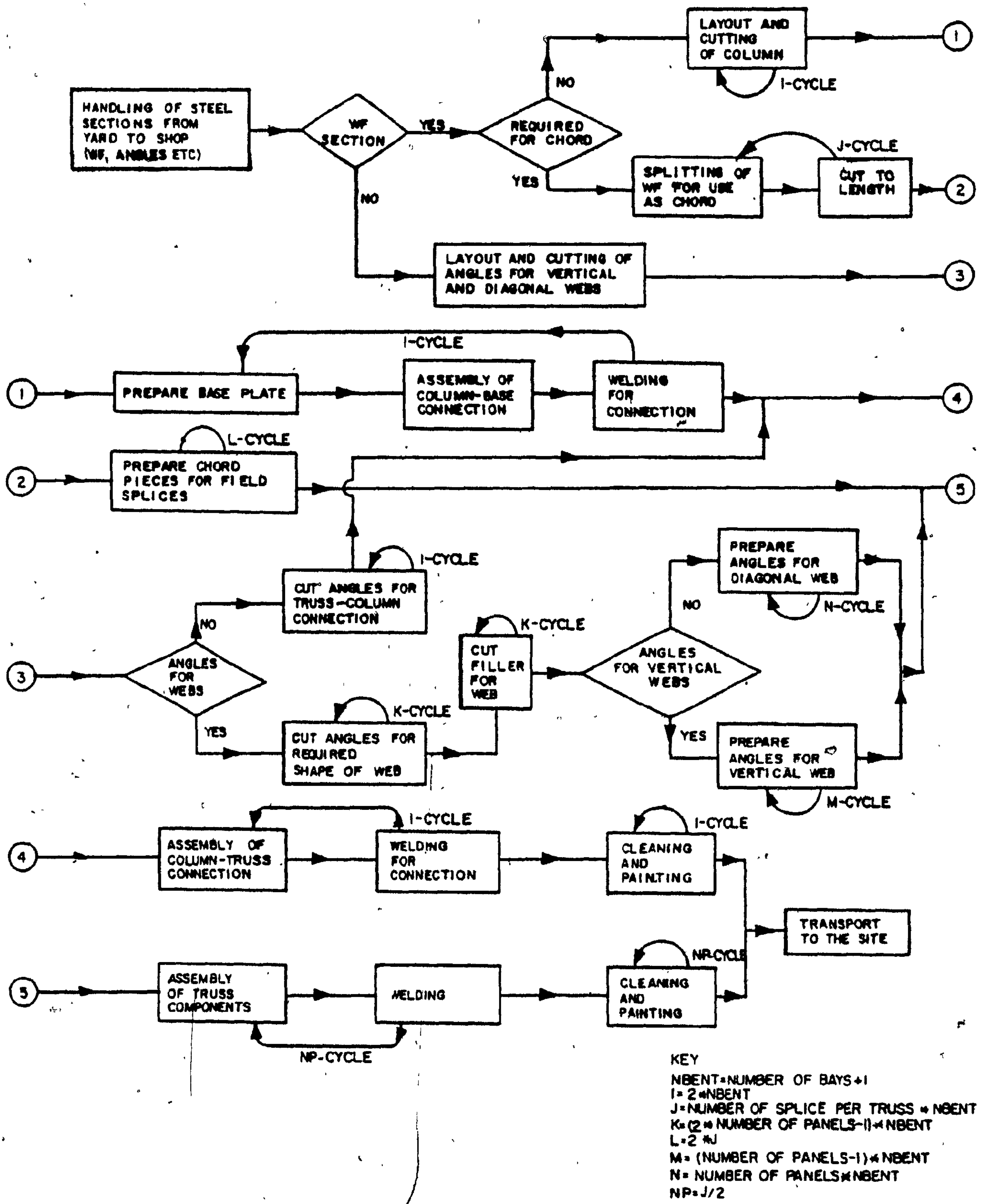


FIGURE 3·8 SEQUENCE OF OPERATIONS IN FABRICATION SHOP FOR STRUCTURAL BENTS

No.	Variables → ↓ Operations	Bent Spacing	Number of Panels	Depth to Span Ratio	Chord Weight	Total Weight	Number of Truss Splices
1	Handling from yard to shop	X				X	
2	Layout and cutting column	X		X			
3	Splitting of WF for use as chord and cut to length	X			X		X
4	Layout and cutting of angles	X	X	X			
5	Prepare base plate, assemble and weld to column	X					
6	Prepare and weld chord pieces for splices	X			X		X
7	Cut angles for column-truss connection	X				X	
8	Cut filler for webs	X	X	X			
9	Prepare angles for webs	X	X	X			
10	Assemble and weld truss column connection	X				X	
11	Assemble and weld truss components	X	X			X	X
12	Cleaning and painting column	X				X	
13	Cleaning and painting truss	X				X	
14	Transportation to site	X				X	X

FIGURE 3.9: INTERACTIONS BETWEEN OPERATIONS AND VARIABLES (INDEPENDENT AND DEPENDENT)

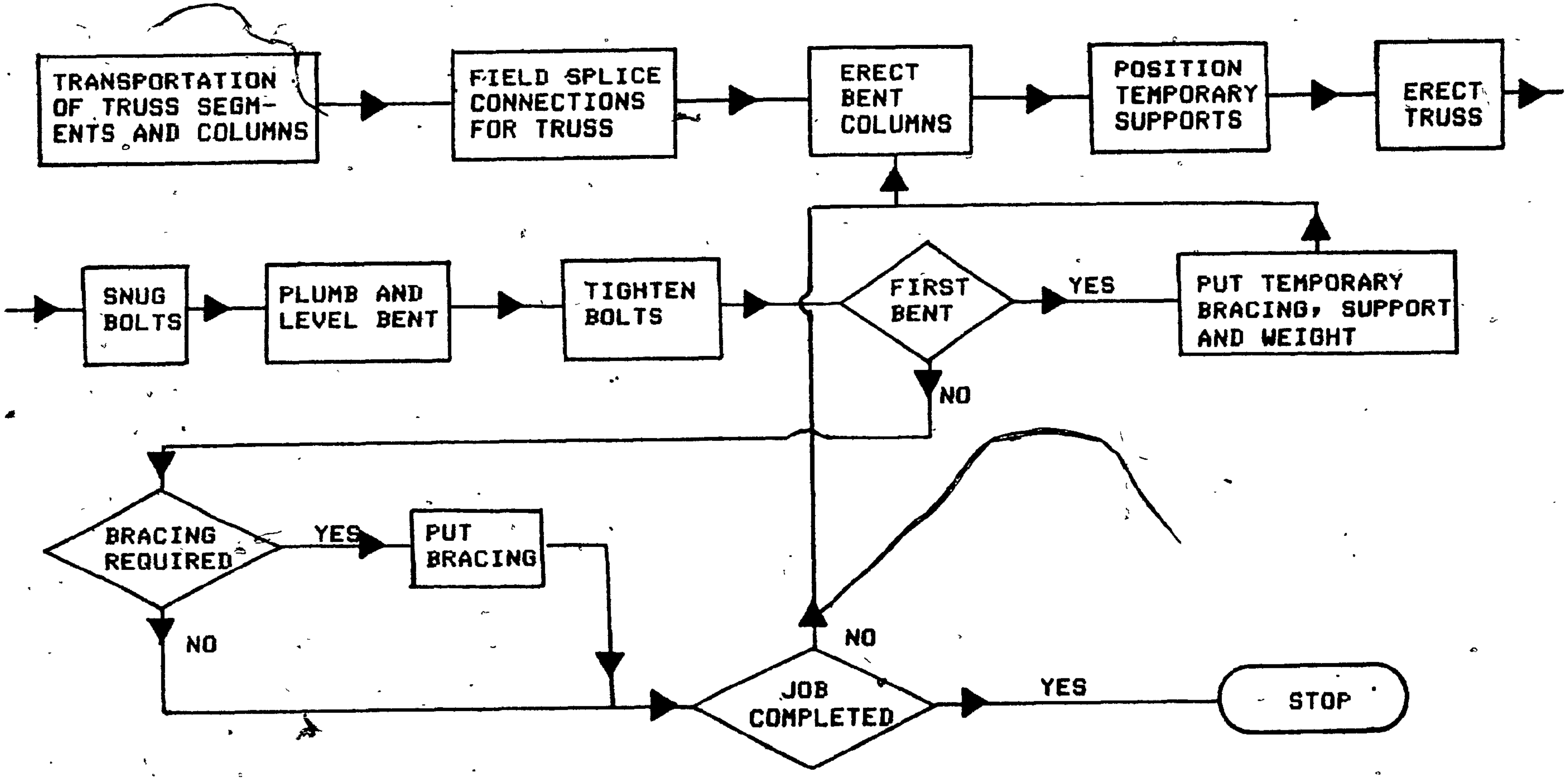
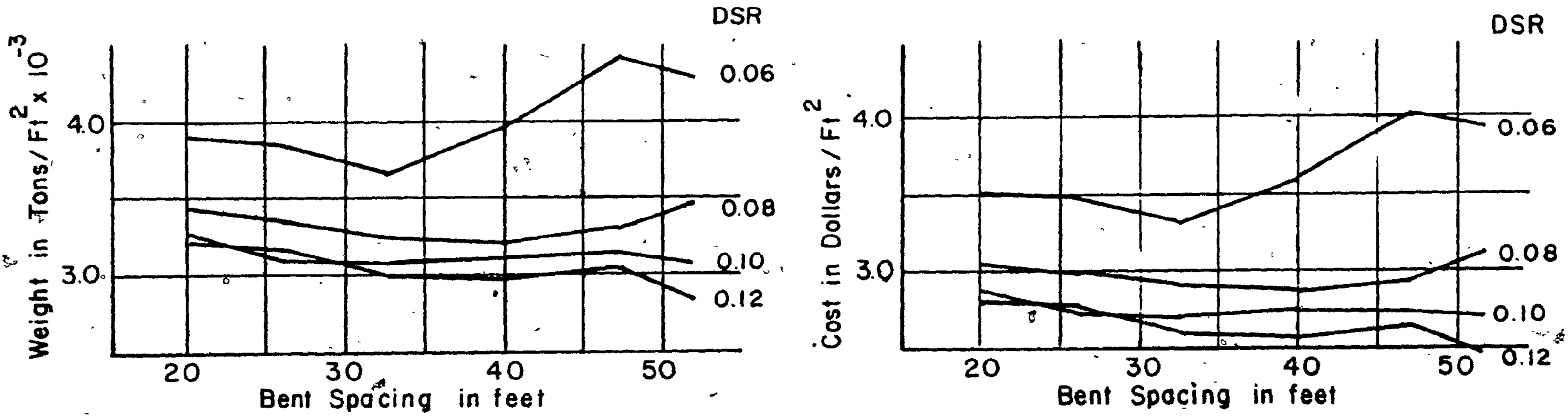
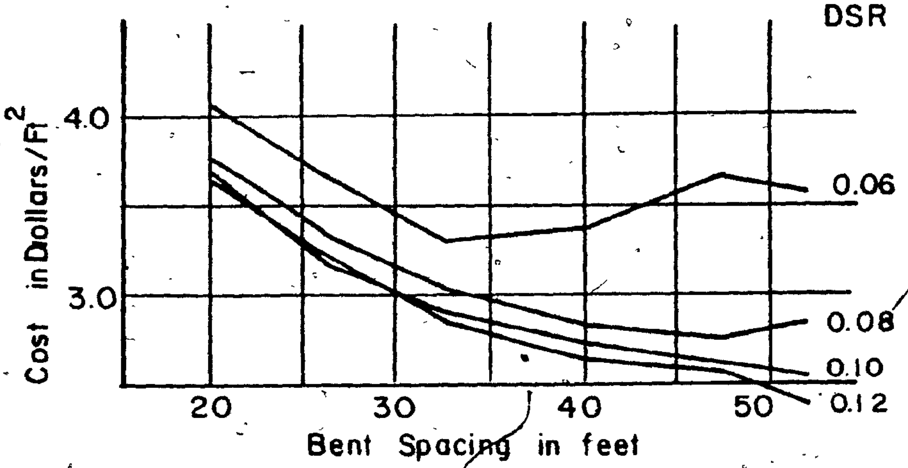


FIGURE 3.10 SEQUENCE OF OPERATIONS FOR THE ERECTION OF STRUCTURAL BENT SYSTEM



(a) BENT WEIGHT

(b) WEIGHT RELATED COST

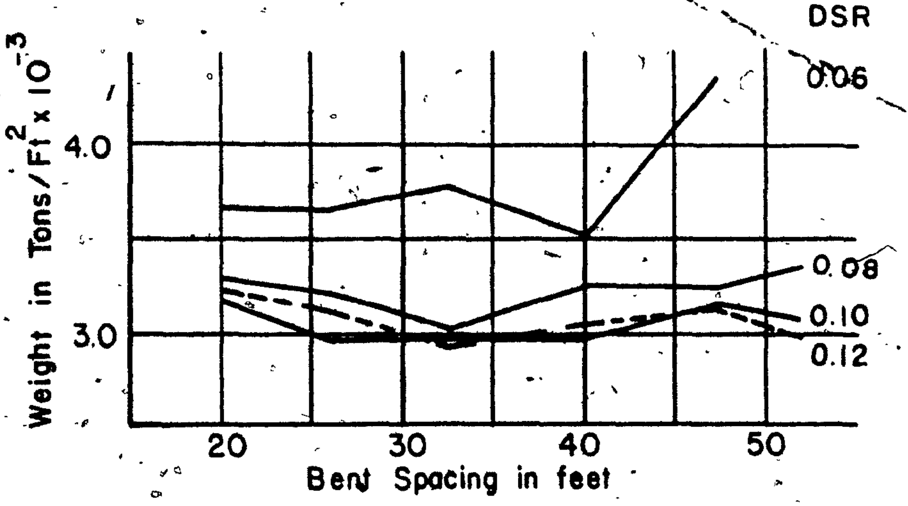


(c) GENERAL COST

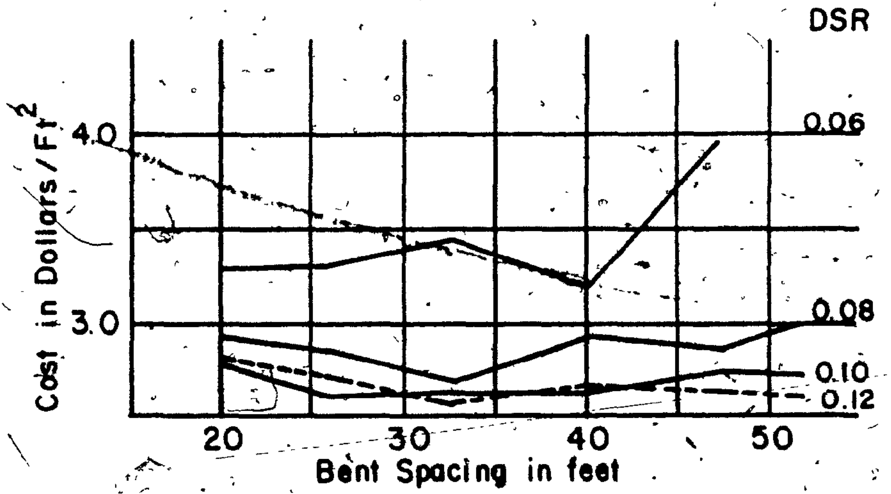
NB: DSR = DEPTH TO SPAN RATIO

(number of truss panel = 8)

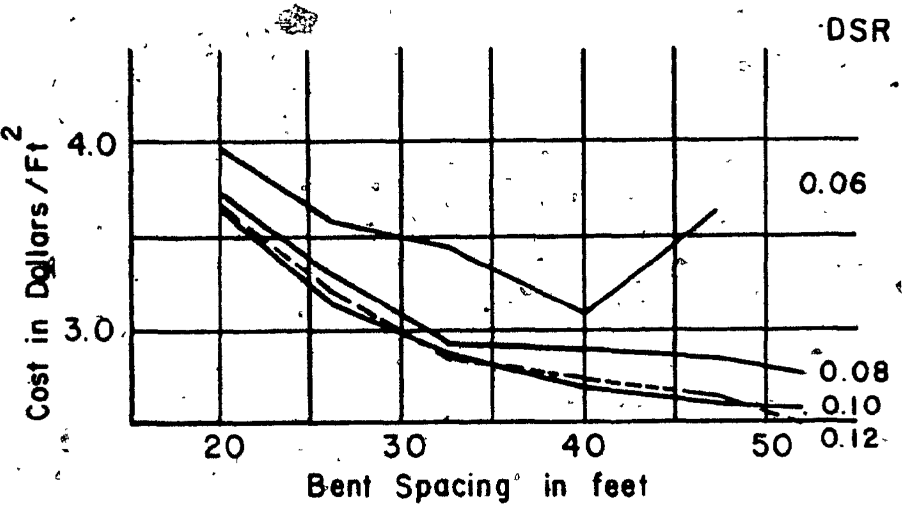
Fig.3.11- VARIATION OF STRUCTURAL BENT SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) BENT WEIGHT



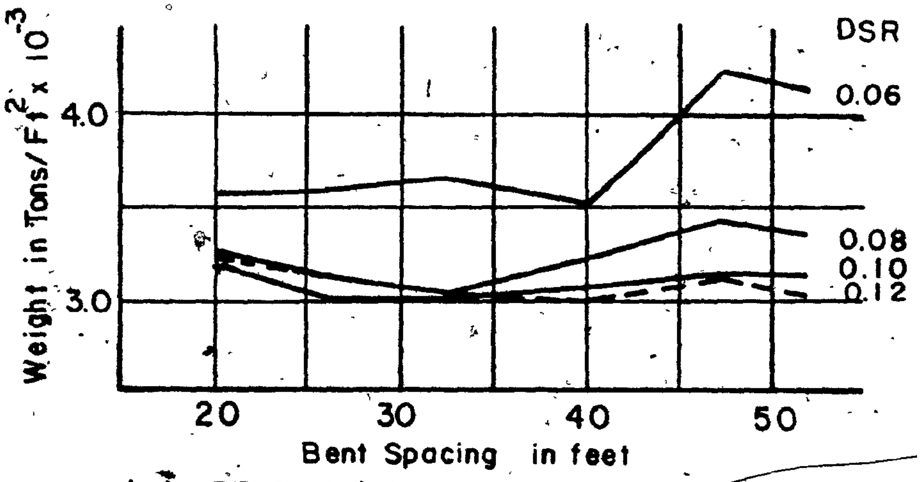
(b) WEIGHT RELATED COST



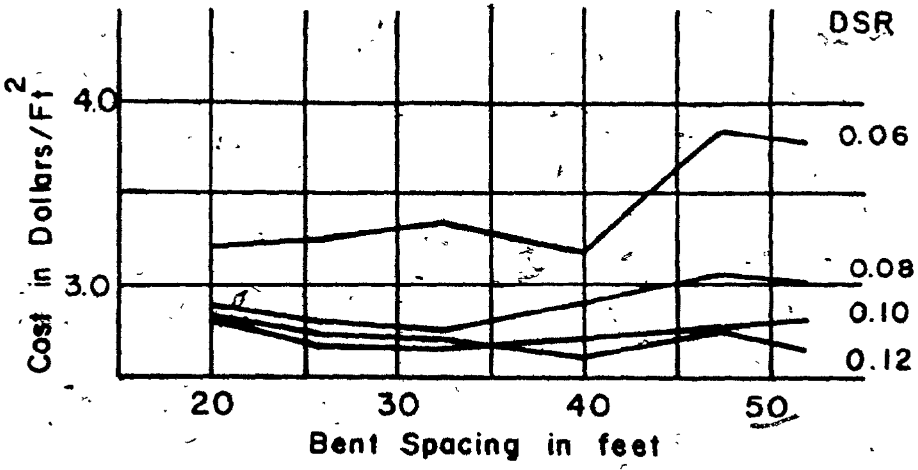
(c) GENERAL COST

(number of truss panels = 10)

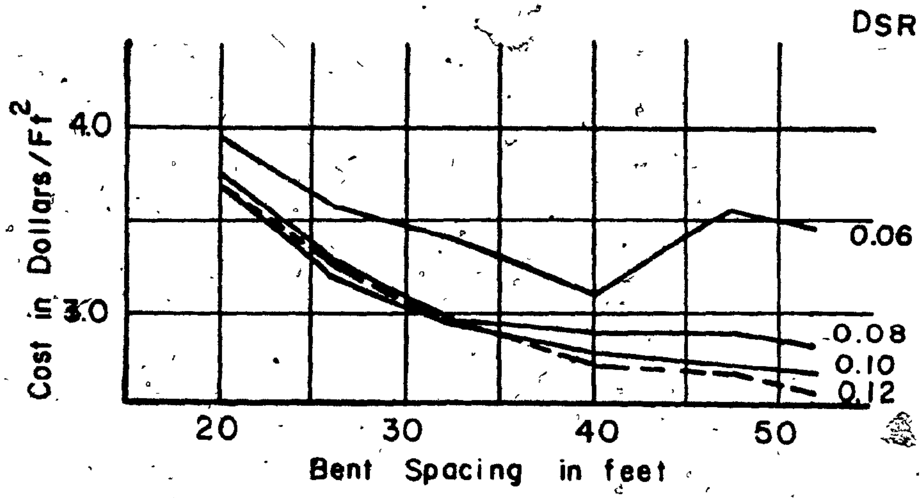
Fig. 3.12 - VARIATION OF STRUCTURAL BENT SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) BENT WEIGHT



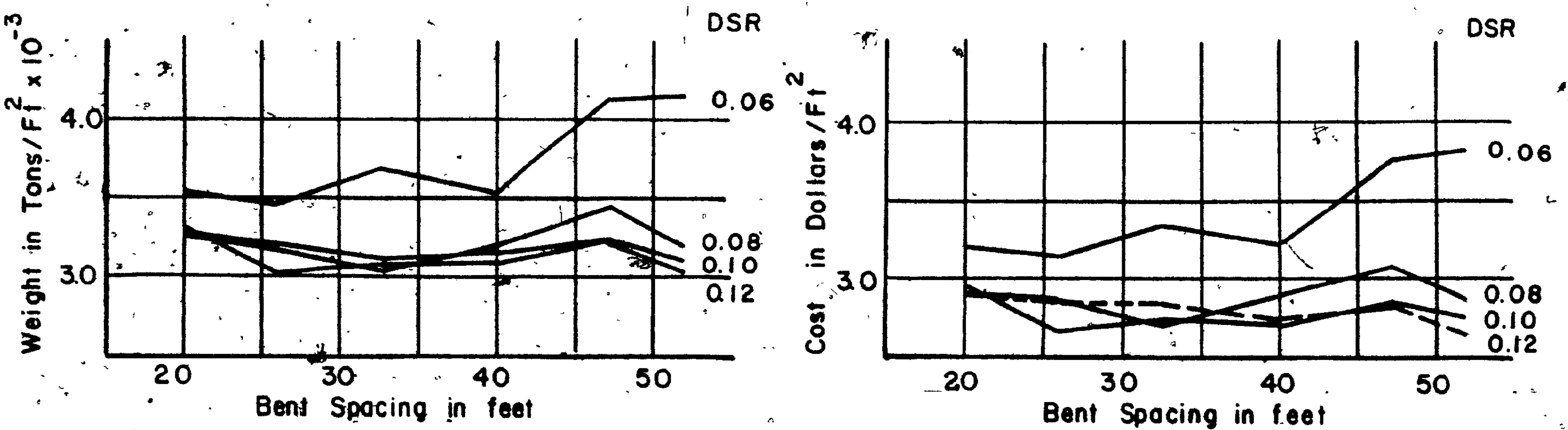
(b) WEIGHT RELATED COST



(c) GENERAL COST

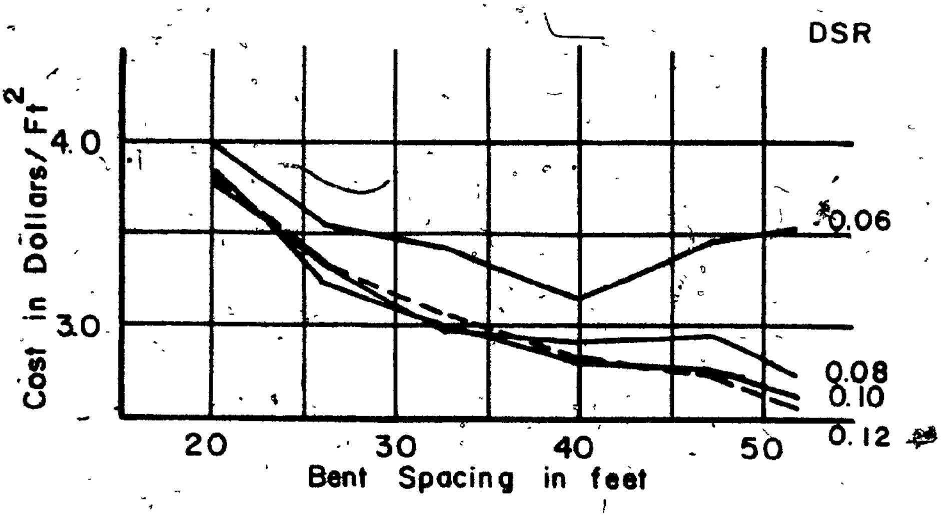
(number of truss panel = 12)

Fig. 3.13 - VARIATION OF STRUCTURAL BENT SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) BENT WEIGHT

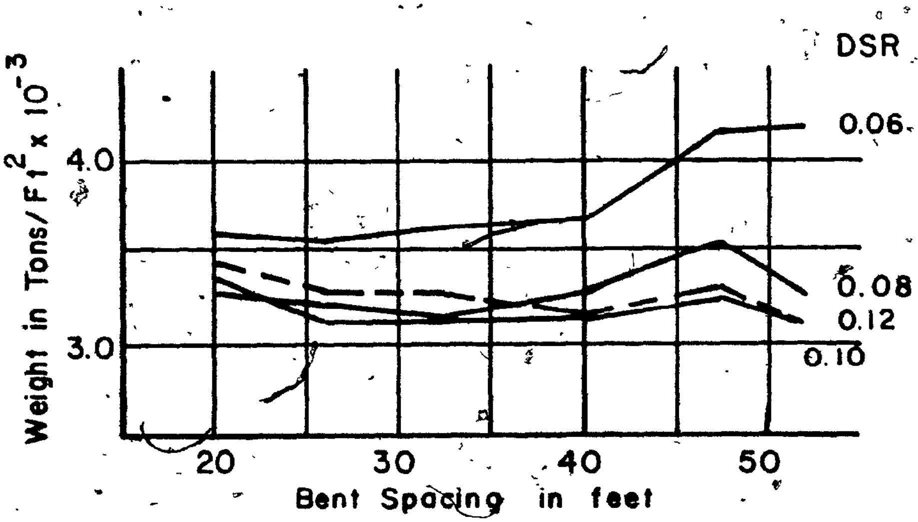
(b) WEIGHT RELATED COST



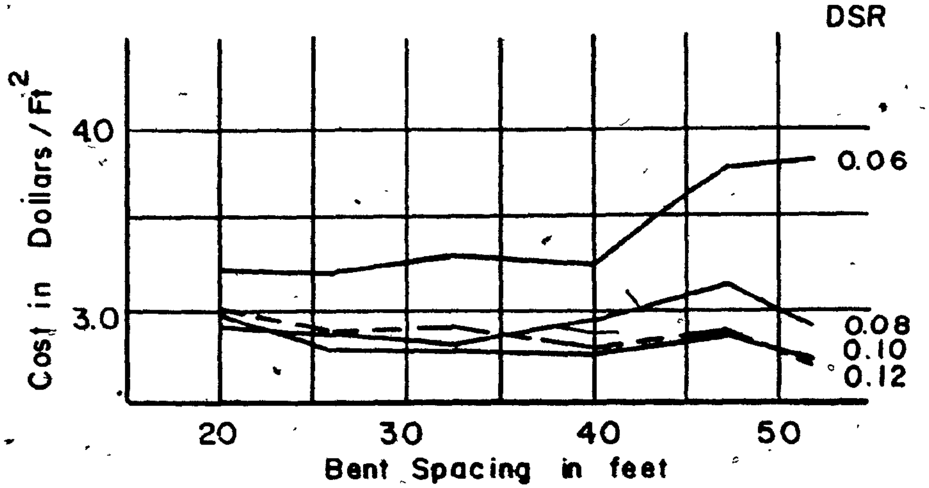
(c) GENERAL COST

(number of truss panel = 14)

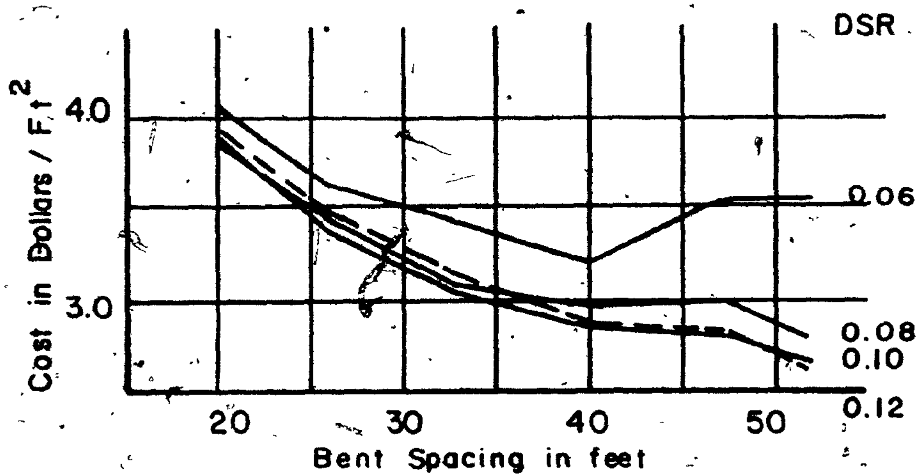
Fig. 3.14 - VARIATION OF STRUCTURAL BENT SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) BENT WEIGHT



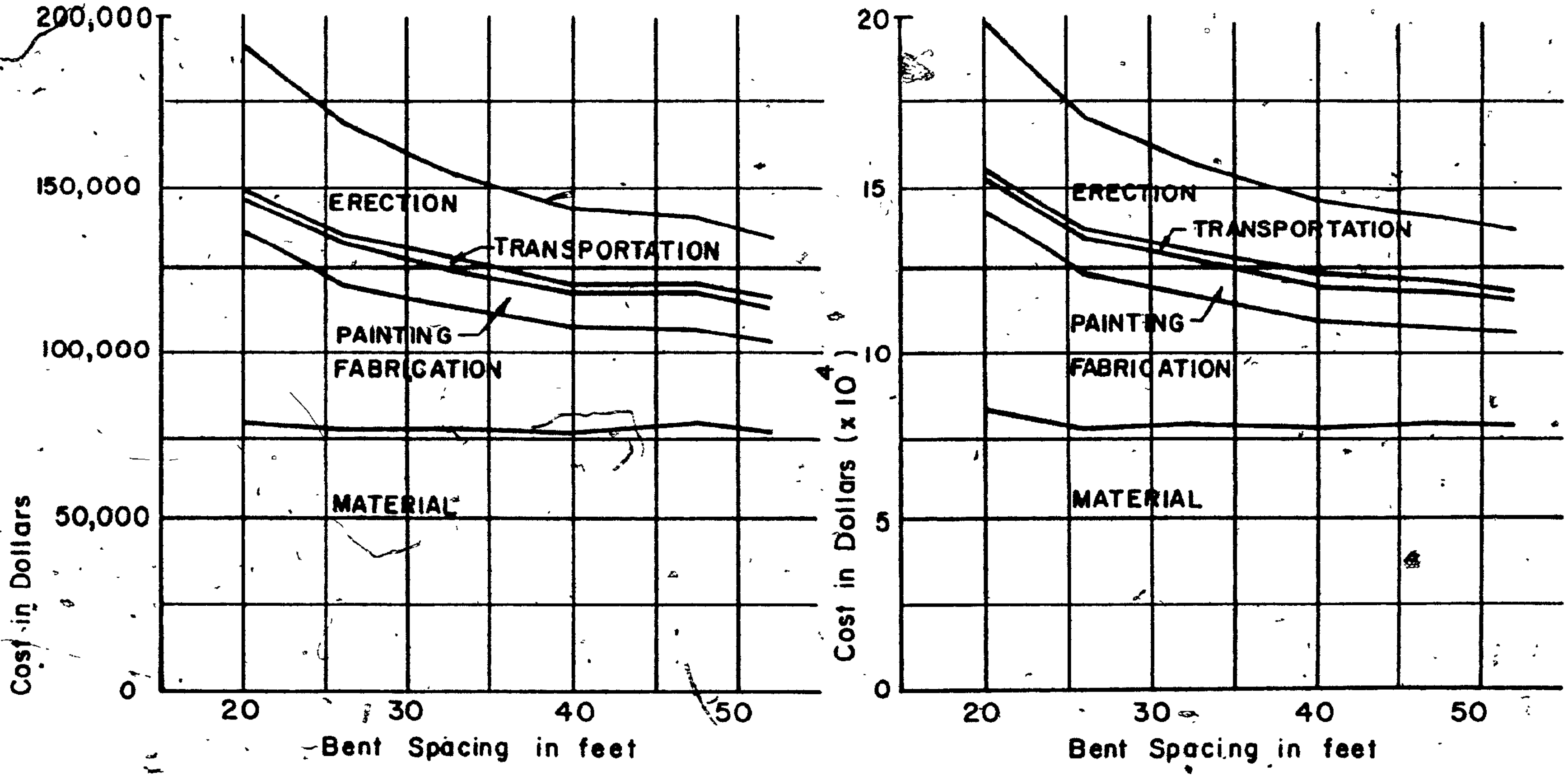
(b) WEIGHT RELATED COST



(c) GENERAL COST

(number of truss panel=16)

Fig.3.15-VARIATION OF STRUCTURAL BENT SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) NUMBER OF PANEL 12

(b) NUMBER OF PANEL 14

(depth to span ratio 0.09)

Fig. 3.16 - BREAKDOWN OF STRUCTURAL BENT COST FOR GENERAL COST MODEL

Alternative	Span (ft)	No. of Truss Panels	No. of Bents	D/S	Material		Fabrication			Total Cost ($)	Remarks
					Weight (ton)	Cost ($)	MH/ton	Total MH	Cost ($)		
1	150.0	10	20	0.08	245.63	81058.00	8.92	2191	31769.50	112827.50	1. All vertical and diagonal web members of same section respectively. 2. All chord members of same section.
2	150.0	10	20	0.08	197.24	65089.00	8.98	1771	25679.50	90768.50	1. Webs symmetrical about the axis. 2. Chord members vary.
3	150.0	14	20	0.08	254.98	84143.40	12.4	3162	45849.00	129992.40	1. All vertical and diagonal web members of same section respectively. 2. All chord members of same section
4	150.0	14	20	0.08	186.80	61644.00	12.7	2372	34394.00	96038.00	1. Webs symmetrical about the axis. 2. Chord members vary.

TABLE 3.1: STUDY OF COST EFFECTIVENESS OF GROUPING MEMBERS

Classification	CONNECTION FACTORS Simple Construction	CONNECTION FACTORS Continuous Construction	COST FACTORS Simple Construction	COST FACTORS Continuous Construction
1. Beams				
a) W up to 35 p/f	1.05	1.1	1.15	1.5
b) W 36-120 p/f	1.05	1.1	1.0	1.3
c) WWF (Welded wide flange)	1.05	1.1	1.1	1.4
2. Columns				
a) W up to 35 p/f	1.15		1.1	
b) W 36-190 p/f	1.15		1.0	
3. Trusses, Parallel Chords Pratt Type				
a) Double L or Tee	1.15		1.3	
b) W	1.15		1.2	
4. Bracing				
a) W	1.1		1.75	
b) L	1.15		1.3	
5. Purlins				
a) W up to 35 p/f	1.02		1.15	
b) W 36-120 p/f	1.02		1.0	
6. Girts				
a) Hot Rolled	1.01		1.1	
b) Cold Formed(F_y>44ksi)	1.02		2.0	
7. Sag Rods		Charge @ $(\frac{CI}{80})$ each c/w nuts		
8. Open-web steel joists and bridging				
a) CSA G40.21 44W	1.05		1.10	
b) High Strength ($F_y \geq 55$ksi)	1.05		1.25	
9. Base Plates Canadian	1.02		1.0	
10. Bolts		Costs included in connection factors		
11. Welds		Costs included in connection factors		
12. Stud Shear Connectors				
a) Shop Applied		Charge @ $\$(\frac{CI}{900})$ each		
b) Field Applied		Charge @ $\$(\frac{CI}{600})$ each		
13. Ancillary Steel Attached, i.e. Hangers, Hung Spandrel Angles Roof and Floor Opening Frames, etc.	1.2		2.3	

TABLE 3.2: CISC COST MODEL FACTORS

DESIGN NUMBER 1	NPANL (NOS) 2	NBENT (NOS) 3	NVW (NOS) 4	NDW (NOS) 5	NSP (NOS) 6	TWT (TON) 7	COLWT (TON) 8	TRWT (TON) 9	CHORDWT (TON) 10	WBWT (TON) 11	MWT (TON) 12	DOMH (HR) 13	TRUSS FABRICATION				TOTAL MH PER TRUSS (HR) 18	ESTIMATED MANHOURS		RESULTS FROM SPSS ANALYSIS		MHCOL (HR) 23	CLEANING& PAINTING TRUSS (HR) 24
													DIAGONAL CUT (HR) 14	MAIN MEMBER CUT (HR) 15	ASSEMBLY (HR) 16	WELDING (HR) 17		MHT (HR) 19	MHS (HR) 20	MHT (HR) 21	MHS (HR) 22		
1	8	46	7	8	6	347.75	1.12	7.56	4.69	2.40	0.47	30	6	17	50	29	102	90	12	91.1	11.8	3.5	15
2	12	46	11	12	6	390.09	1.12	8.48	4.95	3.02	0.51	32	6	18	67	31	122	110	12	[illegible]	12.1	3.5	14
3	16	46	15	16	6	406.64	1.12	8.84	4.69	3.62	0.53	35	6	19	72	34	131	119	12	104.3	11.8	3.5	19
4	8	31	7	8	6	352.16	1.42	11.36	7.80	2.95	0.61	30	7	20	56	34	117	101	16	110.7	17.1	3.5	15
5	12	31	11	12	6	361.46	1.42	11.66	7.09	3.93	0.64	32	7	18	73	34	132	116	16	122.3	15.6	3.5	17
6	16	31	15	16	6	386.57	1.42	12.47	7.09	4.71	0.68	35	7	20	77	46	150	134	16	138.4	15.6	3.5	19
7	8	25	7	8	6	333.75	1.63	13.35	9.15	3.52	0.68	30	10	26	74	49	159	138	21	[illegible]	20.2	3.5	15
8	12	25	11	12	6	345.75	1.63	13.83	8.59	4.54	0.71	32	10	26	79	49	164	144	20	142.4	18.8	3.5	17
9	16	25	15	16	6	367.00	1.63	14.68	9.21	5.70	0.77	35	10	26	92	49	177	161	16	161.6	18.0	3.5	19

NOTE:

NPANL = NUMBER OF PANELS
NBENT = NUMBER OF BENTS
NVW = NUMBER OF VERTICAL WEBS/TRUSSES
NDW = NUMBER OF DIAGONAL WEBS/TRUSSES
NSP = NUMBER OF SPLICES/TRUSS
TWT = TOTAL WEIGHT OF THE STRUCTURAL BENTS
COLWT = WEIGHT PER COLUMN
TRWT = WEIGHT PER TRUSS

CHORDWT = CHORD WEIGHT PER TRUSS
WBWT = WEB WEIGHT PER TRUSS
MWT = MISCELLANEOUS WEIGHT/TRUSS (For connections, filler & splices)
DOMH = TOTAL DRAWING OFFICE MANHOURS
MH = MANHOURS
MHT = MANHOURS PER TRUSS EXCLUDING CHORD SPLICES
MHS = MANHOURS FOR CHORD SPLICES PER TRUSS
MHCOL = MANHOURS PER COLUMN

TABLE 3.3: SUMMARY OF RESULTS FOR THE FABRICATION OF STRUCTURAL BENT

SUMMARY TABLE

STEP	VARIABLE ENTERED	VARIABLE REMOVED	F TO ENTER OR REMOVE	SIGNIFICANCE	MULTIPLE R	R SQUARE	R SQUARE CHANGE	SIMPLE R	OVERALL F	SIGNIFICANCE
1	TRNT		27.64800	.001	.89329	.79797	.79797	.89329	27.64800	.001
2	NPANL		9.59971	.021	.96036	.92229	.12433	.64636	35.60704	.000

(a) STATISTICS FOR TRUSS MANHOUR ESTIMATING RELATIONSHIP

SUMMARY TABLE

STEP	VARIABLE ENTERED	VARIABLE REMOVED	F TO ENTER OR REMOVE	SIGNIFICANCE	MULTIPLE R	R SQUARE	R SQUARE	SIMPLE R	OVERALL F	SIGNIFICANCE
1	CHORDNT		76.13001*	.000	.95697	.91579	.91579	.95697	76.13001	.000

(b) STATISTICS FOR CHORD SPLICE MANHOUR ESTIMATING RELATIONSHIP

<u>TABLE 3.4</u>: SPSS SUMMARY TABLES FOR TRUSS AND CHORD SPLICE MANHOURS ESTIMATING RELATIONSHIPS

CHAPTER 4

ROOF AND ENCLOSURE SYSTEM

4.1 INTRODUCTION

The design and costing of the roof structural system and cladding for the design problem described in Chapter 1 are examined herein. The objectives of this chapter are:

(i) To describe the roof structural system adopted for this study and the algorithm used for its design;

(ii) To formulate cost models for the roof structural system which reflect the design decision variables of number of bays, number of panels and depth to span ratio and which account for material, labour and equipment charges;

(iii) To examine the significance of the cost tradeoffs between material, labour and equipment costs; and

(iv) To examine the sensitivity of both roof system weight and cost to changes in design configuration.

4.2 SYSTEM DESIGN

4.2.1 Roof System

Attention is restricted here to a conventional roof system comprised of purlins, joists, if necessary, and decking. Several alternatives exist for each of these elements. For example, for the purlins, WF sections, manufactured joists and trusses could be used. For the joists, junior members or manufactured joists are feasible while steel or asbestos decking with built up roofing could be used for the roof cover. For this project, attention has been restricted to using manufactured joists and steel decking. Figure 4.1 illustrates the roof system considered herein, as well as the various typical connection details assumed. It is left to a future study to consider a wider range of alternatives for these elements.

With respect to the purlins, the merits of WF sections versus long span joists or manufactured trusses were examined. Of prime consideration were the relative costs of the members and ease of construction with each member type. As per the National Building Code, purlins were designed to satisfy both a strength and deflection criterion. Consideration was given to having the WF sections span one, two and three bays, with the maximum member length being 60 feet (e.g. a maximum of 3-20 ft.bays., 2-30 ft. bays or 1-60 ft.bay). Figure 4.2 shows the moment and deflection values for these WF purlin support conditions. Figure 4.3 presents a comparison of the design of the purlin using WF sections versus manufactured joists for a bay spacing ranging from 15 to 50 feet. The ordinate reflects the weight per foot of the purlin. Only WF members are considered as continuous over two or more bays, as noted in the figure. As seen from the figure, on a weight basis, manufactured joists are the preferred solution. Figure 4.4 depicts a material cost comparison of joists versus WF members. As seen from this figure, even for a joist to WF purlin material cost ratio of 2 to 1 ($C_J/C_{WF} = 2$), the joist remains the preferred solution. (As of December 1977, this ratio is approximately 2 in the Montreal area). From an erection viewpoint, it is not clear that one solution dominates the other in terms of labour input. The considerably greater lateral stiffness of the WF purlin allows the roof system to be erected in place. On the other hand, site conditions permitting, roof sections using joists as purlins could be prefabricated on the ground and lifted into place, thus offsetting the poor lateral stability of the joists before the decking is attached. If the roof system were to be erected in place using joists, erection platforms or temporary supports would probably be required. If manufactured joists are used, some attention must be given to the connection detail between the joist and the purlin. The relatively thin chord member of each could preclude an effective welded connection.

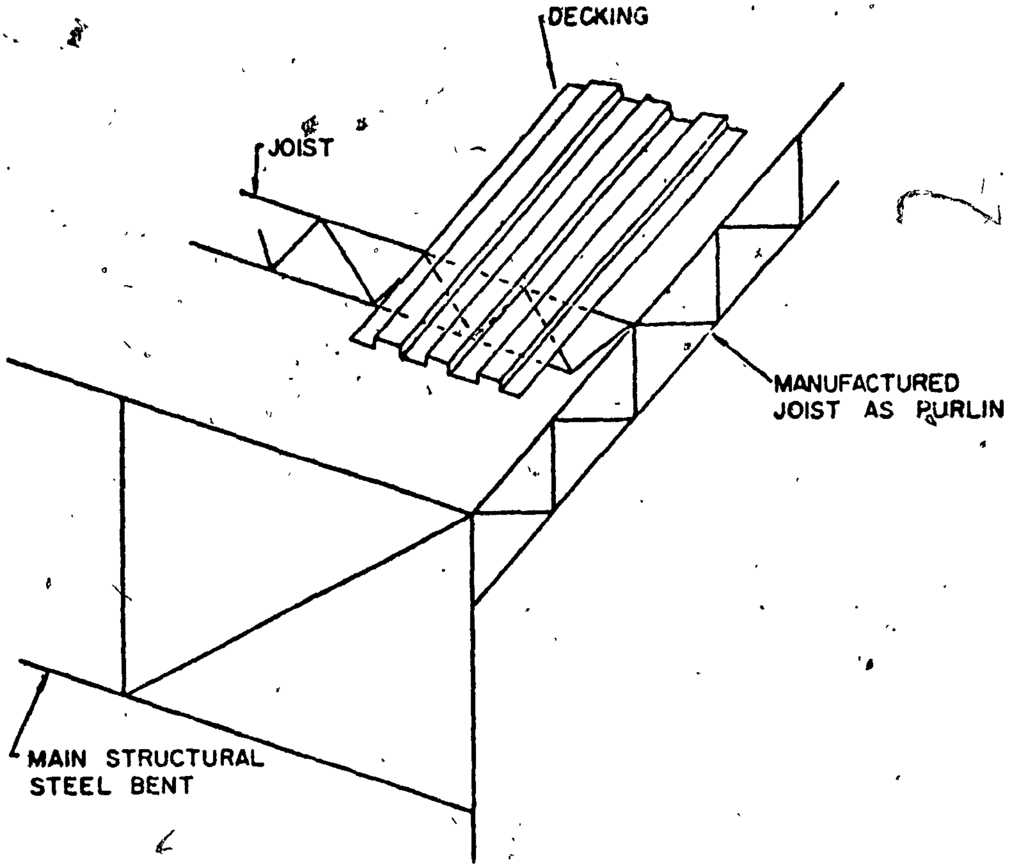
Various strategies could be used to eliminate the need for joists spanning between the purlins because of maximum deck span considerations. They include having a large number of panels, using subdivided trusses or placing purlins between panel joints and designing for primary bending in the chords - see Figure 4.5. Only the first of these three alternatives is considered in this thesis.

Because manufactured elements were used for the roofing system, the design routine developed consisted of a look up table of short span and long span joists and manufactured truss members for purlins and joists and a set of regression equations for the decking.

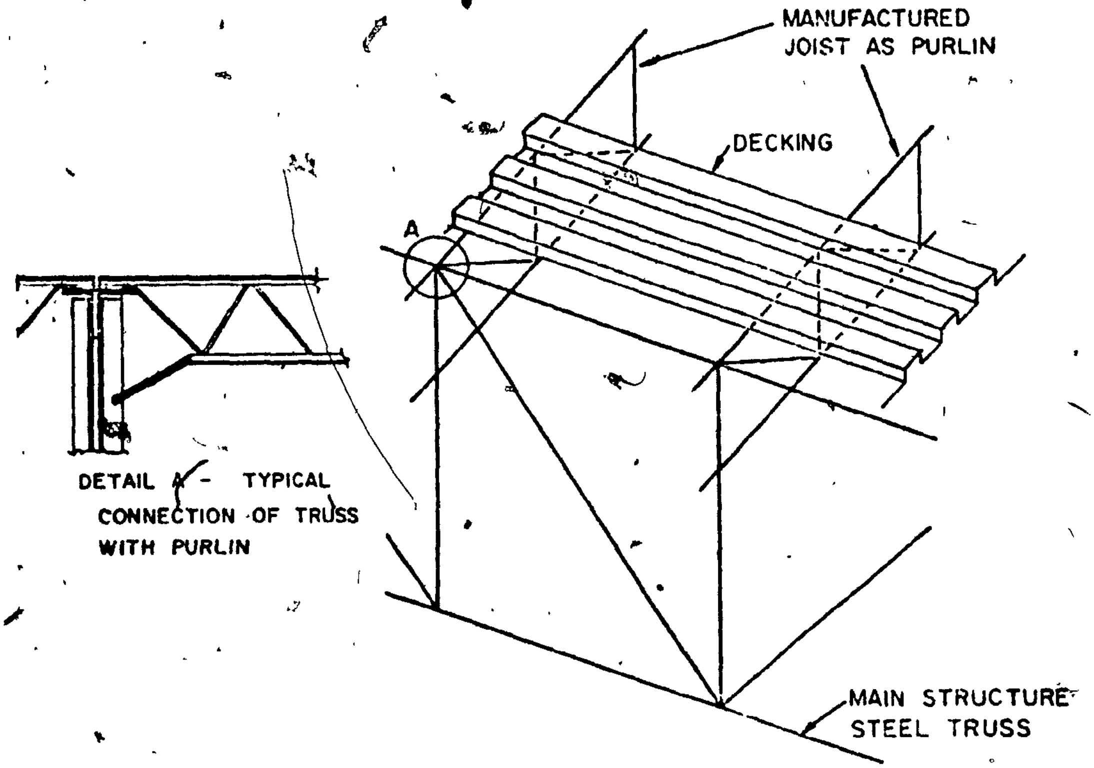
2. The high purlin material weights associated with large truss spacings coupled with the need to use relatively expensive manufactured trusses as purlins for these large spacings make such spacings uneconomical. If attention is limited to the optimal weight related cost solution for each truss spacing examined, then the variation between these optimal solutions within the truss spacing range of 20 to 47.27 feet is 46.5 percent.
3. Results from both cost models indicate that the use of joists, thus minimizing the number of truss panels required, is not economical, at least on the basis of roof system cost alone.
4. Agreement between the two cost models examined is reasonably close when joists are not required (12, 14 and 16 panel cases). When joists are required, the handling costs associated with their lifting, placing and connection, which are treated explicity in the general cost model, result in significant differences in cost prediction between the two cost models. It should be noted that both cost models yield the same optimal roof configuration.
5. When member handling costs are considered, roof configurations which minimize the number of members to be handled become more competitive with minimum weight configurations. This competitiveness is enhanced as the handling costs increase.
6. If attention is limited to the optimal general cost model solution for each truss spacing examined, then the variation between these optimal solutions within the truss spacing range

of 20' to 47.27' is 24.2 percent. This variation is considerably less than for the results based on the weight related cost model.

7. For a given roof system alternative (e.g. purlins plus decking), roof system cost is most sensitive to changes in the independent variable, truss spacing.

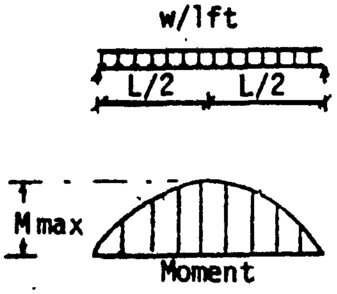


i) ROOF SYSTEM CONSISTING OF PURLIN, JOIST, AND DECKING.



ii) ROOF SYSTEM CONSISTING OF PURLINS AND DECKING

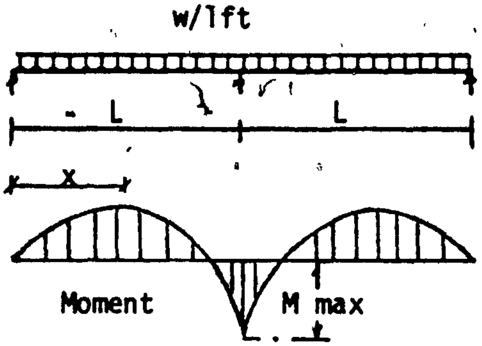
FIGURE 4.1: SCHEMATIC OF ROOF SYSTEM



M max (at centre) = $0.125\ wL^2$

Δ max (at centre) = $0.013\ wL^4/EI$

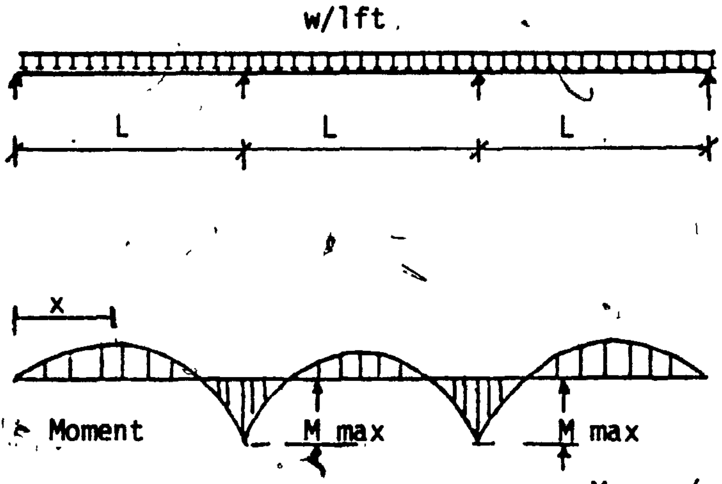
FIGURE: 4.2(a) SINGLE SPAN



M max (at mid support) = $0.125wL^2$

Δ max (at $x = 0.4215L$) = $0.0054wL^4/EI$

FIGURE: 4.2(b) PURLIN CONTINUOUS OVER TWO SPANS



M max (at penultimate support) =

$0.100wL^2$

Δ max (at $x = 0.4L$) = $0.0069wL^4/EI$

FIGURE: 4.2(c) PURLIN CONTINUOUS OVER THREE SPANS

FIGURE: 4.2 MAXIMUM MOMENT AND DEFLECTION VALUES FOR PURLIN SUPPORT CONDITIONS.

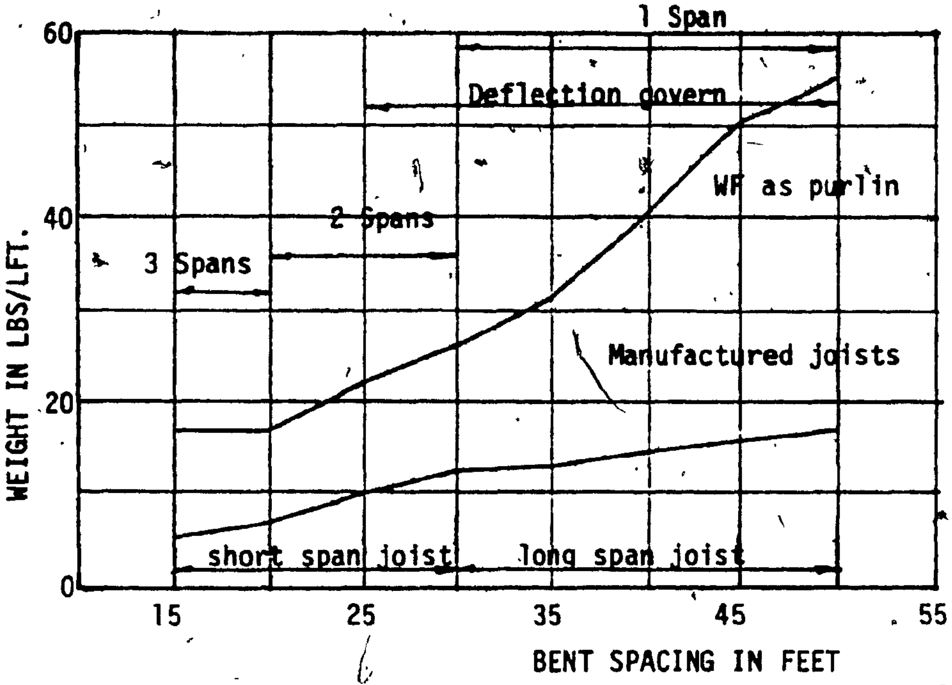


FIGURE: 4.3 COMPARISON OF THE DESIGN OF THE PURLIN USING WF SECTIONS VERSUS MANUFACTURED JOISTS.

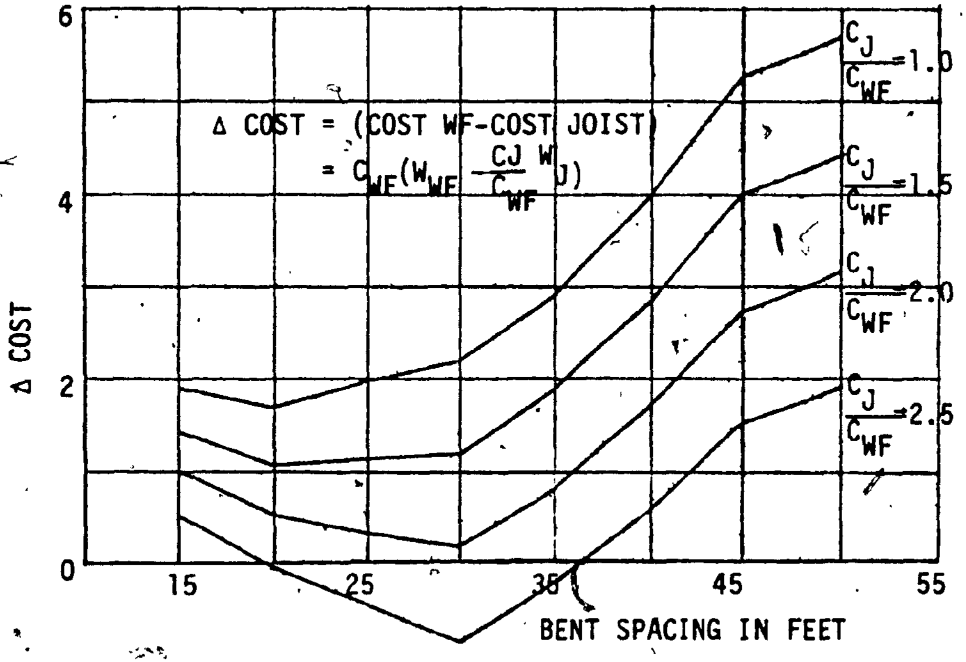
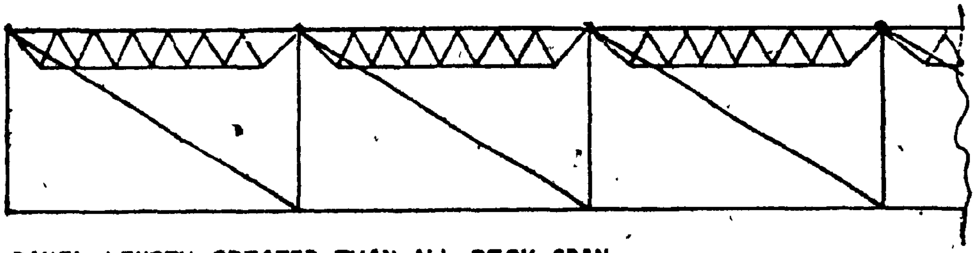
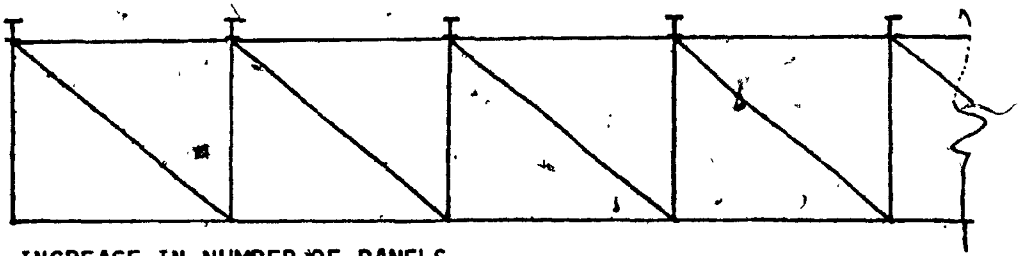


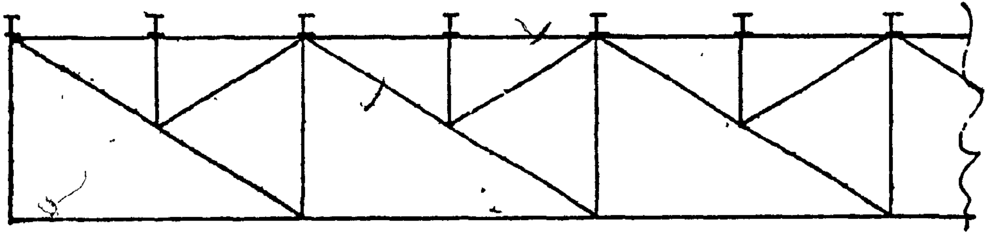
FIGURE: 4.4 MATERIAL COST COMPARISON OF JOISTS VERSUS WF MEMBERS FOR PURLINS.



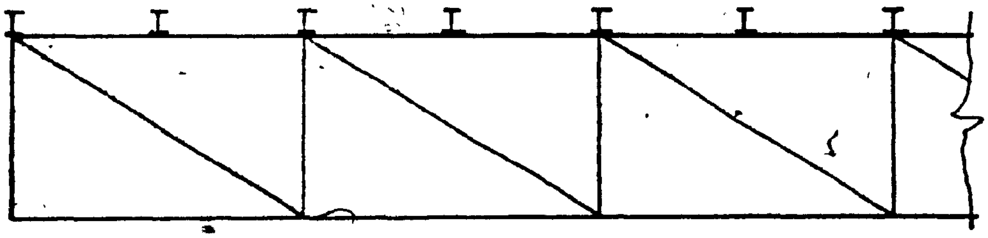
(a) PANEL LENGTH GREATER THAN ALL DECK SPAN.
Joists required.



(b) INCREASE IN NUMBER OF PANELS
Joists eliminated



(c) SUBDIVIDED TRUSS
Joists eliminated.



(d) CHORDS DESIGNED FOR PRIMARY BENDING.
Joists eliminated

FIGURE 4.5 STRATEGIES TO ELIMINATE JOISTS

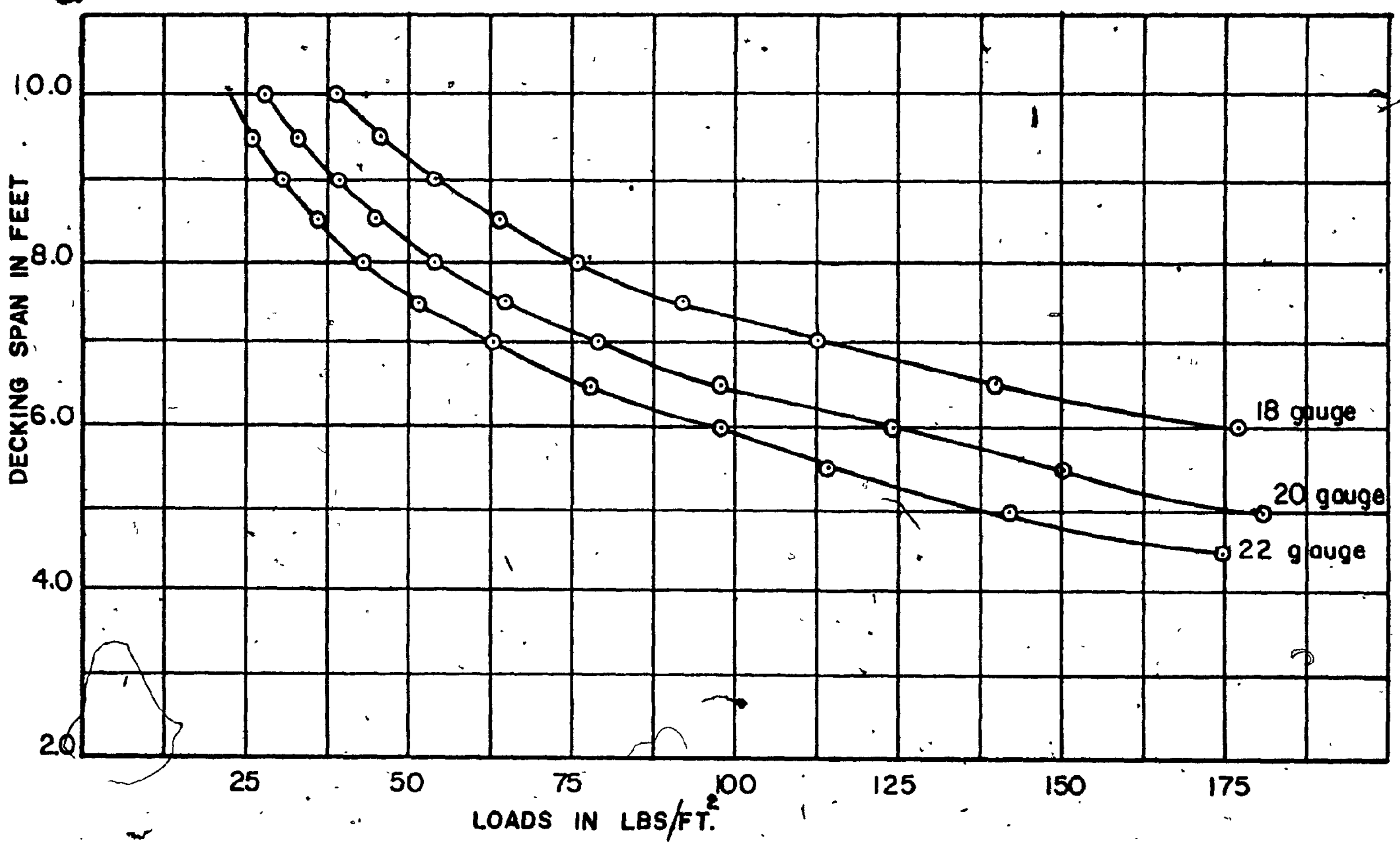
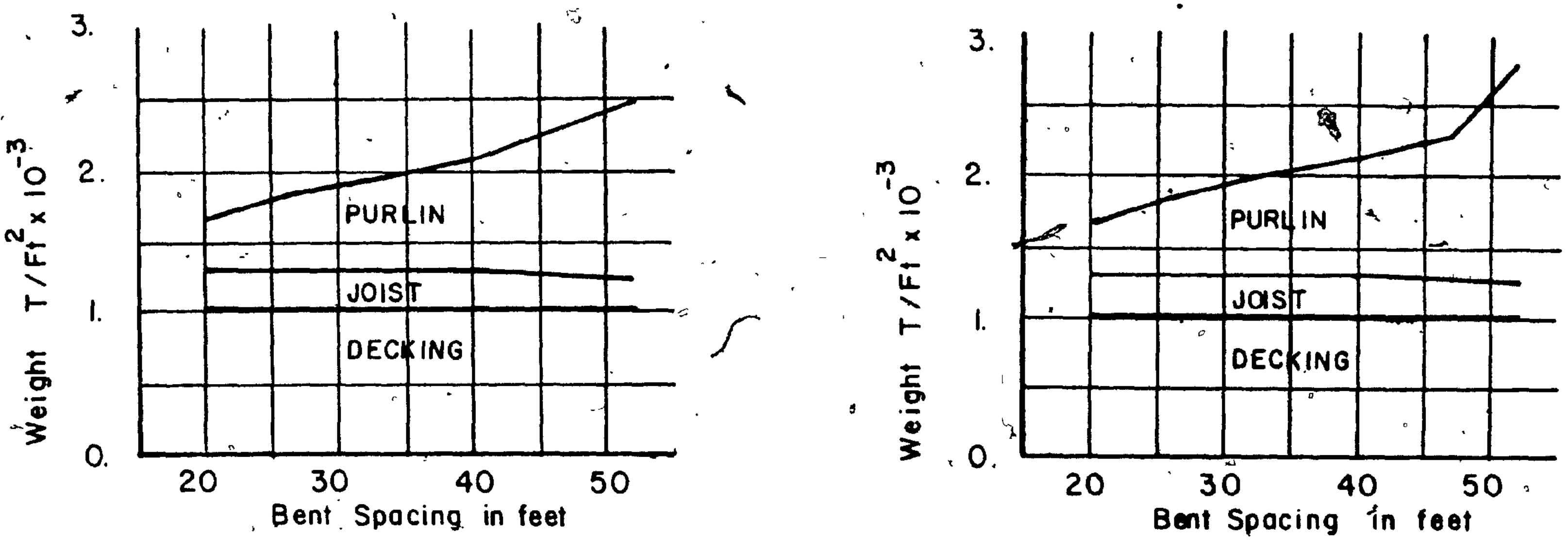
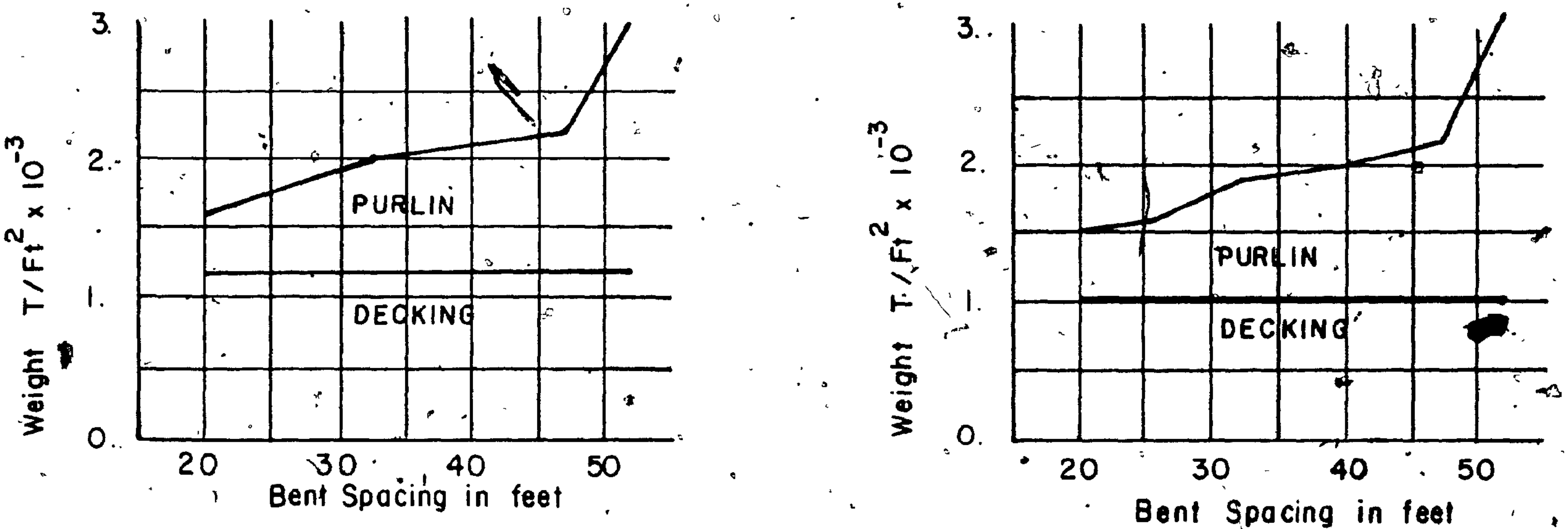


FIGURE 4·6– REGRESSION CURVES FOR ALLOWABLE DECKING SPAN VERSUS LOAD FOR MULTIPLE SPAN CASE. (7)



(a) NUMBER OF TRUSS PANELS8

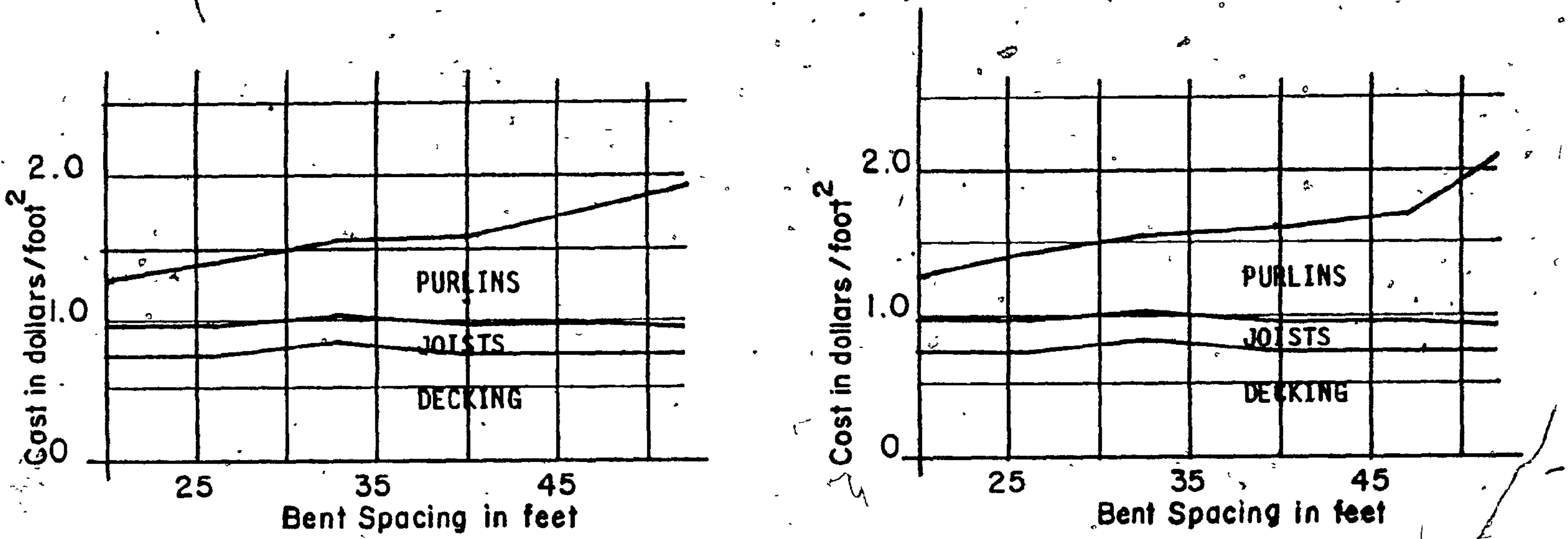
(b) NUMBER OF TRUSS PANELS10



(c) NUMBER OF TRUSS PANELS12

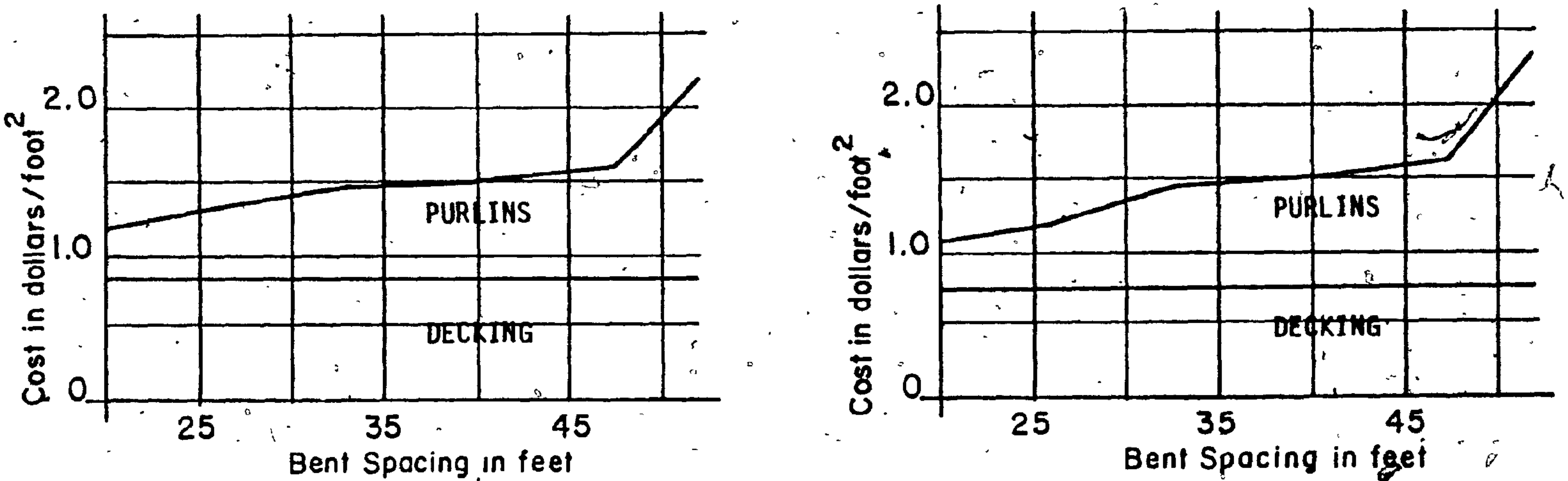
(d) NUMBER OF TRUSS PANELS14

Fig.47- VARIATION OF ROOF SYSTEM WEIGHT WITH CONFIGURATION



(a) NUMBER OF TRUSS PANELS = 8

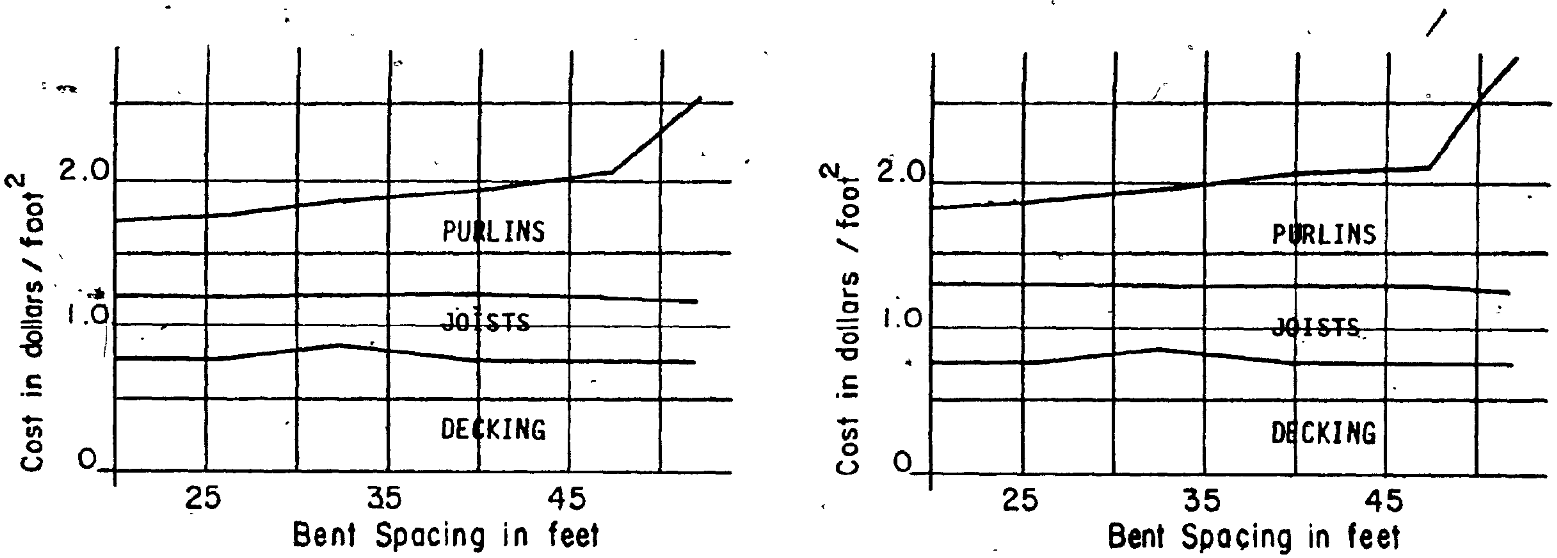
(b) NUMBER OF TRUSS PANELS = 10



(c) NUMBER OF TRUSS PANELS = 12

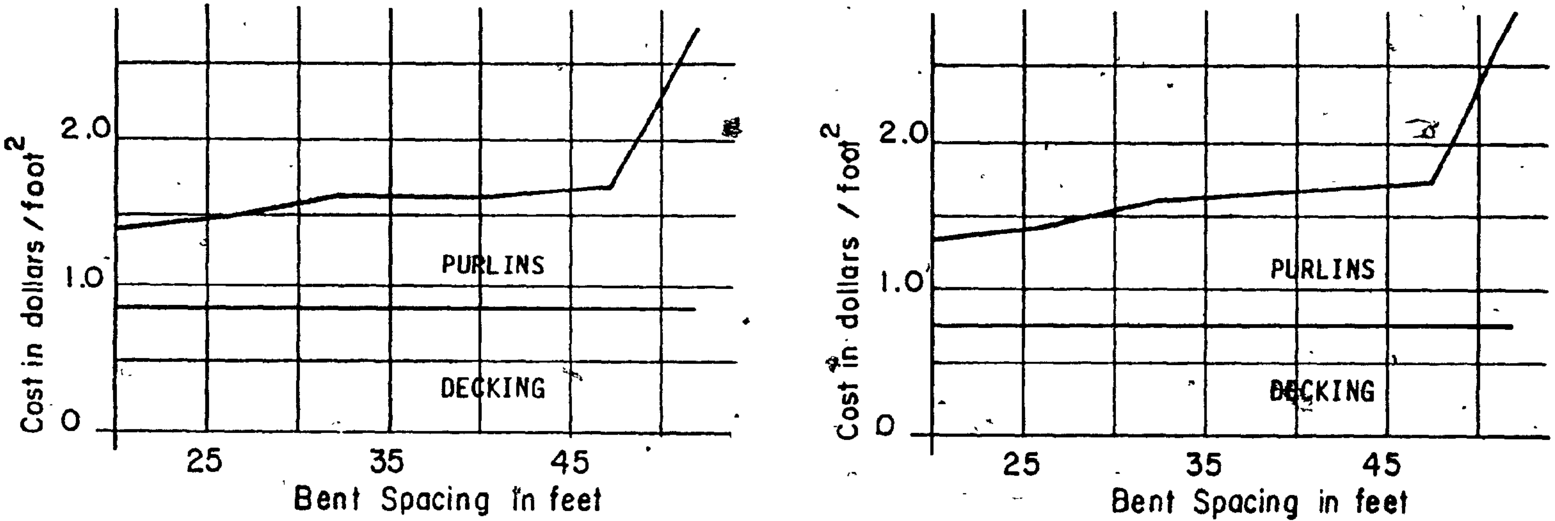
(d) NUMBER OF TRUSS PANELS = 14

FIG. 4·8 WEIGHT RELATED COST MODEL FOR ROOF SYSTEM



(a) NUMBER OF TRUSS PANELS = 8

(b) NUMBER OF TRUSS PANELS = 10



(c) NUMBER OF TRUSS PANELS = 12

(d) NUMBER OF TRUSS PANELS = 14

FIG. 4·9 GENERAL COST MODEL FOR ROOF SYSTEM

Gauge	Thickness (inch)	Depth (inch)	Weight (lb/sq. ft.)	Reaction at support lb.	MID SPAN Moment Inertia (in^4)	MID SPAN Section Modulus (in^3)	SUPPORT Moment Inertia (in^4)	SUPPORT Section Modulus (in^3)
22	0.030	1.500	1.93	504	0.1477	0.1847	0.1752	0.1842
20	0.036	1.506	2.26	805	0.1872	0.2414	0.2197	0.2349
18	0.048	1.518	2.96	1,523	0.2754	0.3368	0.3099	0.3387

Properties established according to C.S.A. S-136 for width of 12 inches.

(a) PHYSICAL PROPERTIES OF DECKING

SPAN (feet)	SINGLE SPAN						DOUBLE SPAN						MULTIPLE SPAN					
	22		20		18		22		20		18		22		20		18	
	B	D	B	D	B	D	B	D	B	D	B	D	B	D	B	D	B	D
4'6"	141	120	184	153	256	219	140	140	179	179	258	258	175	175	224	224	322	322
5'0"	114	89	149	113	208	162	114	114	145	145	209	209	142	142	181	181	261	261
5'6"	94	68	123	86	172	122	94	94	120	120	173	173	117	117	150	150	216	216
6'0"	79	53	103	67	144	95	79	79	101	101	145	145	99	98	126	124	181	177
6'6"	67	42	88	53	123	75	67	67	86	86	124	124	84	78	107	98	154	140
7'0"	58	34	76	43	106	60	58	58	74	74	107	107	72	63	92	79	133	113
7'6"	51	28	66	35	92	49	50	50	64	64	93	93	63	52	80	65	116	92
8'0"	45	23	58	29	81	41	44	44	57	57	82	82	55	43	71	54	102	76
8'6"	39	20	52	25	72	34	39	39	50	50	72	72	49	36	63	45	90	64
9'0"	35	17	46	21	64	29	35	35	45	45	64	64	44	31	58	39	81	54
9'6"	32	14	41	18	58	24	31	31	40	40	58	58	39	26	50	33	72	46
10'0"	28	12	37	15	52	21	28	28	36	36	52	50	35	23	45	28	65	39

Steel A-446-72, Grade B
Column B indicates total load for f = 22,400 psi
Column D indicates total load for 1/240 deflection

(b) LOAD CARRYING CAPACITY OF DECKING

TABLE 4.1 DECKING DATA (7)

GAUGE	DECKING SPAN (DKSPAN) IN FEET	
	DOUBLE SPAN	MULTIPLE SPAN
22	$16.73532931 - 0.34670339L$ $+ 0.00450635L^2 - 0.00002881L^3$ $+ 0.00000007L^4$	$13.90960625 - 0.22965451L$ $+ 0.00279761L^2 - 0.00001659L^3$ $+ 0.00000004L^4$
20	$16.78983901 - 0.27181842L$ $+ 0.0027580L^2 - 0.0000138L^3$ $+ 0.00000003L^4$	$13.76739854 - 0.17676078L$ $+ 0.00167915L^2 - 0.00000776L^3$ $+ 0.00000001L^4$
18	$15.87548453 - 0.16114938L$ $+ 0.00104337L^2 - 0.00000339L^3$	$13.57501806 - 0.11992311L$ $+ 0.00079254L^2 - 0.00000255L^3$

L = Governing load in psi

TABLE: 4.2 REGRESSION EQUATIONS DEVELOPED FOR DIFFERENT DECKING GAUGES AND SPANS

Source	Crew Size	Crew Cost	Fringe Benefits	Total Crew Cost	Number of Lifts Per Day	Number of Joists Per Lift			Number of lifts Per Tie Joist	Joists Connected Per Day	Remarks
						Up to 30' Span	30-40' Span	Over 40' Span			
A	1 Foreman + 2 Welders + 2 Steel Erectors	$51.90	$18.50	$70.40	60	6	4	1	1	$2 \times \frac{TL}{N}$	
B	½ Foreman + 4 Steel Erectors	$46.71	$16.65	$63.36	60W 50S	4	3	1	1		Lifting of Joists
	½ Foreman + 1 Welder + 1 Steel Erector	$25.95	$9.25	$35.20						150*	Connection of Joists

NB
TL = Total lifts
W = Winter
S = Summer
N = Number of lifts per day

* Joists per day

TABLE 4.3 JOISTS INSTALLATION TIME AND COST DATA

SOURCE	DECKING TYPE (GAUGE)	MATERIAL COST* $/ft²	CREW SIZE	CREW COST $/hr.	FRINGE BENEFITS $/hr.	TOTAL CREW COST $/hr.	INSTAL-LATION RATE ft²/hr.	UNIT COST FOR INSTAL-LATION $/ft²	UNIT GIVEN COST FOR INSTALLATION $/ft²
A	22	0.40	1 Foreman +2 Welders + 2 Serc.	51.90	18.50	70.40	3125	0.023	.07
	20	0.46	- do -	51.90	18.50	70.40	2500	0.028	.07
	18	0.635	- do -	51.90	18.50	70.40	1250	0.056	.07
B	22	0.48	1 Foreman +1 Welder + 3 Serc.	51.90	18.50	70.40	425	0.166	.10
	20	0.54	- do -	51.90	18.50	70.40	425	0.166	.10
	18	0.68	- do -	51.90	18.50	70.40	425	0.166	.10
C	22	0.41	1 Foreman +1 Welder + 3 Serc.	51.90	18.50	70.40	625	0.113	.09
	20	0.47	- do -	51.90	18.50	70.40	625	0.113	.09
	18	0.62	- do -	51.90	18.50	70.40	625	0.113	.09
D	22	0.365	1 Foreman +1 Welder + 4 Serc.	62.28	22.20	84.48	1250	0.068	
	20	0.412	- do -	62.28	22.20	84.48	1250	0.068	
	18		- do -	62.28	22.20	84.48	1250	0.068	
MEAN'S (6)	22		1 Foreman + 8 Serc.	93.42	33.30	126.72	1150	0.110	
	20		- do -	93.42	33.30	126.72	1075	0.118	
	18		- do -	93.42	33.30	126.72	1062.5	0.119	

* Includes federal tax, but excludes provincial tax.

TABLE 4.4: DECKING MATERIAL COST AND INSTALLATION TIME AND COST DATA

ITEM	UNIT	COST	REMARKS
1. Material:			
- joist	lbs	0.25	Short span joist
- joist for purlin	lbs	0.26	Long span joist
- truss for purlin	lbs	0.35	Manufactured truss
- decking			
- 22 gauge	ft^2	0.41	All material cost exclusive of provincial tax
- 20 gauge	ft^2	0.47	
- 18 gauge	ft^2	0.62	
2. Equipment:			
- crane			
- 50 ton	hr.	85.00	Crane operator (\$9.70/hr.) and oiler (\$9.31/hr.) included
- 30 ton	hr.	70.00	
- welding machine	hr.	2.00	
- compressor	hr.	1.75	
3. Labour:			
- steel erector	hr.	14.08	\$3.70 as fringe benefits included
- fabricator	hr.	9.01	\$2.12 as fringe benefits included
4. Production:			
- joist's connection			80 joists per day
- purlins connections			
8 and 10 panel case			3 bays per day
12, 14 & 16 panel case			2 bays per day
- bridging installation			120 lft per day
- decking installation			546 ft^2 per hr.
5. Other:			
- make up cost etc (M)			7.50% of direct cost
- sales tax (S_T)			8.00 % of direct cost
- overhead & profit (O_H)			20.00% of direct cost

TABLE 4.5: COST DATA

Truss Spacing in feet	No. of Bays	No. of Panels	No. of Purlins	No. of Joists	Purlin Size	Joise Size	Decking Gauge,	Total Weight Ton/ft²	Total Cost $/ft²	
									Weight Related	General
20.00	26	8	234	624	20CA8.5	4CA12	22	0.00170	1.266	1.710
	26	10	286	780	20CA7	4CA8	22	0.00170	1.268	1.817
	26	12	338	-	18CA6.5	-	20	0.00161	1.158	1.413
	26	14	390	-	16CA6	-	22	0.00146	1.091	1.374
	26	16	442	-	16CA6	-	22	0.00162	1.136	1.445
26.00	20	8	180	640	26CA12	4CA12	22	0.00186	1.390	1.751
	20	10	220	800	26CA10.5	4CA8	22	0.00190	1.418	1.882
	20	12	260	-	26CA9.5	-	20	0.00181	1.305	1.496
	20	14	300	-	26CA8	-	22	0.00167	1.204	1.425
	20	16	340	-	24CA8	-	22	0.00169	1.254	1.481
32.50	16	8	144	512	28CA15	4CA12	20	0.00211	1.533	1.864
	16	10	176	640	28CA13	4CA8	20	0.00215	1.563	1.960
	16	12	208	-	28CA13	-	20	0.00203	1.476	1.633
	16	14	240	-	28CA12	-	22	0.00191	1.429	1.615
	16	16	272	-	28CA12	-	22	0.00203	1.519	1.701
40.00	13	8	117	624	34CA17.5	4CA12	22	0.00210	1.570	1.925
	13	10	143	780	34CA15.5	4CA8	22	0.00217	1.619	2.076
	13	12	169	-	34CA13.5	-	20	0.00206	1.500	1.619
	13	14	195	-	34CA13.5	-	22	0.00203	1.514	1.659
	13	16	221	-	34CA13.5	-	22	0.00216	1.615	1.757
47.27	11	8	99	616	34CA23.5	4CA12	22	0.00237	1.770	2.080
	11	10	121	770	34CA18	4CA8	22	0.00230	1.719	2.107
	11	12	143	-	34CA15	-	20	0.00220	1.598	1.706
	11	14	165	-	34CA15.5	-	22	0.00218	1.626	1.730
	11	16	187	-	34CA15.5	-	22	0.00233	1.743	1.872
52.00	10	8	90	560	57CA28	4CA12	22	0.00254	1.902	2.516
	10	10	110	700	57CA28	4CA8	22	0.00282	2.112	2.865
	10	12	130	-	57CA28	-	20	0.00301	2.208	2.743
	10	14	150	-	57CA28	-	22	0.00311	2.330	2.928
	10	16	170	-	57CA28	-	22	0.00339	2.540	3.202

<u>TABLE 4.6</u>: DESIGN AND COST DETAILS FOR VARIOUS ROOF SYSTEM CONFIGURATIONS

CHAPTER 5

SYSTEM PERFORMANCE AND OPTIMIZATION

5.1 INTRODUCTION

As stated in Chapter 1, the overall goals of this thesis are:

(i) To develop a practical computerized design aid for the design of the foundation, structural and enclosure subsystems of light industrial type buildings in such a way as to permit tradeoffs between these subsystems in order to optimize overall system performance; and

(ii) to demonstrate the importance of careful formulation of the performance measure used for determining the optimal configuration of the system.

Work in Chapters 2 through 4 has been directed at formulating and computerizing design algorithms and cost models for the foundation, bent, roof and cladding subsystems, respectively. Also examined in these chapters was the manner in which subsystem material quantities and costs varied with changes in design configuration. Only one alternative was examined for each of the subsystems.

Following the development of the models described in the previous three chapters, they were integrated into a computerized design package. The coordinating or interface variables between components of this package are depth to span ratio, number of panels and truss spacing. These three variables influence other interface parameters such as load transmitted from the roof system to the bent system and from the bent system to the foundation.

The objectives of this chapter relate directly to the goals stated above and are:

(i) to briefly describe the computerized design aid developed;

(ii) to examine system performance in terms of weight and cost as a function of the interface variables by way of an exhaustive search procedure;

(iii) to describe an optimization search procedure for determining values for the interface variables so as to minimize a specific objective function; and

(iv) to examine the effectiveness of this optimization search procedure.

5.2 DESCRIPTION OF THE COMPUTERIZED DESIGN AID

Figure 5.1 depicts the major components and their relationship for the computer program developed. One of three criteria can be selected for evaluating the overall system. The first is structural system weight, which is written as:

$$\text{SYSTEM WEIGHT} = \text{BENT SYSTEM WEIGHT} + \text{ROOF SYSTEM WEIGHT} \tag{5.1}$$

This criterion has the deficiency that it does not reflect all the subsystems (foundation and cladding are excluded) nor does it reflect all the resource inputs required for construction of the system. It is, however, representative of a performance measure often used by civil engineers in assessing system effectiveness, and is taken as a proxy or surrogate for cost as a performance measure.

The second and third criteria reflect cost, with the second criterion being a material or weight related cost function while the third criterion reflects the labour and equipment inputs required for construction as well as the material inputs. The form of these two criteria have been examined in detail in Chapters 2 through 4. For both criteria, total system cost per square foot may be written as:

$$\text{SYSTEM COST }/\text{FT}^2 = (\text{FOUNDATION SYSTEM COST} + \text{BENT SYSTEM COST} + \text{ROOF SYSTEM COST} + \text{CLADDING SYSTEM COST})/\text{BUILDING AREA} \qquad (5.2)$$

The computer program may be operated in one of two modes. In the first mode, the designer specifies values for the interface variables, and the design is then executed. In the second mode, the interface variables are free to float, and values are determined for them in such a way as to optimize system performance in terms of one of the three criteria previously described.

The program is practical in the sense that discrete member spectrums are used and all members are sized in accordance with the appropriate code. In particular, load combinations as specified by the National Building Code are used, CSA Standard S-16-1969 is used for steel member sizing and footings are sized according to ACI318-71 Building Code. Present program limitations include a lack of alternatives from which to choose for each subsystem, no deflection constraints on the bent, no bracing design and no detailed joint design.

Further, only limited efforts were made to ensure program efficiency in terms of speed and storage. Some of these limitations would have to be removed for the computer system to be used commercially.

The major advantage of the design package is that it allows the designer to investigate, at low cost, the impact on system performance of changes in design configuration. Existing design procedures do not have this advantage. Most of the effort in these procedures is directed at generating subsystem designs given values for the interface variables. Thus the opportunity to investigate system performance as a function of these variables seldom arises, despite the importance of doing so.

5.3 EXHAUSTIVE SEARCH RESULTS

An example problem was selected for purposes of examining the performance of the computer package and for determining system performance in terms of weight and cost as a function of the interface variables. The building chosen had plan dimensions of 100' -0" x 520' -0" and a clear height of 25' -0" to the underside of the trusses.

Results from the exhaustive search are summarized in Figures 5.2 through 5.6 and in Appendix V. Results are based on the cost parameter values and production rates identified in Chapters 2 through 4. Cost parameters reflect 1977 rates.

The following observations are noted based on these results.

(i) For the three performance measures examined, the optimal configurations are:

CRITERION	OPTIMAL CONFIGURATION DSR	NPANL	TSP (ft)	WEIGHT (TON/FT^2)	WEIGHT RELATED COST (\$/ft^2)	GENERAL COST MODEL (\$/FT^2)
Minimum weight	.08917	14	21.67	.004545	6.0684	7.2581
Weight related cost	.08490	14	24.76	.004656	6.1166	7.0423
General cost model	.08820	12	43.33	.005120	6.4184	6.5922

The nature of the differences between the optimal configurations generated by the two cost models is of interest. Both cost models yielded a purlin-decking combination as the best roof system (no joists). However, because the general cost model accounts for member handling charges, a 12 panel truss with 20 gauge decking was selected over the 14 panel truss and lighter 22 gauge decking selected by the weight related model. These handling charges relate to the number of web members per truss, the number of bents and the number of purlins.

(ii) The tradeoff between material costs and labour and equipment costs affected by the general cost model yield a reasonably broad range of depth to span ratio and truss spacings yielding similar cost. A similar range of almost constant cost is not indicated for the weight-related cost model.

(iii) 209 designs were examined in the exhaustive search. For truss spacings 20.00 feet and 52.00 feet, a cost variance greater than 10% over the least cost exhaustive search general cost model configuration result of $\$6.6548/ft^2$ is noted. For the remaining 140 designs, 120 designs were within 10%, 42 designs within 5% and 11 designs within 2% of the minimum cost of $\$6.6548/ft^2$. In terms of total dollars these percentages represent $34,605, $17,303 and $6,921 respectively on a minimum total cost of $346,050.

(iv) The total cost variations for the general cost model and the weight related cost model for all configurations examined are 32.50% and 36.43% respectively.

(v) Based on examination of Figure 5.9, a clear ranking of interface variables in terms of impact on both cost functions is not possible.

(vi) The impact of cladding cost on the least cost depth to span ratio for both cost models is examined in Figure 5.7. The nature of the tradeoff in this study is examined in Figure 5.8. As expected, the least cost depth to span ratio decreases with increasing cladding cost, with the general cost model demonstrating greater sensitivity because of its relative insensitivity to bent weight.

5.4 THE DESIGN PROBLEM AS AN OPTIMIZATION PROBLEM

The design problem studied in this thesis may be written as an optimization problem as follows:

$$\text{Minimize } f(\underline{x}) = \frac{1}{S*L}\left[2(x_1 + 1)C_F + (x_1 + 1)C_B + x_1 C_R + 2(H + Sx_3)(S + L)C_C\right] \qquad (5.3)$$

where

$f(\underline{x})$ = total cost /ft^2

S = span

L = building length

H = clear height of the building

C_F = cost per foundation

C_B = cost per bent

C_R = cost of roof system per bay

C_C = cost of cladding/ft^2

x_1 = number of bays

x_2 = number of panels

x_3 = depth to span ratio

$\underline{x}$ = vector of decision variables

Subject to

$\text{TSLB} \leq L/x_1 \leq \text{TSUB}$, x_1 an integer

$\text{NPLB} \leq x_2 \leq \text{NPUB}$, x_2 an even integer

$\text{DSLB} \leq x_3 \leq \text{DSUB}$

where

TSLB = lower bound for truss spacing

TSUB = upper bound for truss spacing

NPLB = lower bound for number of panels

NPUB = upper bound for number of panels

DSLB = lower bound for depth to span ratio

DSUB = upper bound for depth to span ratio and the design decisions variables pertaining to member sizes be selected as to satisfy all binding codes such that C_F, C_B, C_R and C_C are optimized for each (x_1, x_2, x_3) tuple. In particular,

(i) the foundation design must satisfy ACI 318-71 Building Code and National Building Code of Canada, 1975;

(ii) bent number sizing must be done in accordance with CSA Standard S16-1969; and

(iii) roof system components must be sized according to CSA Standard S16-1975, CSA-A 136-1974 and CSA-W95-1.

The problem, as stated, is a non-linear mixed integer mathematical programming problem for which no all-inclusive optimization algorithm exists. The complexity of the problem is such that neither the objective function nor the constraints may be written explicitly in terms of the independent variables. One way to solve such a problem is to break it up into a series of problems and find a method of coordinating the solution of each of the subproblems so as to optimize an overall objective function.

In this study, the problem was decomposed as follows. A master program was defined which had the three interface variables as its decision variables and the system cost (or weight) as the coordinating function. Values for the interface variables were determined using Box's Complex Method (Section 5.4). Subproblems were then defined for the foundation, bent and roofing subsystems (no design procedure was used for the cladding system). These subproblems ~~had as~~ their goal the optimization of subsystem design variables, given specific values for the interface variables. Different functions were used to select optimum values for the subsystem variables. The foundation design function was a "satisficing" one - i.e. find a feasible design; bent member sizes were determined on the basis of a fully stressed design criterion while roof system design was determined on the basis of an exhaustive search with subsystem cost (or weight) as the merit criterion. Figure 5.10 depicts the hierarchy of design problems for the system considered.

5.5 BOX'S COMPLEX METHOD

5.5.1 Description

In this study, Box's Complex Method (4) was used to determine the optimal values of the interface variables x_1, x_2 and x_3. This technique has been successfully applied to other complex structural design problems (15), (16), (17).

Box's method is effectively an improved form of the "simplex method" of Nelder and Mead (22). The complex method has more flexibility than the simplex method because the complex can expand or contract and turn corners in the feasible design space, whereas a simplex maintains regular shape.

Box's method starts by determining a complex of k points, with $k \geq n + 1$. It is assumed that an initial feasible point is available. The remaining k-1 vertices of the complex are generated randomly as follows:

$$\underline{x}_j = \underline{x}_L + r_j(\underline{x}_U - \underline{x}_L)^T, \; j = 1, 2, \ldots\ldots k-1 \tag{5.4}$$

where

$\underline{x}_j$ = j^{th} point in the initial complex;
r_j = uniformly distributed random number over the interval [0,1] generated for the j^{th} point;
$\underline{x}_L$ = vector of lower limits for the independent variables; and
$\underline{x}_U$ = vector of upper limits for the independent variables.

This process ensures that explicit contraints of the form

$$x_{Li} \leq x_i \leq x_{Ui}, \; i = 1, \ldots\ldots\ldots n$$

are satisfied but does not ensure that implicit constraints of the form

$$x_{Li} \leq x_i \leq x_{Ui}, \; i = n + 1, \ldots\ldots\ldots m$$

where

$$x_i = g_i(x_1, x_2, \ldots\ldots\ldots\ldots x_n), \; i = n + 1, \ldots\ldots\ldots m$$

are satisfied.

Except for the case of integer variables, the violation of implicit constraints may be treated by moving the trial point halfway towards the centroid of those points already selected (where the given initial point is included). Ultimately a satisfactory point will be found if the feasible design space is convex.

The objective function is then evaluated for each point in the complex. The point having the worst objective function value is then replaced by a point reflected through the centroid of the remaining points $\alpha \geq 1$ times the distance between the centroid and the worst point on a line connecting the centroid with the worst point. If this new point does not represent an improvement, it is moved halfway towards the centroid of the remaining points to give a new trial point. This procedure is repeated until some constraint is violated.

When an explicit constraint is violated, the value for the offending variable is set to its upper or lower limit, as the case may be. If an implicit constraint is violated, the trial point is moved halfway towards the centroid of the remaining points.

Values recommended for k and α by Box are 2n and 1.3 respectively. For smaller values of k, the complex is liable to collapse into a subspace. Smaller values of α also tend to lead to a collapse of the complex.

Box suggested the use of only one stopping criterion, it being that the program shall stop itself when five consecutive equal (within ε of each other) function evaluations have occurred. For checking to see if a global optimum has been attained, he suggested that the search be conducted several times, each time using a different starting complex. Convergence to the same solution in each case infers that the global optimum has been reached.

For this study, only explicit constraints were involved. The most costly part of the optimization procedure was the evaluation of the objective function for each new trial point. Several modifications were made to Box's method to account for the integer nature of two of the independent variables and the expense of evaluating the objective function.

In determining a new trial point , x_1 was first treated as continuous and then rounded off to the nearest integer for purposes of checking the constraints and for evaluation of the objective function. A slightly different procedure was required for x_2, number of panels, because of it being constrained to assume even integer values. Rather than just examine one trial point corresponding to the even integer value of x_2 closest to the continuous approximation, two trial points (x_2^1, x_2^2) were examined and the point having best objective function value selected. The other point considered corresponded to $x_2^2 = x_2^1 - 2$, where x_2^1 was the even integer value closest to the continuous value of x_2 generated by Box's method. This approach of examining two values for x_2 kept the complex from collapsing onto one value of x_2 for all points in the complex. This tendency to collapse was noted in preliminary runs, and hence the procedure described.

Modifications to Box's method were made as follows

(i) If more than one explicit constraint was violated for a trial point, the reflection factor α was halved.

(ii) Instead of continuously halving α, if no improvement in the objective function value was found when $\alpha = \alpha/2$, the centroid was then used. If the centroid still did not represent an improvement, then a point halfway between the centroid and the best point in the complex was evaluated. If no improvement resulted, the search was terminated.

(iii) The user had the option to use either one or two search cycles for each computer run. If one cycle was selected, then the above procedure was used, with the search being terminated by one of three cases:

a) an improved point over the worst point could not be found;

b) the complex had collapsed into a region such that

$$\frac{f(\underline{x}_W) - f(\underline{x}_B)}{f(\underline{x}_B)} \leq \text{TOL}$$

where

$f(\underline{x}_W)$ = objective function value for worst point in complex.

$f(\underline{x}_B)$ = objective function value for best point in complex.

TOL = tolerance value set by user (0.005 used for this study).

c) the maximum number of iterations (NIT) is reached.

For use of the two cycle option, the user is required to input the maximum number of iterations for each cycle, the size of the complex for each cycle, the initial point for the first cycle and the random number starting point for each cycle. The best point from the first cycle is used as the initial point for the second cycle. Use of two cycles automatically provides a check on whether the first cycle has converged to the global optimum and also helps avoid the problem of the search procedure collapsing into a subspace of the total design space.

Other modifications to Box's method have been examined in the literature. For example, Lipson and Agrawal (15) and Lipson and Gwin (16) in their work compared a new trial point with the second worst point in the complex. If the function value was less and all the implicit constraints were satisfied then this point was taken as the improvement and the next iteration was then initiated. If function value was greater than the second worst point, or if the implicit constraints were not satisfied, a new point was selected halfway towards the centroid. If this new point resulted in no improvement, it was replaced by the centroid. If the function value of the centroid was still greater than the second worst point in the complex, it was replaced by a new point generated randomly. These modifications were not considered for the study reported herein.

5.5.2 Behaviour of Box's Method

Several runs were made to study the behaviour of Box's method with respect to varying complex size, k, reflection factor, α, number of cycles and initial starting point. The criterion of weight optimization was arbitrarily selected for these runs. So that a graphical display of the method's behaviour could be made, the variable x_2, number of panels was set at 14. Results are summarized in Figure 5.11 through 5.22 and in Tables 5.1 and 5.2.

The starting point provided by the user is circled on each figure. Trial points are primed in order of sequence for those cases where several points had to be examined before improvement could be made for a given iteration. When the centroid was used as a trial point, it is indicated by a triple prime. If the centroid still resulted in no improvement, a new point generated between the centroid and the best point in the complex was examined and is denoted by the quadruple prime.

Subscripts on trial points refer to cycle number.[1] Objective function values for points in the initial complex are given in parentheses.

The results of these runs may be described briefly as follows:

(a) Influence of Complex Size

Figures 5.11, 5.16 and 5.21 reflect the influence of complex size on the search procedure. When $k < 2n$ (Figure 5.11), the complex collapsed onto a line. Even when the initial starting was changed (Figure 5.12), the complex still collapsed onto a line. Increasing k to k = 2 n (Figure 5.16) prevented the complex from collapsing onto a line. For k > 2 n (Figure 5.21) the complex collapsed onto a line after several iterations.

(b) Influence of Starting Point

Figures 5.12 and 5.18 reflect the influence of starting point on the search procedure. Results obtained from this search can be compared with Figures 5.11 and 5.14 respectively, which have the same starting complex except for the starting point input by the user. While the movement of the complex caused by the change in starting point appears significant in visual terms, in terms of the optimum weight the change is insignificant. The optimum objective function value for the search shown in Figure 5.12 was 0.22% poorer than for that of Figure 5.11 while the search shown in Figure 5.18 resulted in an optimum some 0.67% less than that for Figure 5.17.

(c) Influence of Reflection Factor α

Two groups of runs were made in order to examine the influence of α on the search procedure. They consist of runs 1w, 9w and 10w for k equal to 3 and 5w, 11w and 12w for k equal to 4. Three value of α were examined: $\alpha = 0.9$, 1.3 and 1.7. For α equal to 0.9, the complex collapsed inside the initial complex for run 9w and inside the initial complex for the second cycle of run 11w. For run 9w, the optimum found was 0.58 percent greater than the optimum of run 1w while for 11w, the optimum found was 0.73 percent greater than the optimum of run 5w. For α equal to 1.7, the complex collapsed on the boundary of the design space for run 10w but outside the initial complex. The optimum for this run was some 0.28 percent less than for run 1w. For run 12w, the complex did not collapse but converged to a region outside the initial complex and yielded an optimum some 0.09 percent greater than for run 5w.

(d) Influence of number of cycles

To assess the effectiveness of using a two cycle search procedure, several runs were made. Results are described for runs 4w to 6w (Figures 5.15, 5.17 and 5.22). These runs were made for the same constraints as used for runs 1w to 3w. The total number of iterations was maintained constant at 18, but divided into 10 and 8 for the first and second cycles respectively. On the basis of the runs made, it would seem that a one cycle search procedure is more effective than a two cycle procedure (compare final results of runs 1w to 3w with 4w to 6w). However, later experience with the cost optimization runs seemed to indicate that a two cycle approach was more effective in locating the optimum and/or avoiding local optima and premature collapse of the complex.

5.6 WEIGHT OPTIMIZATION USING BOX'S COMPLEX METHOD

Tables 5.1 and 5.2 summarize the results of several runs made with weight minimization as the objective function. Figure 5.23 depicts the nature of the design space when x_2, number of panels, was set equal to 14. The 14 panel case corresponds to a roofing system having no joists and 22 gauge decking. As seen from this figure, there are many local optima, mainly because of the discrete member spectrum used in the design process. The lowest weight solution was found for run number 3w with a weight of 0.004545 ton/ ft^2. The 0.00475 contour shown in Figure 5.23 is within 4.5 percent of the optimal weight solution and indicates that a broad range of depth to span ratio yield near optimal results. Such is not the case for the variable bent spacing. As seen from Table 5.2, a one cycle search procedure yielded the lowest weight configuration.

5.7 COST OPTIMIZATION USING BOX'S COMPLEX METHOD

Several runs were made using minimim cost as the objective function. Both cost models were examined. Results are summarized in Tables 5.3 through 5.8 and in Figures 5.24 through 5.26.

When cost was computed according to the general cost model, invariably x_2 equal to 12 was selected as the optimum number of panels, except in those cases where the complex collapsed into a subspace. In all cases, however, the need for joists was eliminated. For the 12 panel truss configuration, the roofing system was comprised of purlins and 20 gauge decking. In general, a 2 cycle search procedure was more effective than a single cycle.

Observations made on the basis of the results presented are summarized as follows:

1. Run 12 (Table 5.5) yielded the optimum general cost model solution at a cost of \$6.5922/ft^2. At 43.33 feet, the optimum bent spacing is considerably higher than the minimum weight configuration. The optimum cost configuration

using Box's method was some $0.06261/ft^2 less than the best exhaustive search result.

2. Run 1 (Table 5.7) yielded the optimum weight related cost model solution cost of $6.11658/ft^2 which is some $0.03775/ft^2 less than the best exhaustive search result.
3. For the general cost model results, the search procedure in runs 1, 3, 4 and 11 collapsed into local minimum number 4 on Figure 5.26. Use of a two cycle procedure failed to push it toward the apparent global minimum located in region 3, Figure 5.26.
4. Between the local minima denoted 3 and 4, Figure 5.26 is a saddle point. The complex for the first cycle of run 12 collapsed on this saddle. The second cycle pushed the complex into region 4.
5. The $6.90 cost contour which is approximately within 5 percent of the optimal cost encloses a broad range of configurations both in terms of depth to span ratio and bent spacing.
6. Two runs (21, 22) were made to examine the behaviour of the search procedure when the boundaries of the design space were tightened. While the two cycle procedure gave better results than a one cycle procedure, no significant improvement in the results was noted as compared to those obtained from a search over a larger design space.
7. The optimum values computed on the basis of the general cost model ranged from a low of $6.59222 to a high of $6.80532 or a 3.2 percent variation for the 25 runs made. Results

from 21 out of 25 of the runs were within 1.6 percent of the optimum value. Optimum values for the weight related cost model results varied from a low of $6.11658 to a high of 6.31801, which corresponds to a variation of 3.3 percent for the 8 runs made.

8. Bssed on the experience gained with the search procedure to date, it would appear that the best strategy for using it is to make a minimum of two computer runs, using two cycles and a different random number starting point for each run.

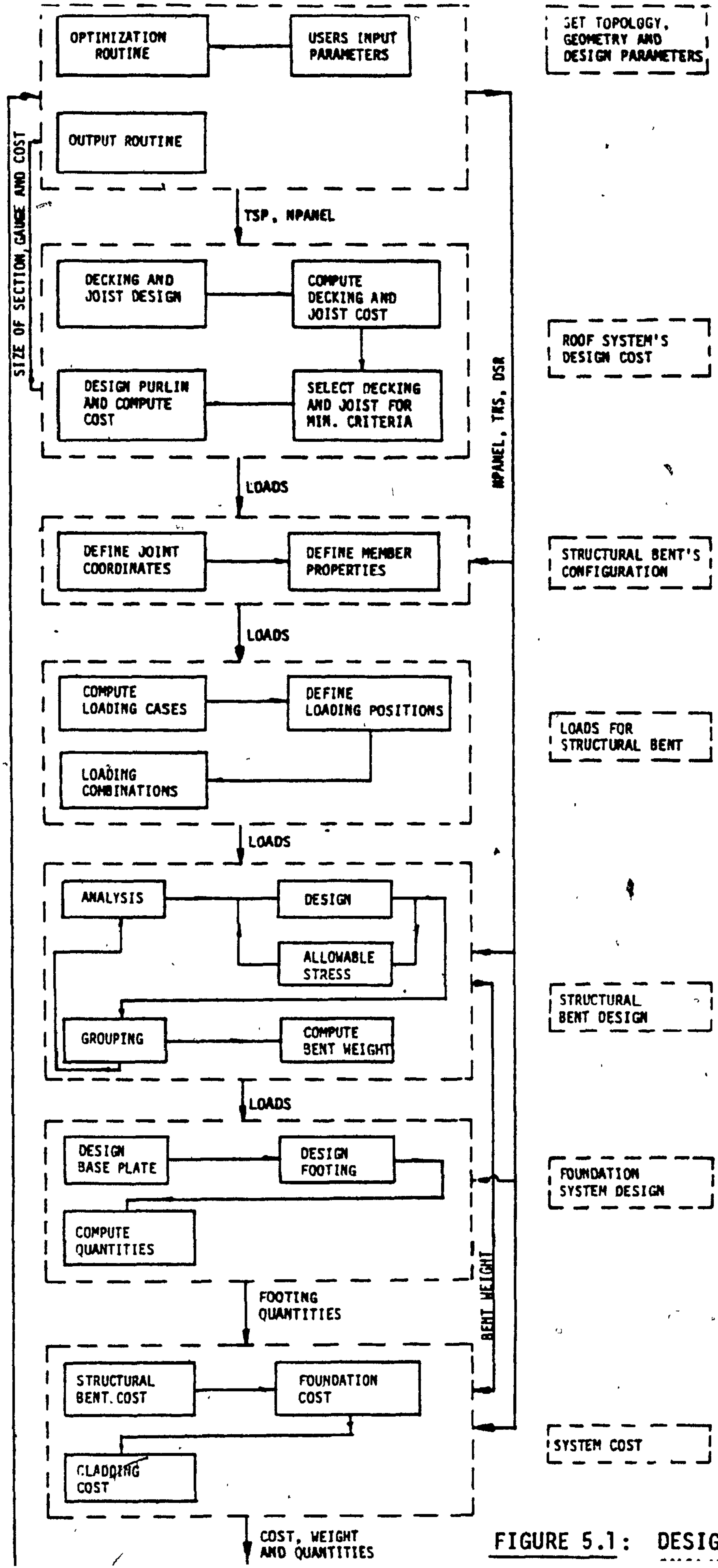
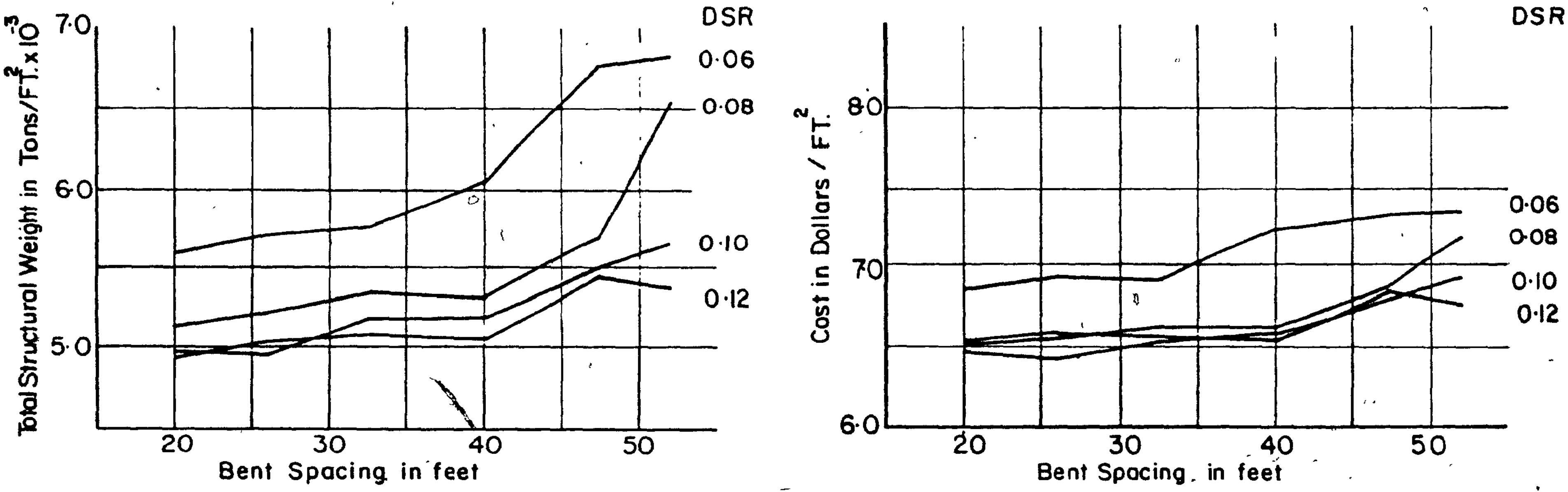
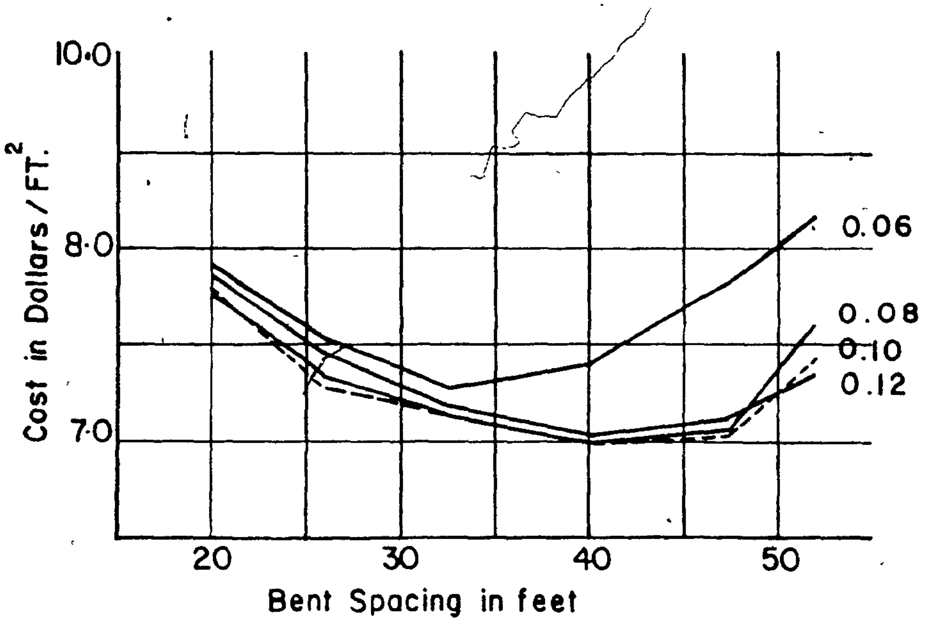


FIGURE 5.1: DESIGN COST



(a) TOTAL WEIGHT

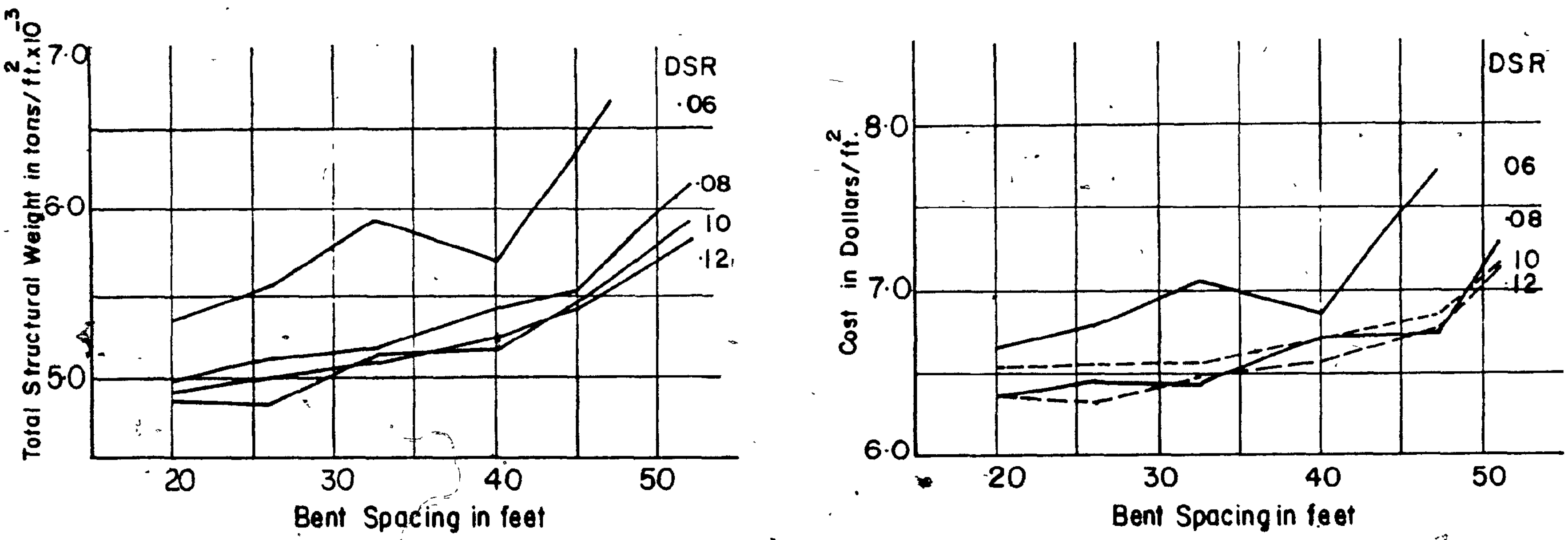
(b) WEIGHT RELATED COST



(c) GENERAL COST

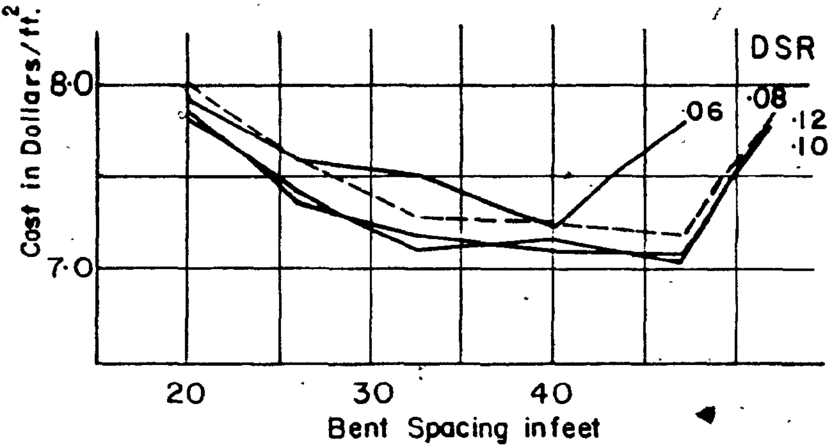
(number of truss panel = 8)

Fig.5·2-VARIATION OF SYSTEM PERFORMANCE MEASURES WITH BENT SPACING.



(a) TOTAL WEIGHT

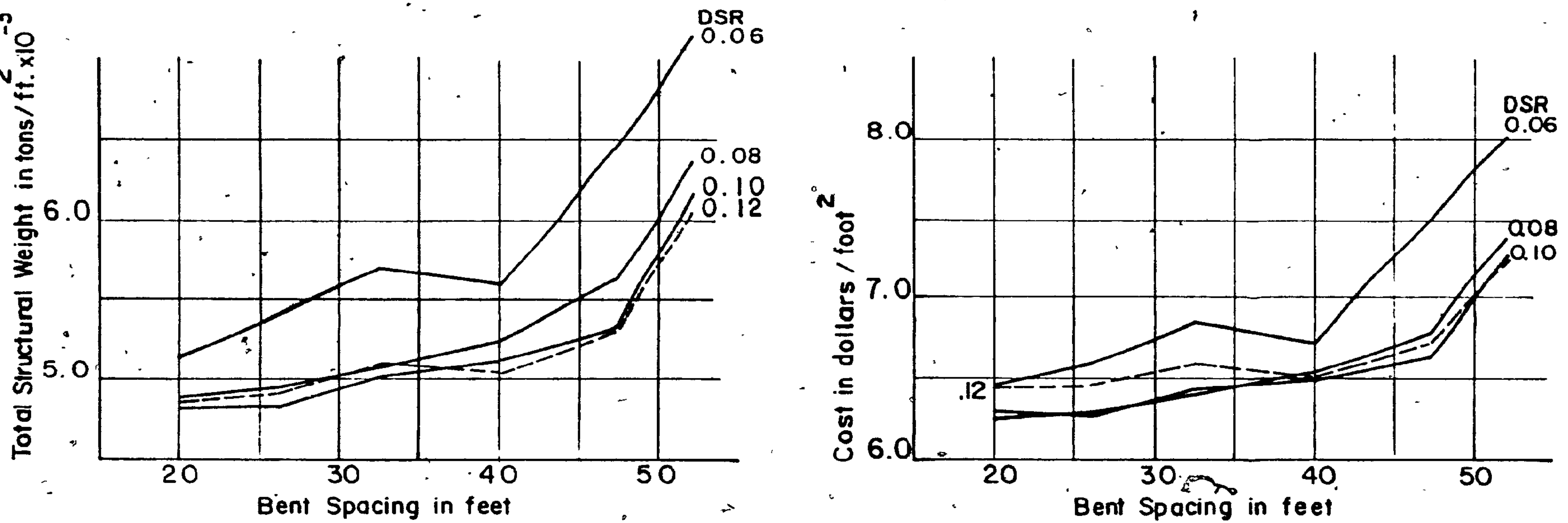
(b) WEIGHT RELATED COST



(c) GENERAL COST

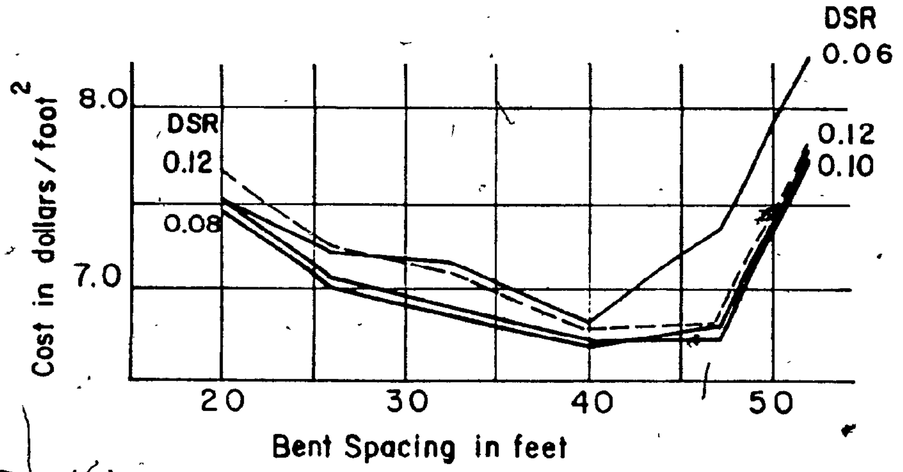
(number of truss panel = 10) ,

Fig. 5.3 - VARIATION OF SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) TOTAL WEIGHT

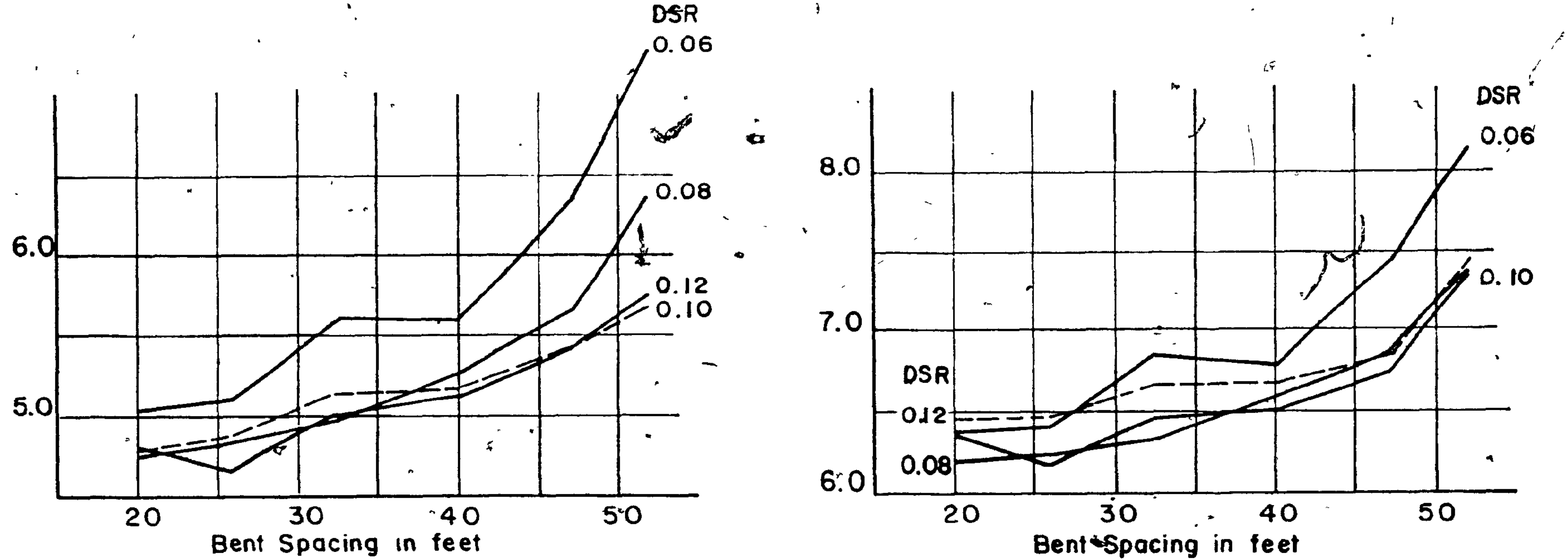
(b) WEIGHT RELATED COST



(c) GENERAL COST

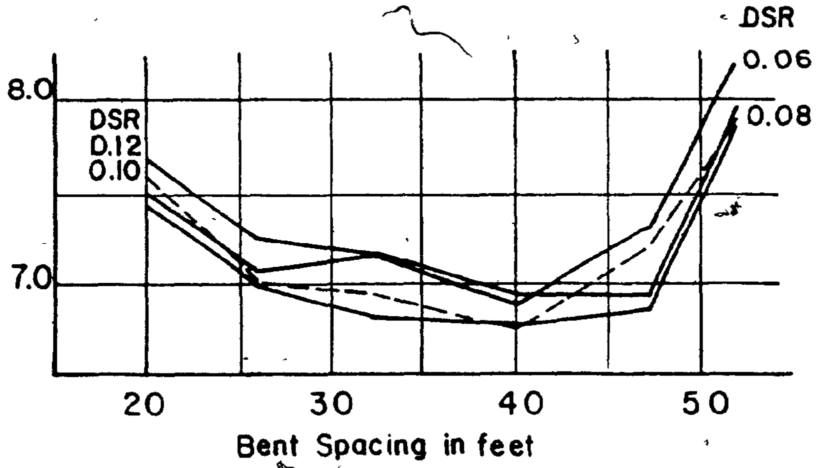
(Number of truss panels =12)

FIG,5.4 VARIATION OF SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) TOTAL WEIGHT

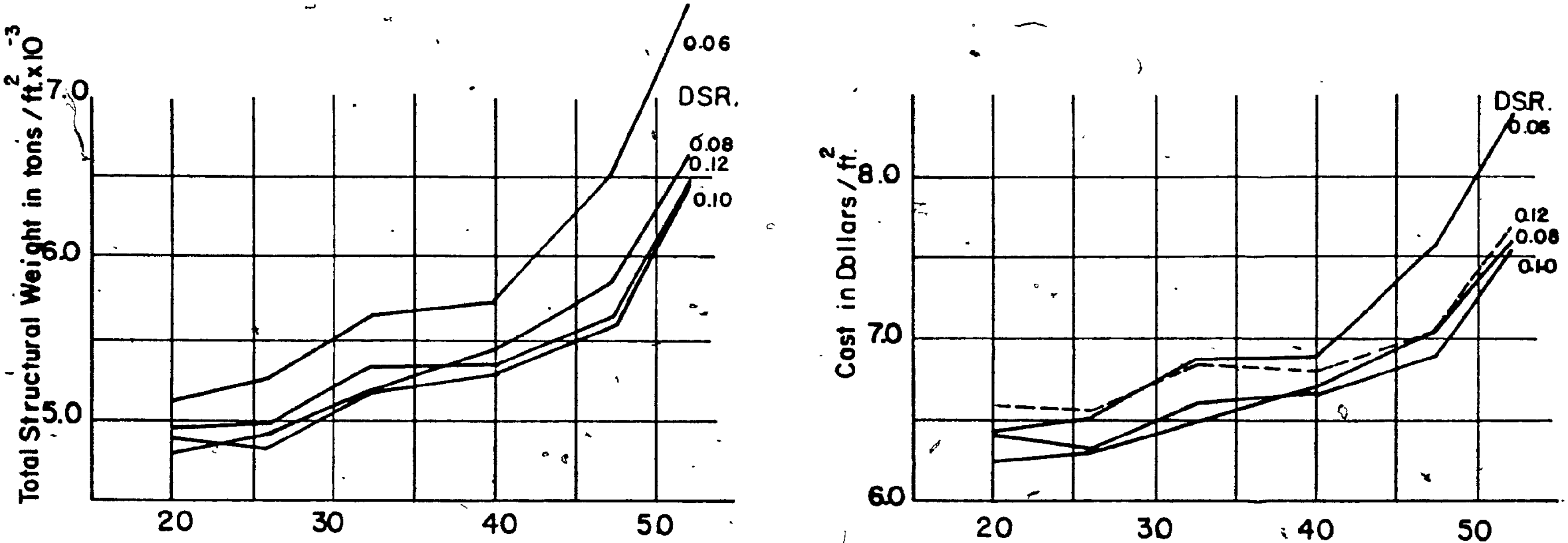
(b) WEIGHT RELATED COST



(c) GENERAL COST

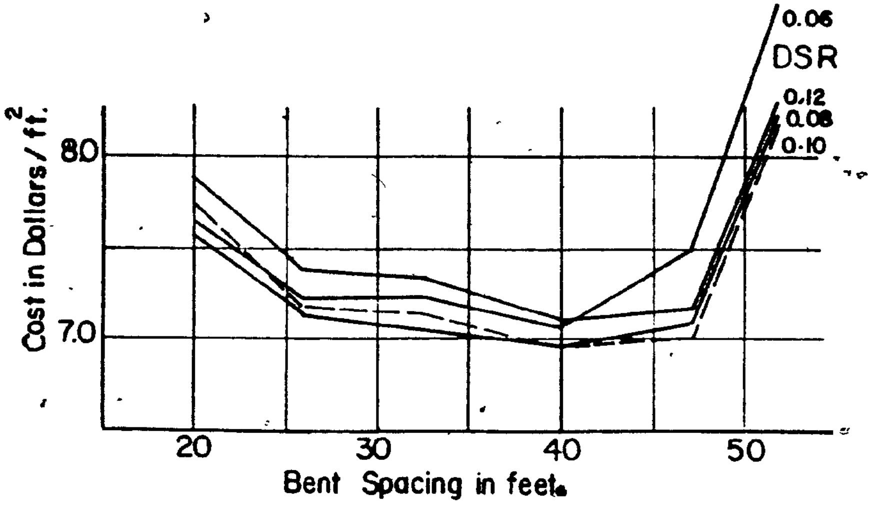
(Number of truss panels = 14)

FIG.5·5 VARIATION OF SYSTEM PERFORMANCE MEASURES WITH BENT SPACING



(a) TOTAL WEIGHT.

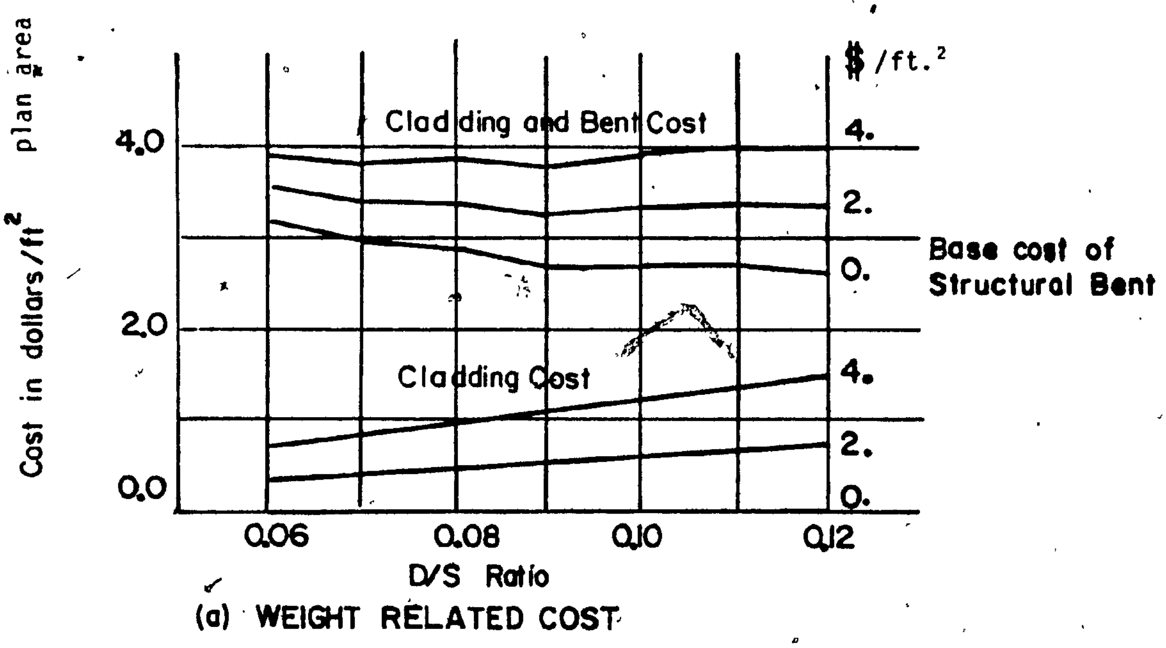
(b) WEIGHT RELATED COST.



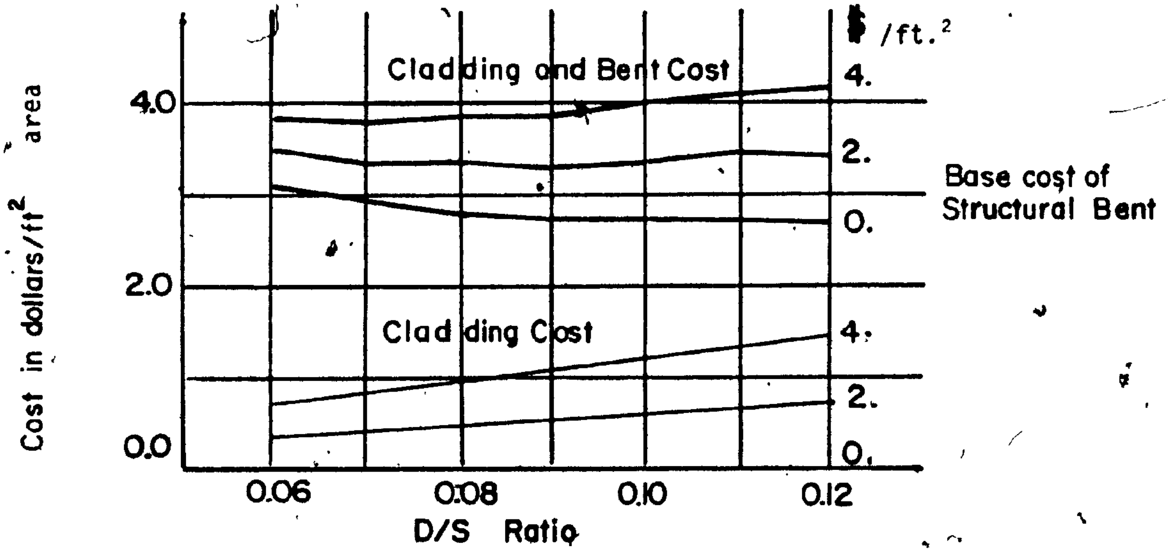
(c) GENERAL COST

(number of truss panels = 16)

Fig. 5.6 - VARIATION OF SYSTEM PERFORMANCE MEASURES WITH BENT SPACING.

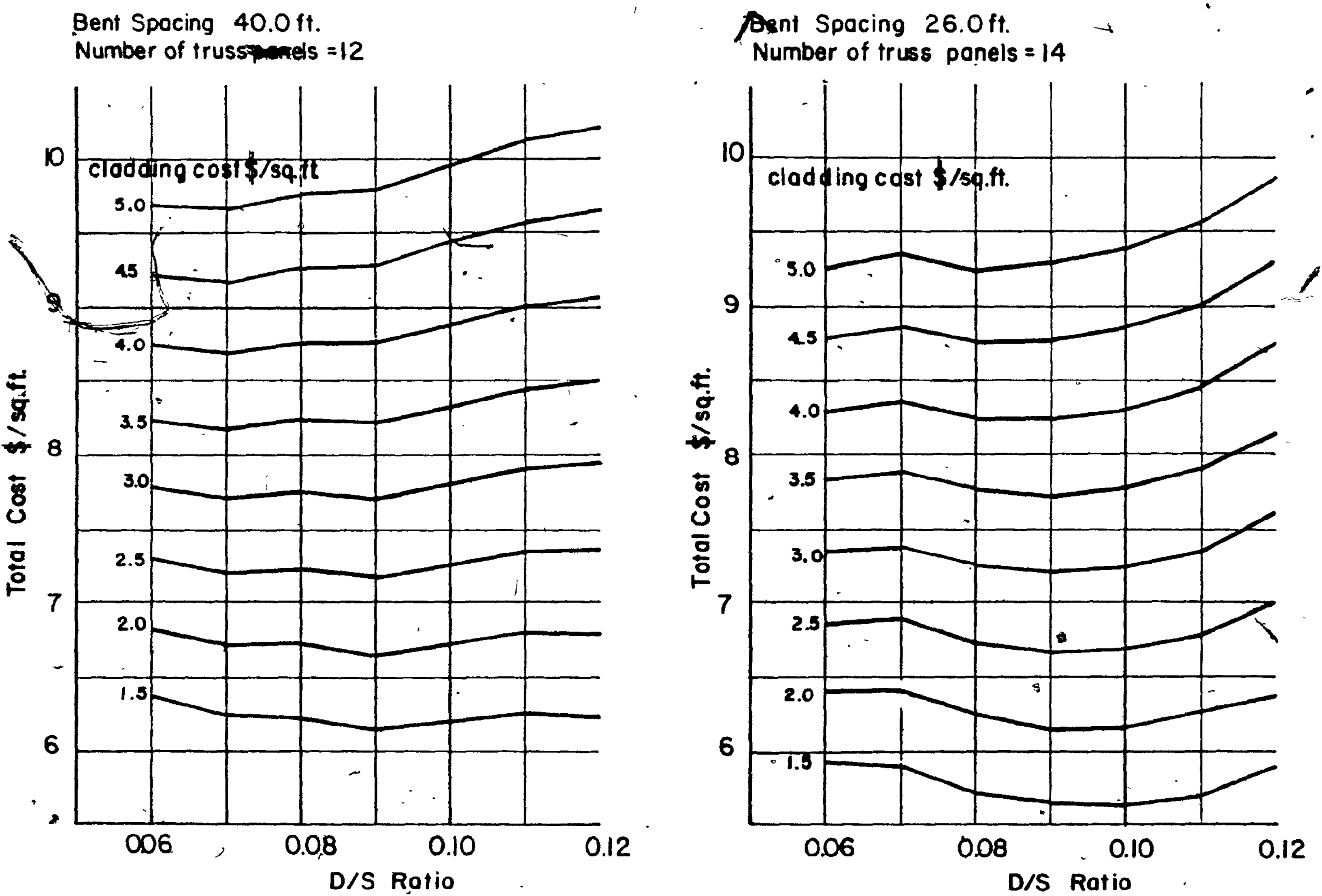


(a) WEIGHT RELATED COST



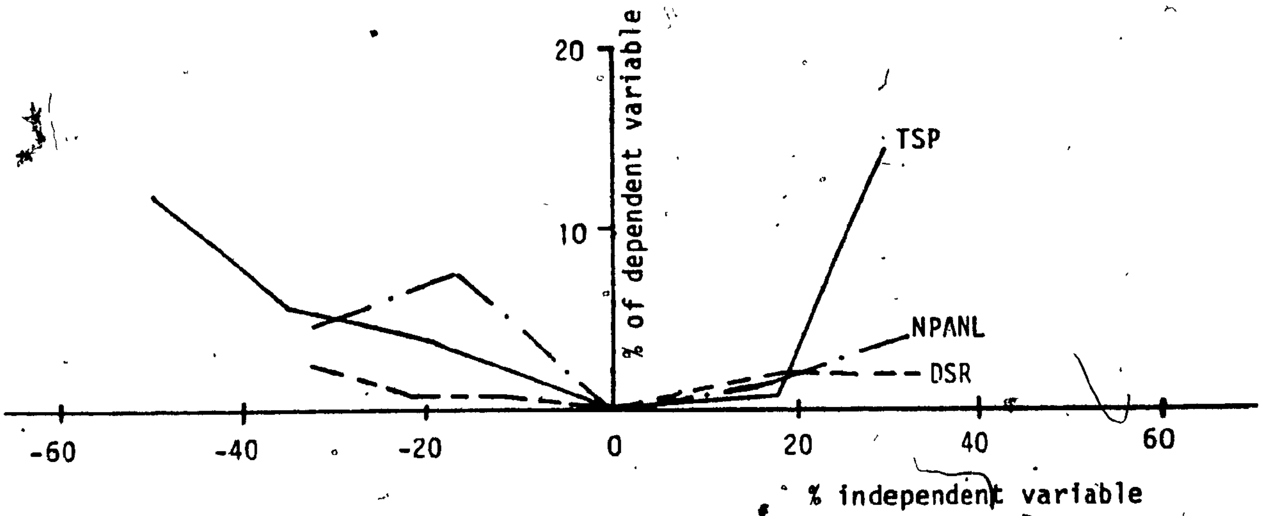
(b) GENERAL COST (Cladding cost \$/ft² cladding area)

Fig.5.7- IMPACT OF CLADDING COST ON THE LEAST COST DEPTH TO SPAN RATIO



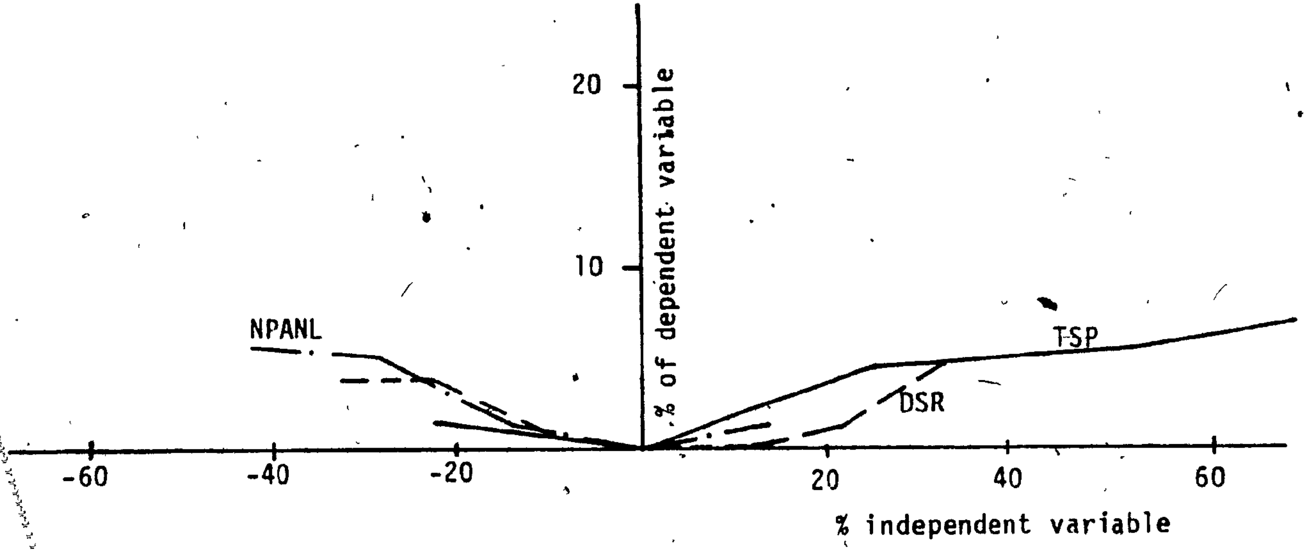
(a) GENERAL COST MODEL* (b) WEIGHT RELATED COST MODEL

Fig.5.8- STUDY OF THE EFFECT OF CLADDING COST FOR OPTIMAL CASES.



(TSP = 40.0'; DSR = 0.09; NPANL = 12)

(a) GENERAL COST MODEL



(TSP = 26.0'; DSR = 0.09; NPANL =14)

(b) WEIGHT RELATED COST MODEL

FIGURE 5.9: SENSITIVITY OF COST FUNCTION TO CHANGES IN DESIGN CONFIGURATION

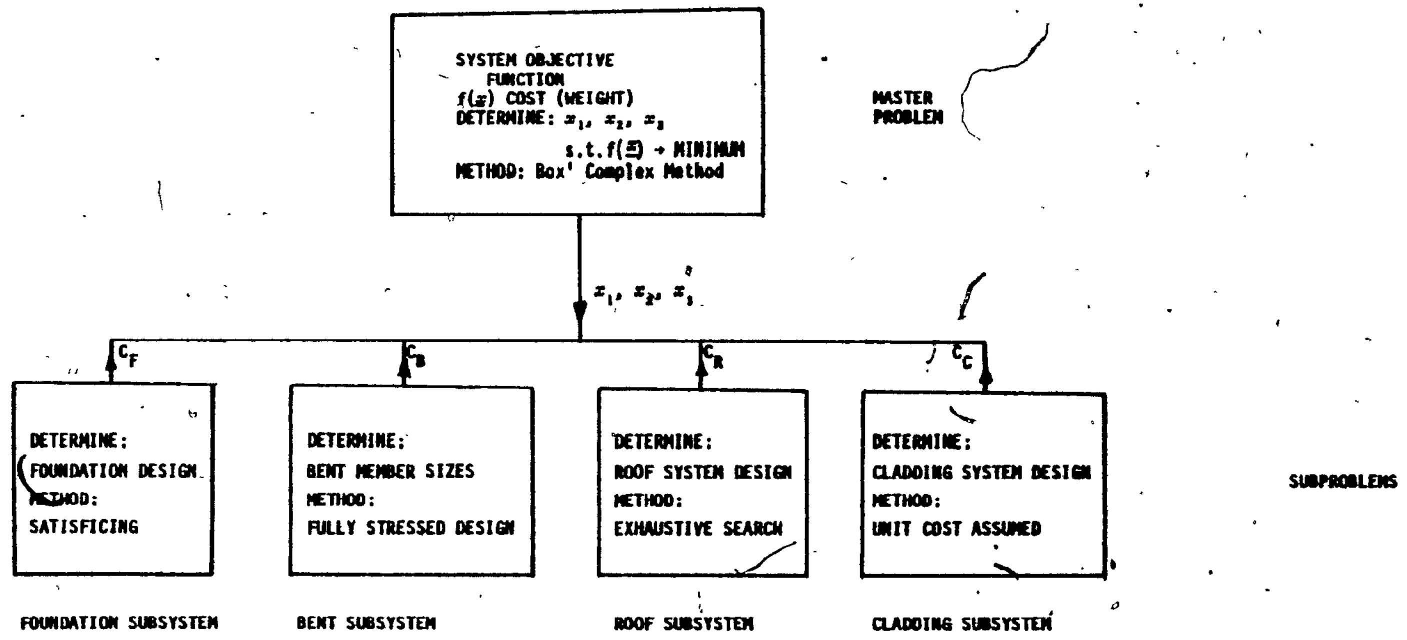


FIGURE 5.10: HIERARCHY OF OPTIMIZATION PROBLEMS FOR SYSTEM DESIGN

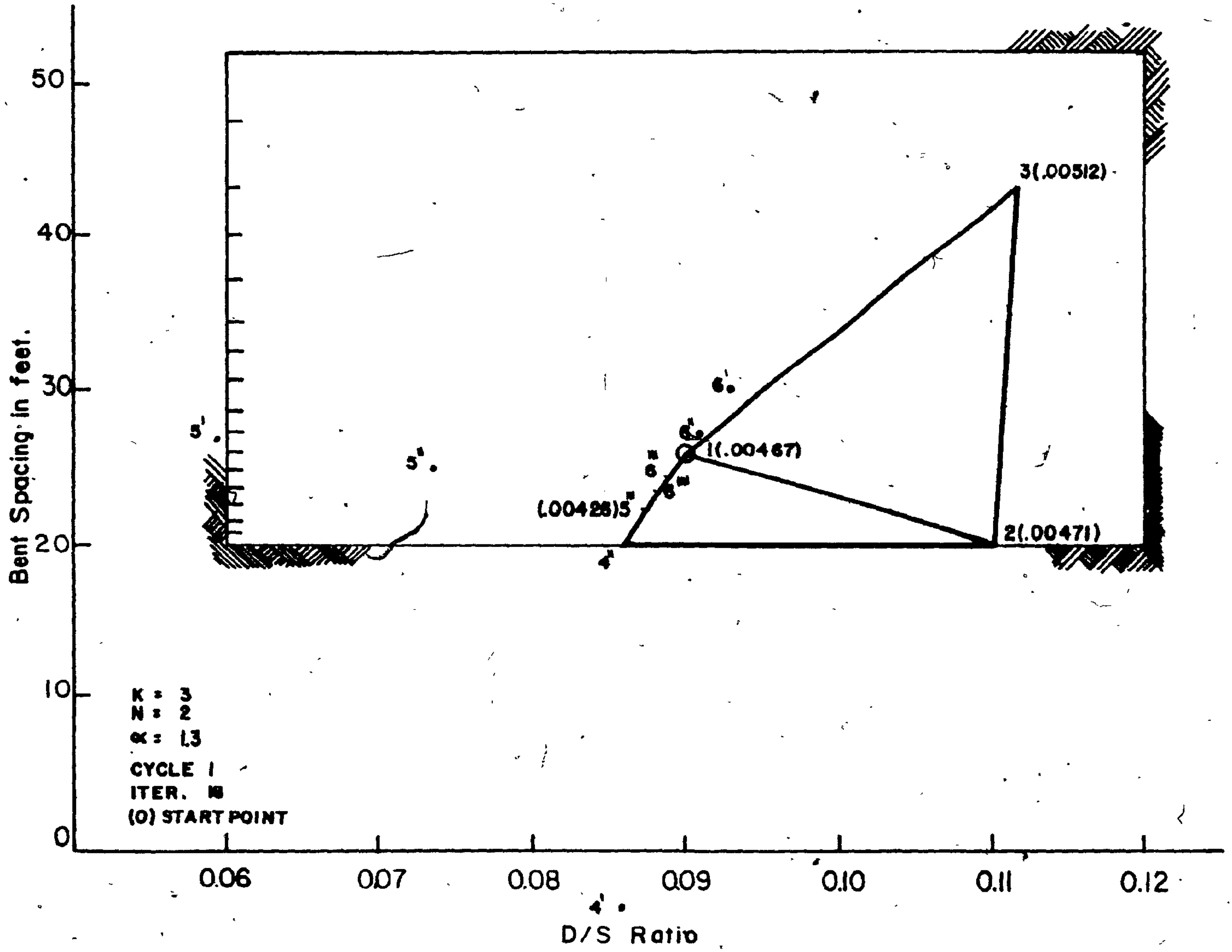


Fig. 5.11- BEHAVIOUR OF BOX METHOD - RUN I W.

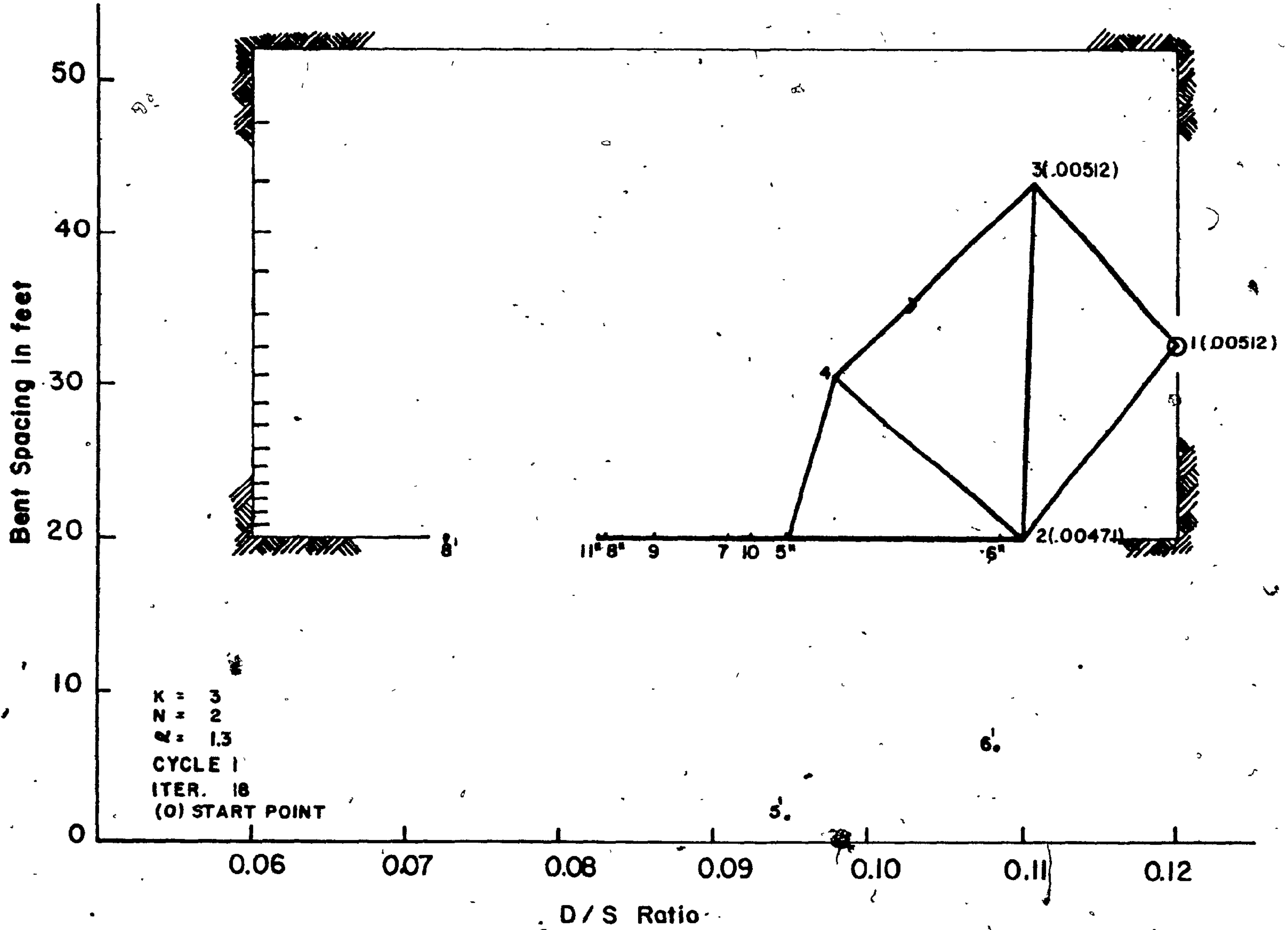


Fig. 5.12-BEHAVIOUR OF BOX METHOD - RUN 7W

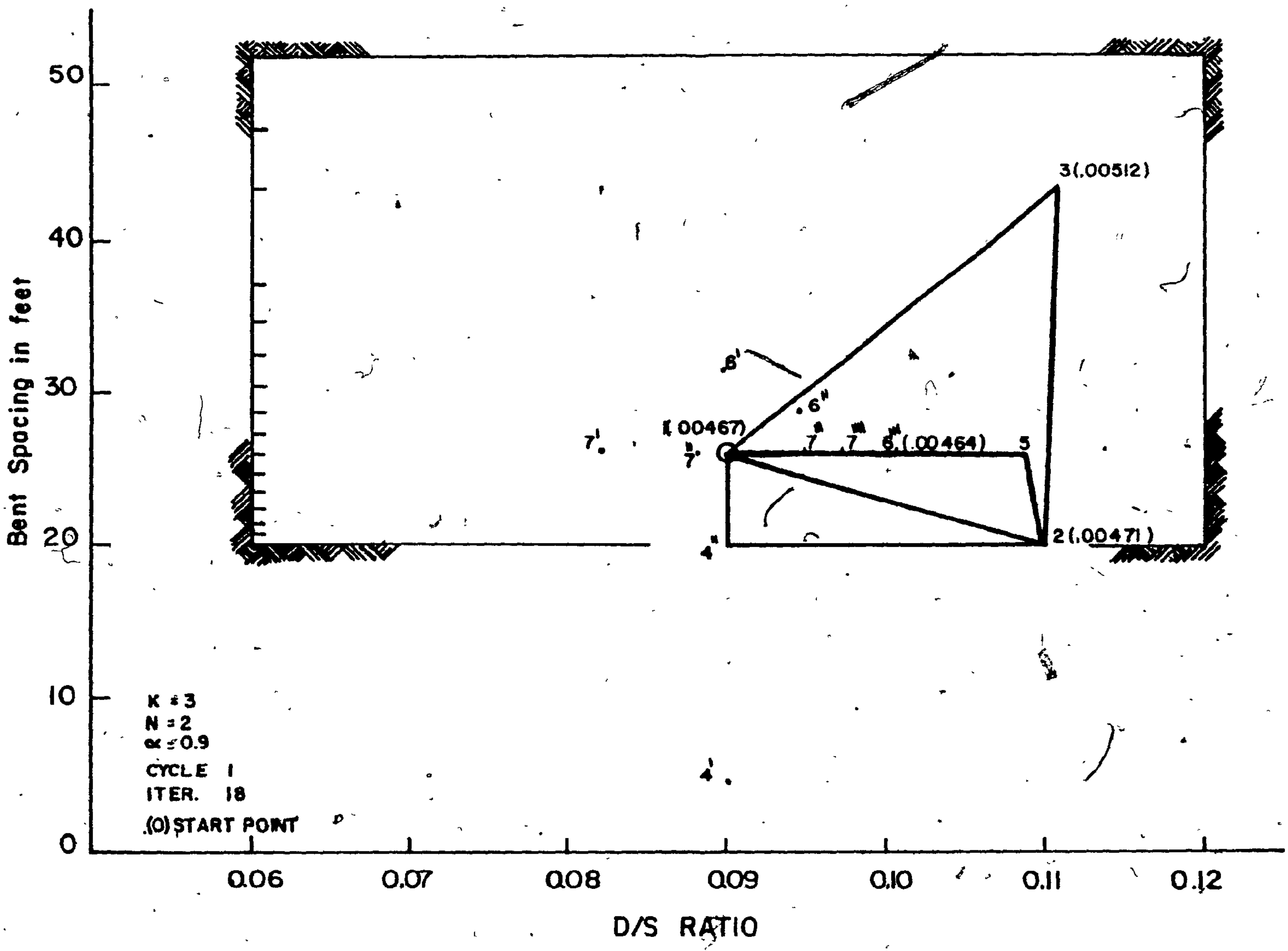


Fig.5.13 - BEHAVIOUR OF BOX METHOD. - RUN 9W

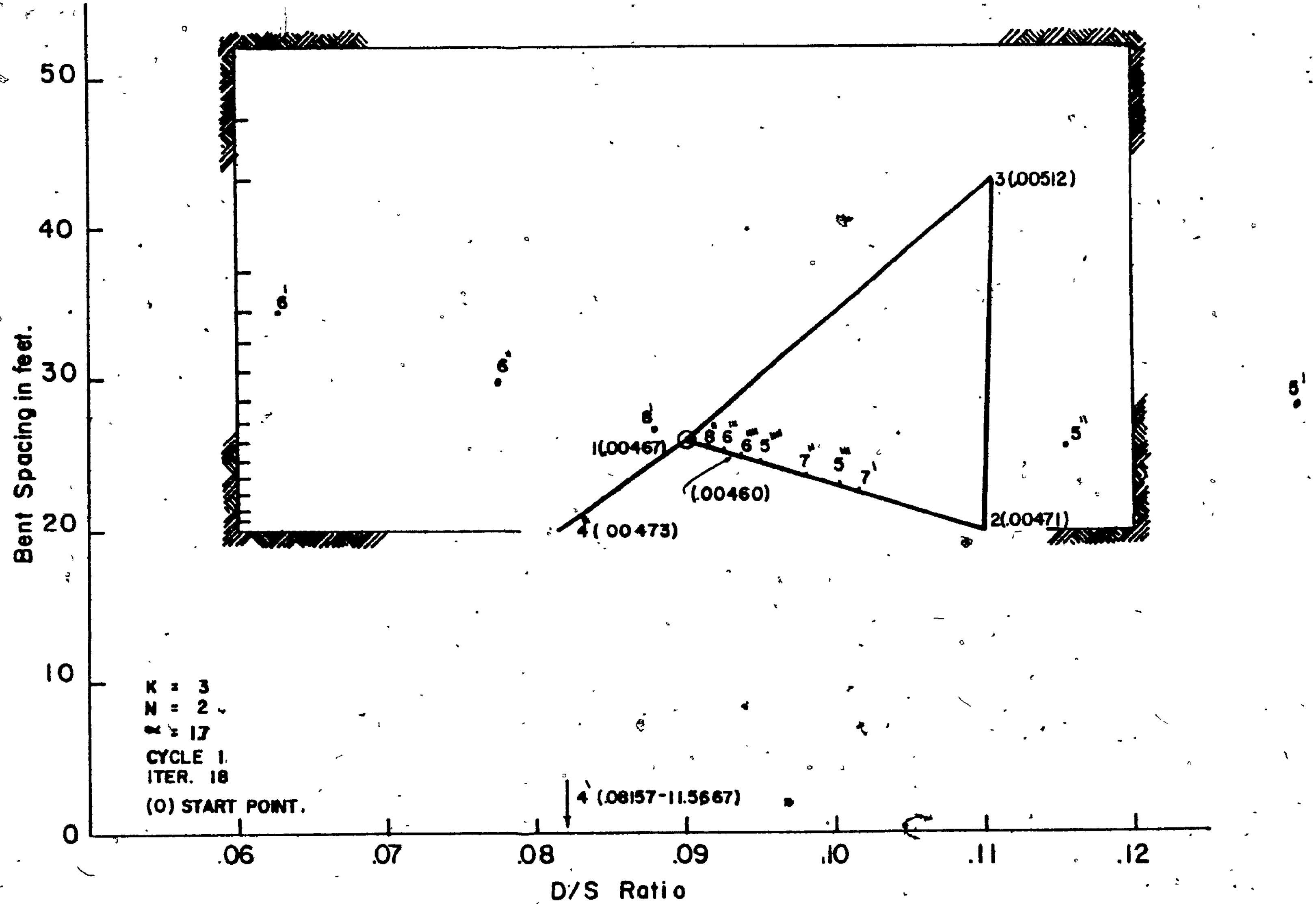


Fig.514 -BEHAVIOUR OF BOX METHOD -RUN IOW

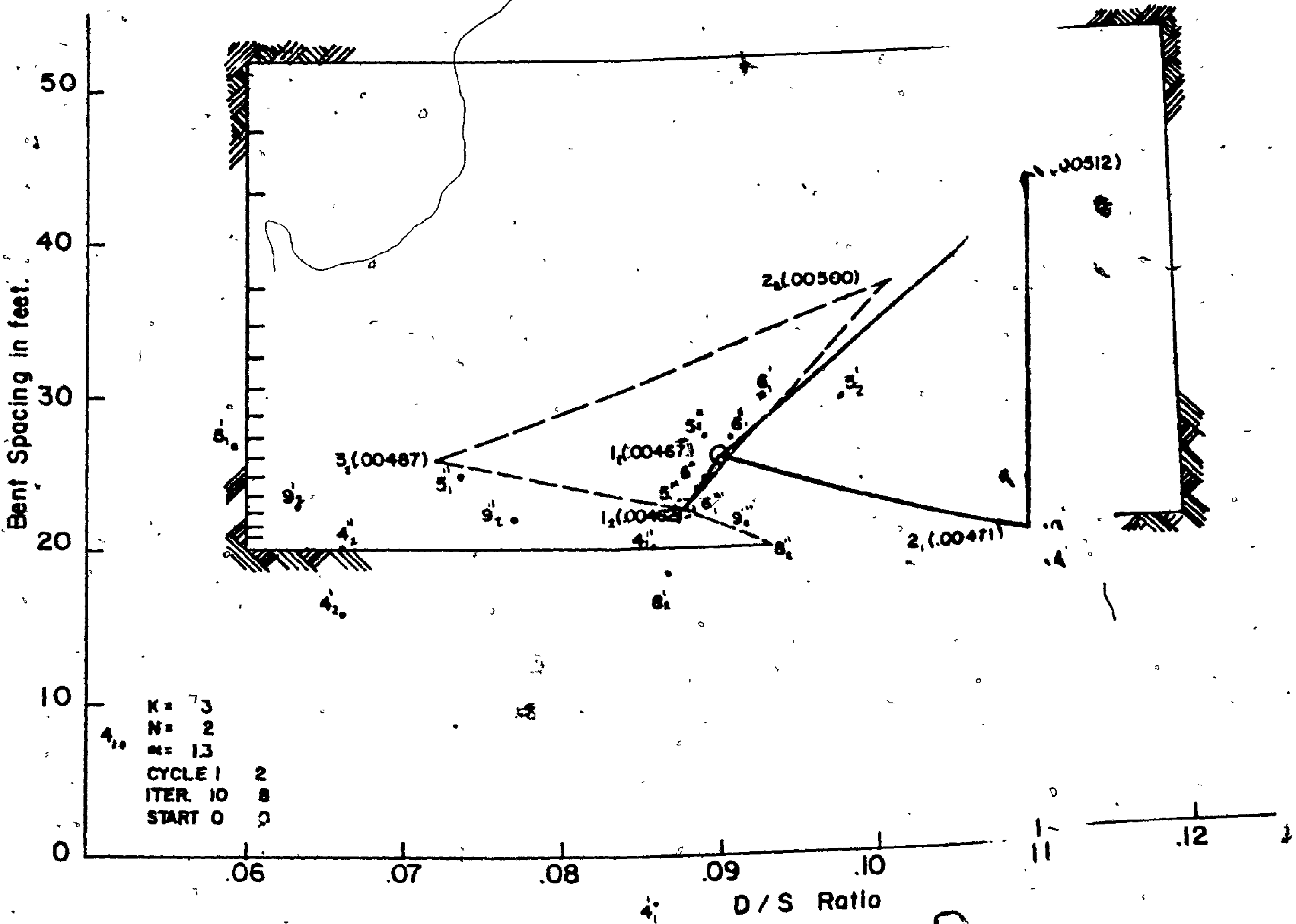


Fig. 5.15 - BEHAVIOUR OF BOX METHOD - RUN 4W

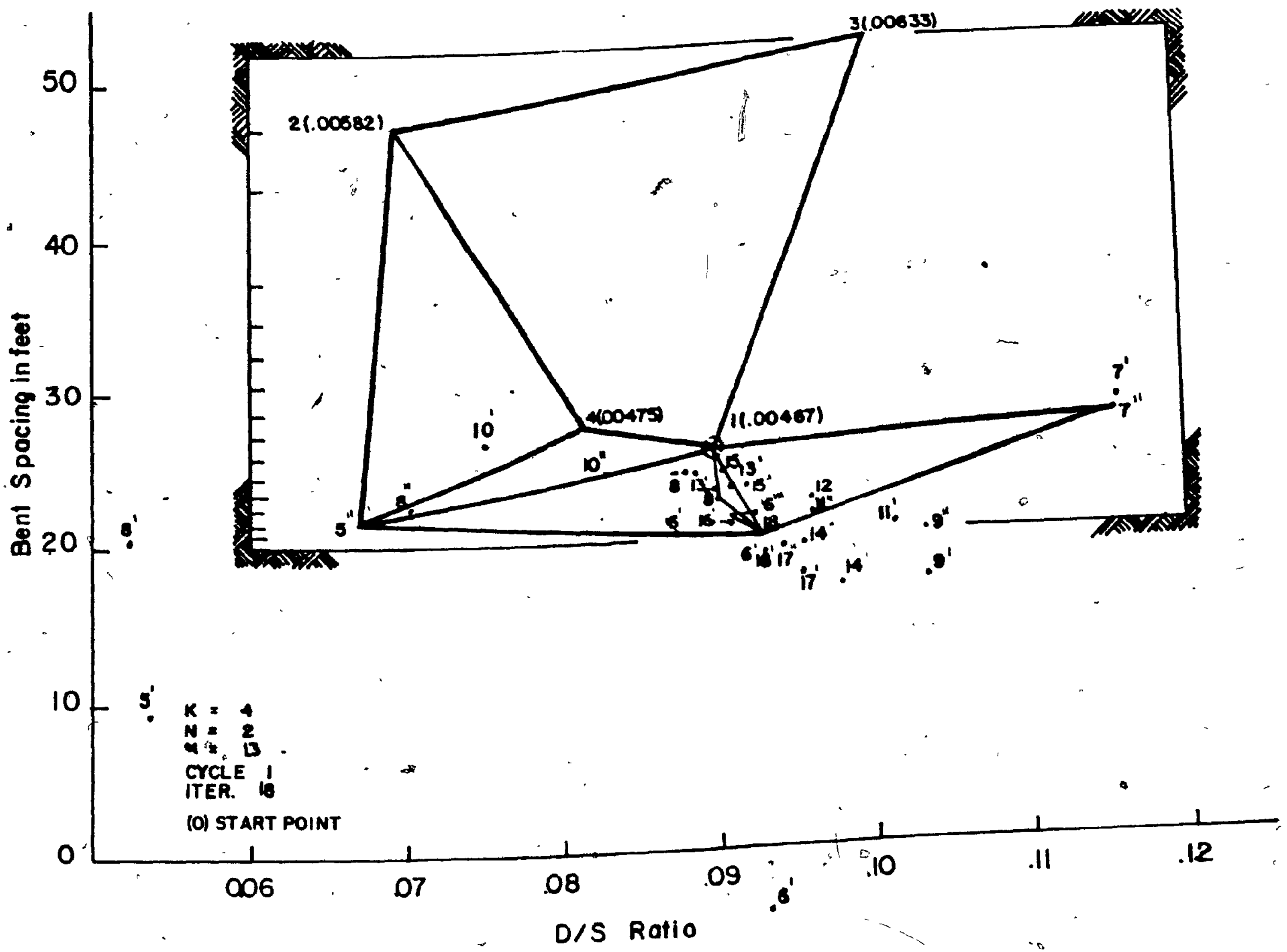


Fig.5.16 -BEHAVIOUR OF BOX METHOD - RUN 2 W

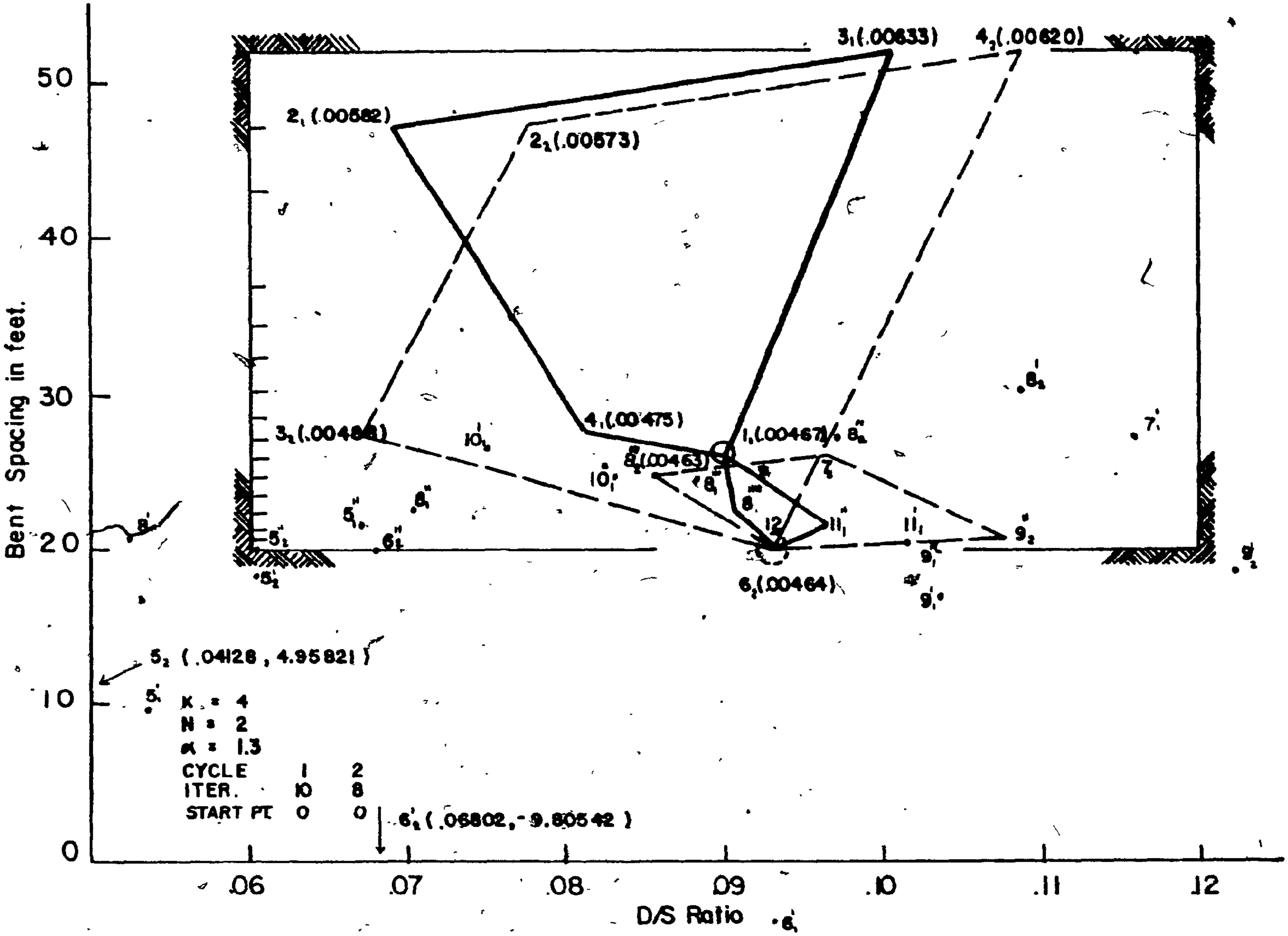


Fig.5.17 - BEHAVIOUR OF BOX METHOD - RUN 5 W

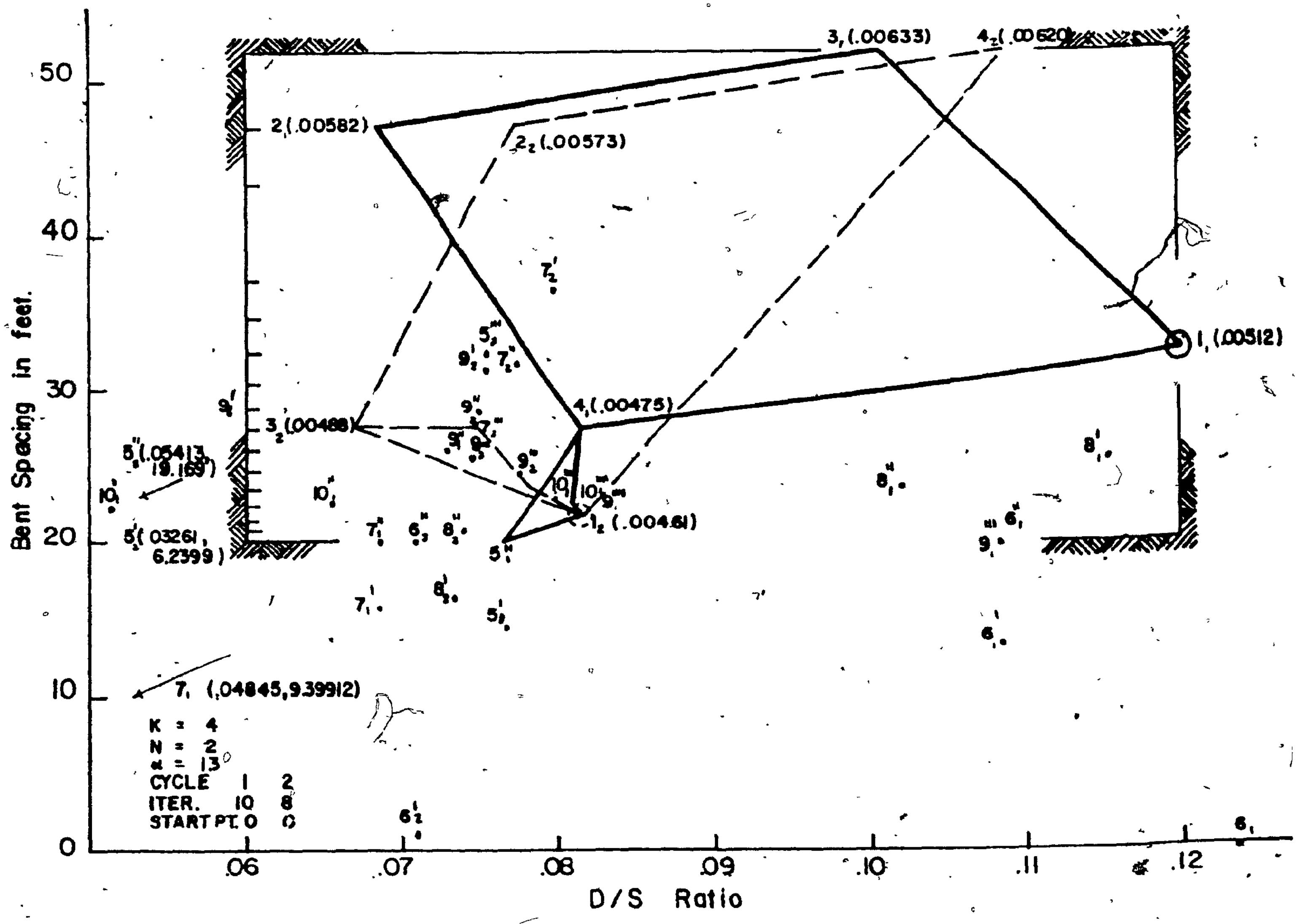


Fig.5.18 -BEHAVIOUR OF BOX METHOD - RUN 14W

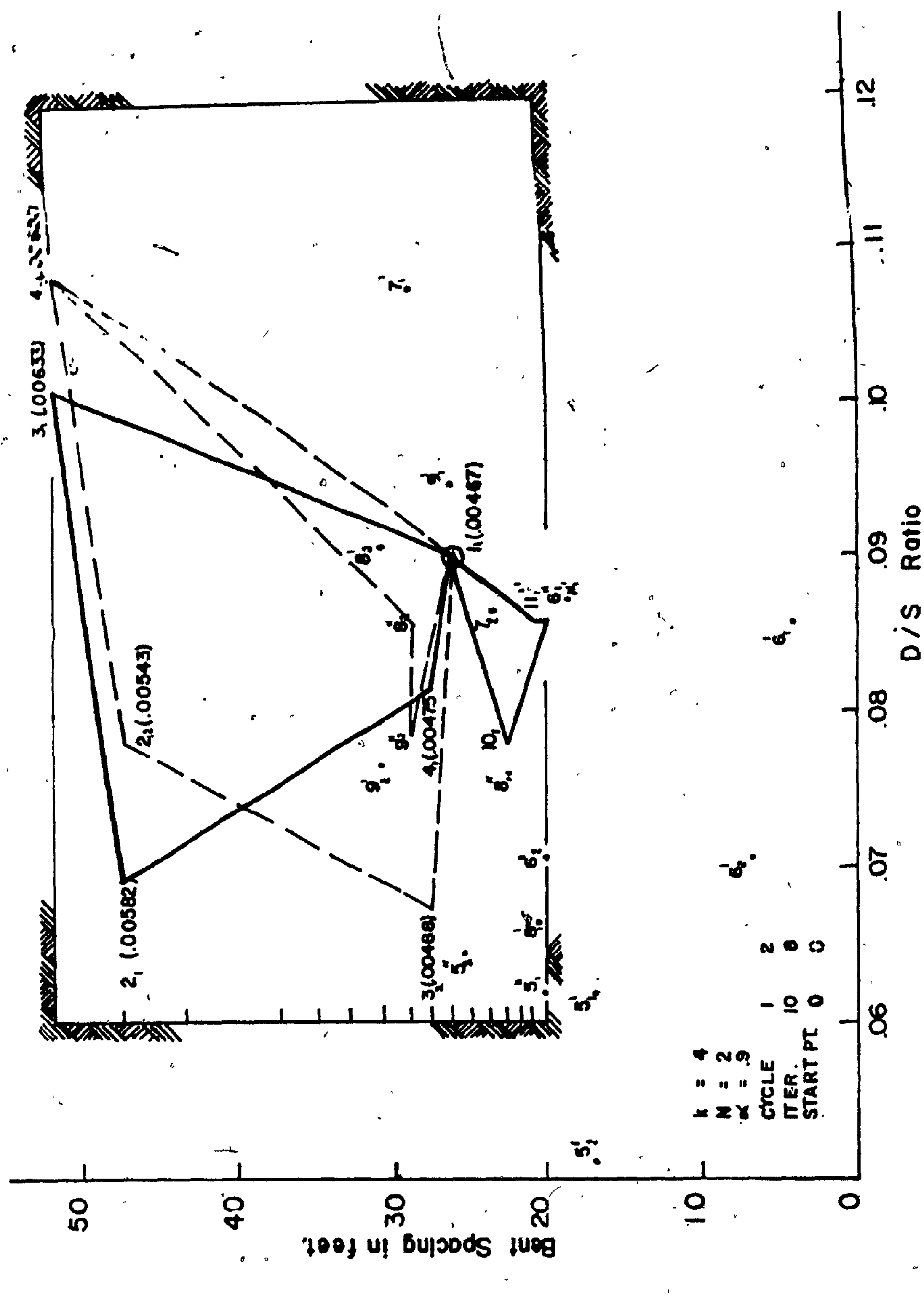


Fig. 5.19 -BEHAVIOUR OF BOX METHOD - RUN 11 W

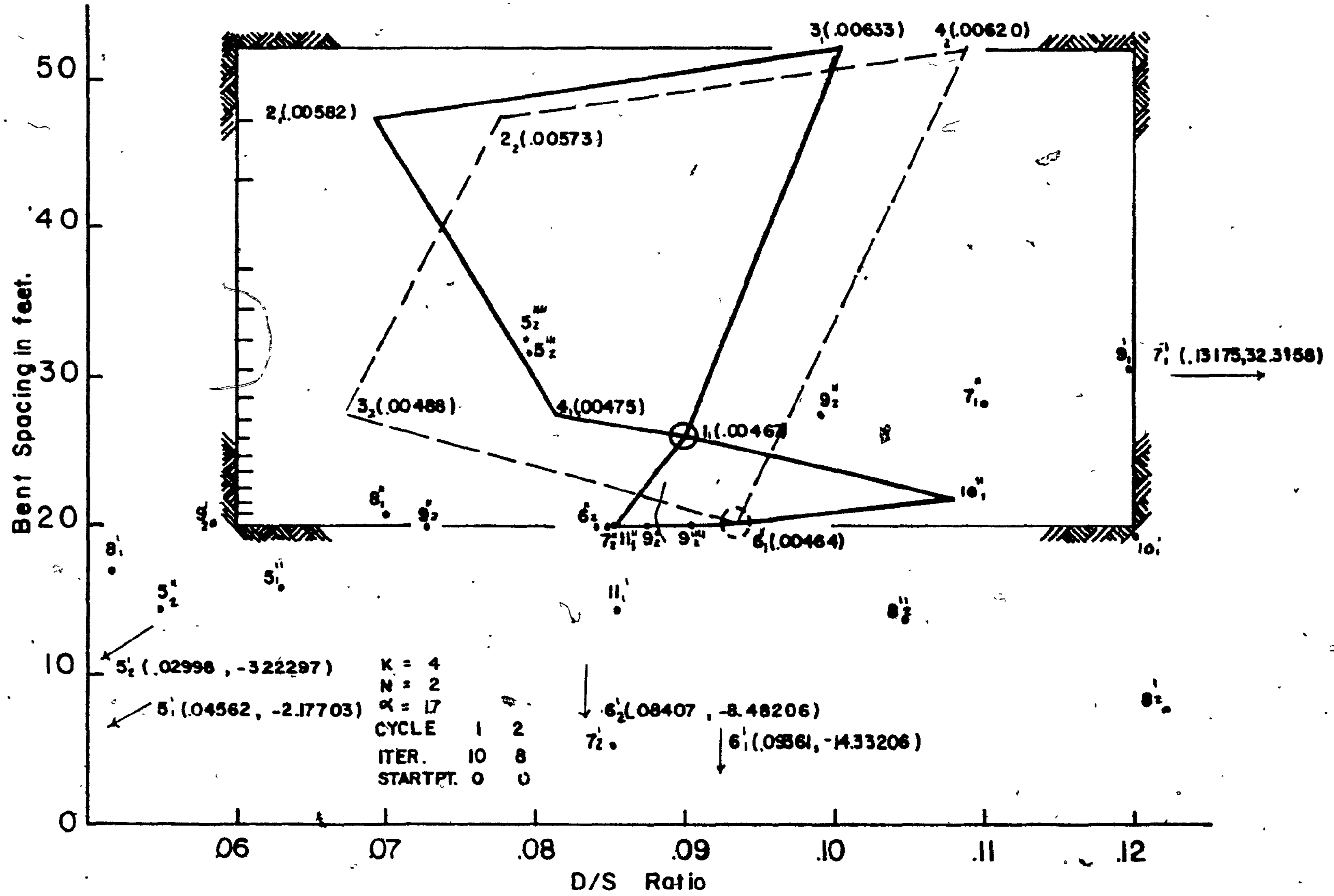


Fig. 5.20-BEHAVIOUR OF BOX METHOD - RUN 12 W.

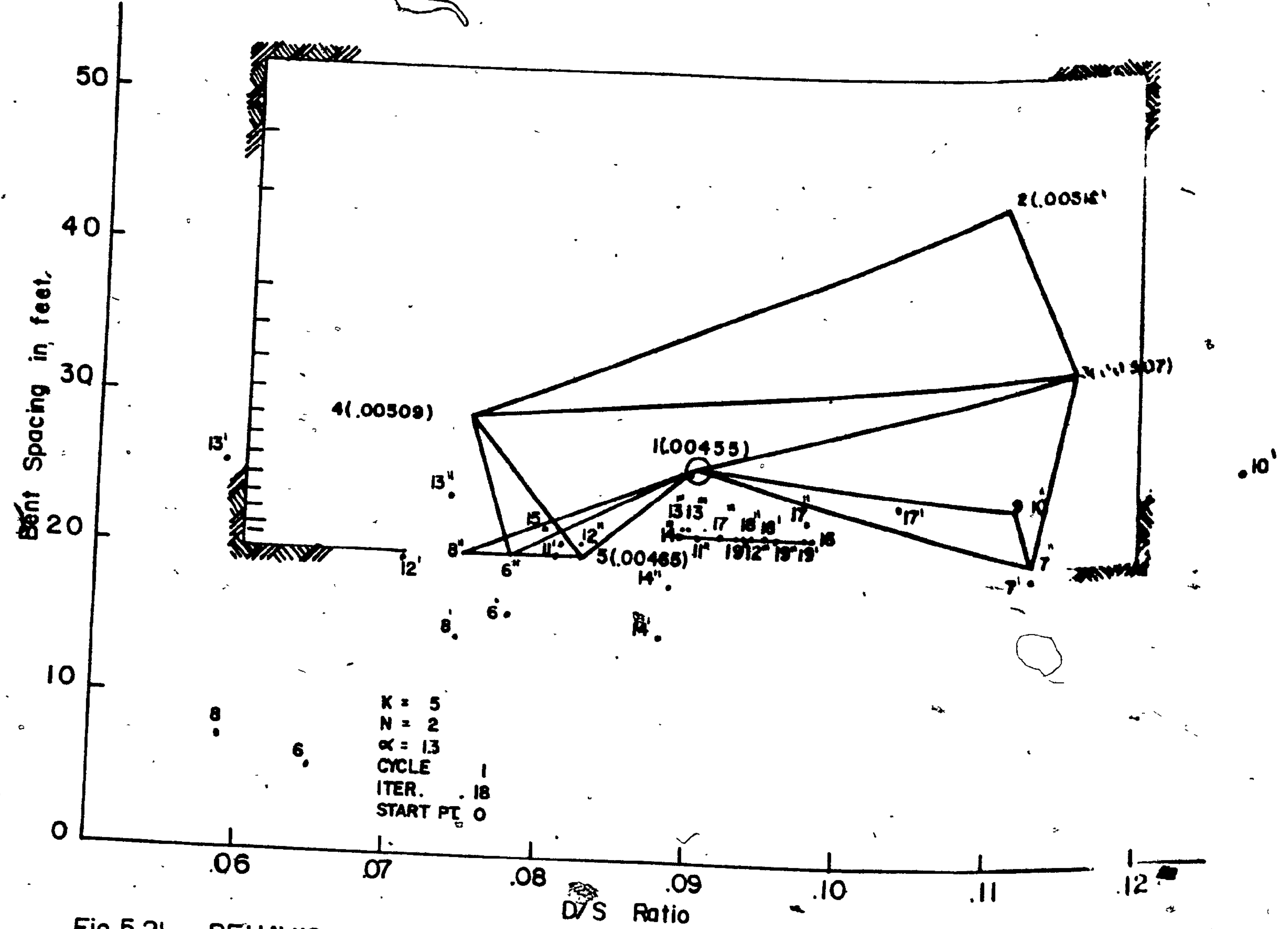


Fig.5.21 - BEHAVIOUR OF BOX METHOD - RUN 3 W.

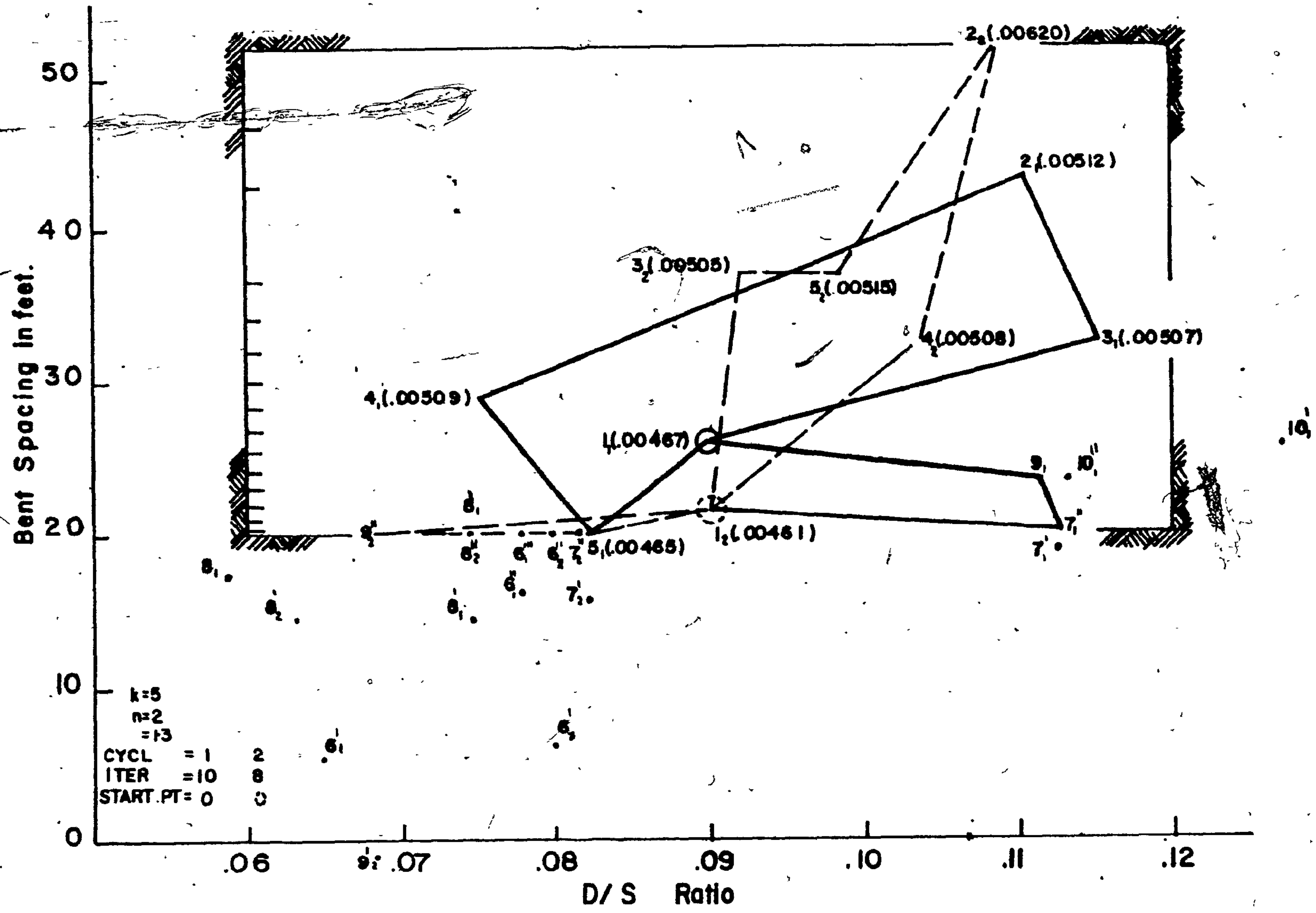


Fig. 5.22 - BEHAVIOUR OF BOX METHOD - RUN 6 W.

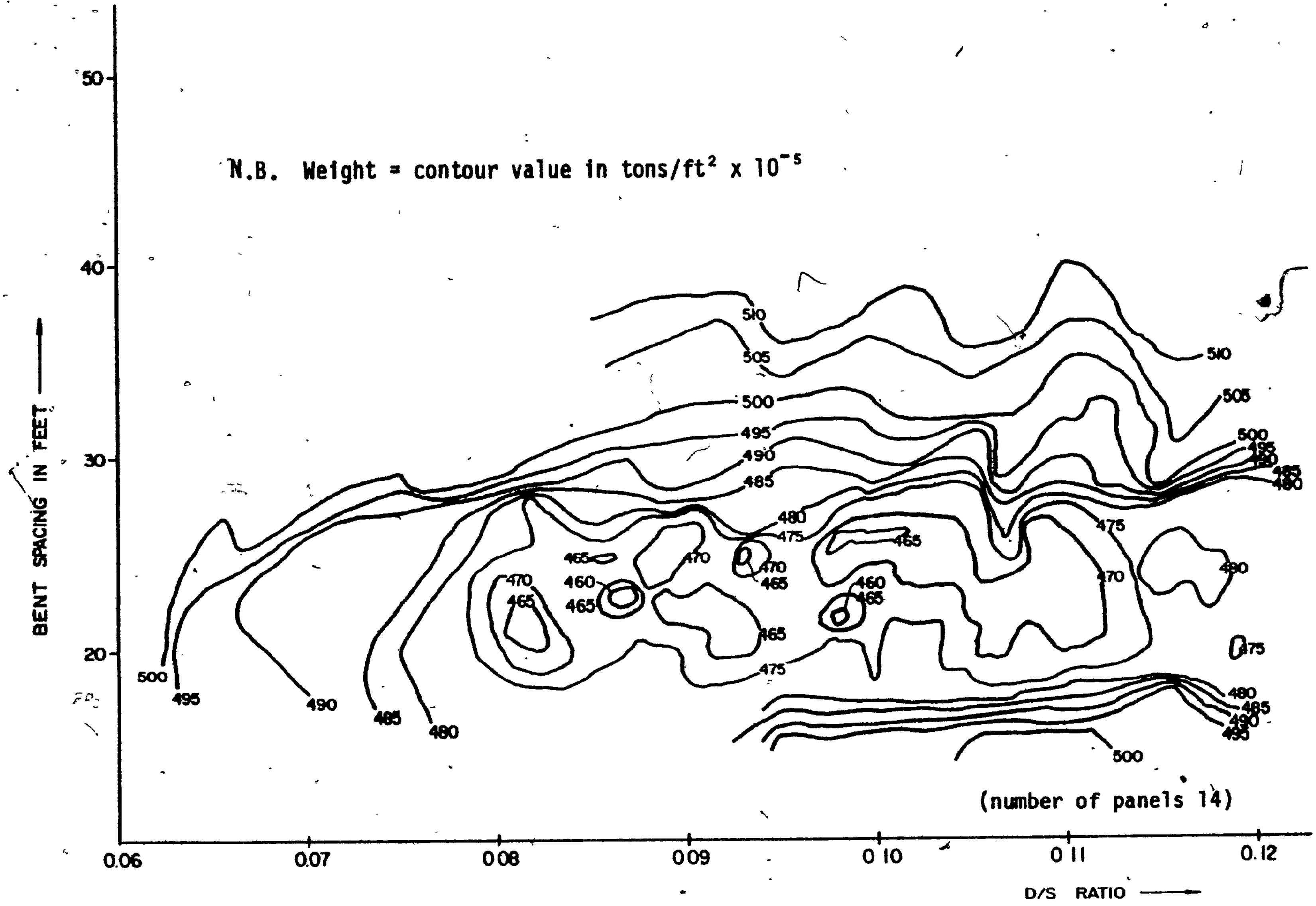
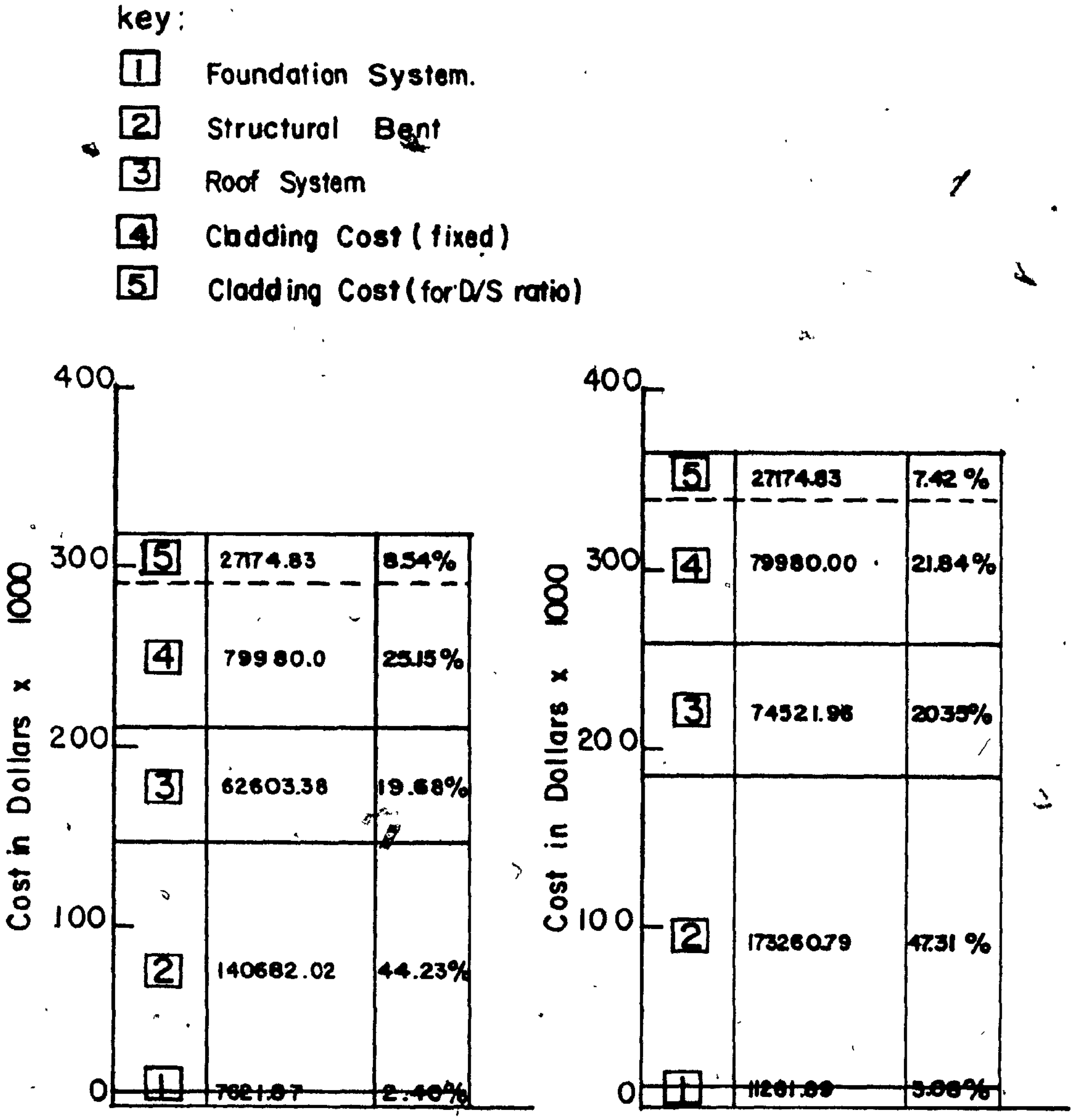


FIGURE 5.23: DESIGN SPACE FOR TOTAL STRUCTURAL WEIGHT



(a) Break Down of Total Cost For an Optimal Design_ Weight Related Cost Model.

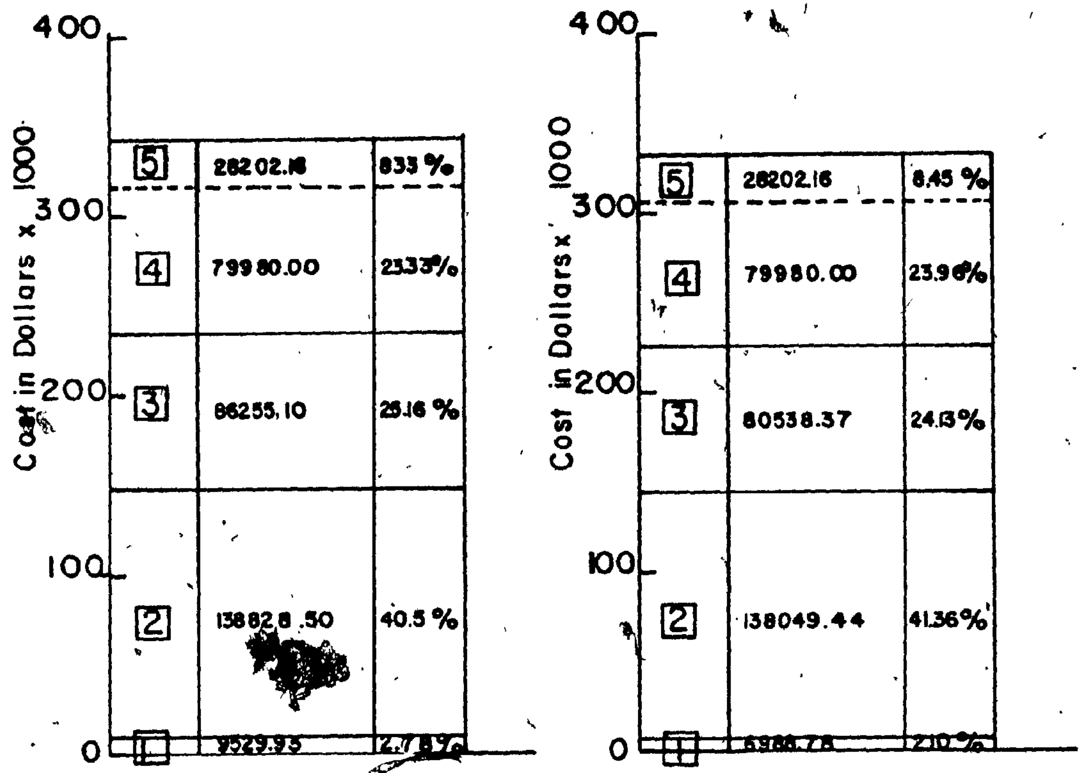
(b) Break Down of Total Cost For an Optimal Design_ General Cost Model.

truss spacing =24.7619'
number of panels =14
depth to span ratio =0.084943

Fig. 5.24-BREAK DOWN OF THE TOTAL COST FOR AN OPTIMAL DESIGN ON THE BASIS OF WEIGHT RELATED COST MODEL.

key:

- [1] Foundation System
- [2] Structural Bent
- [3] Roof System
- [4] Cladding (fixed cost)
- [5] Cladding (for D/S ratio)

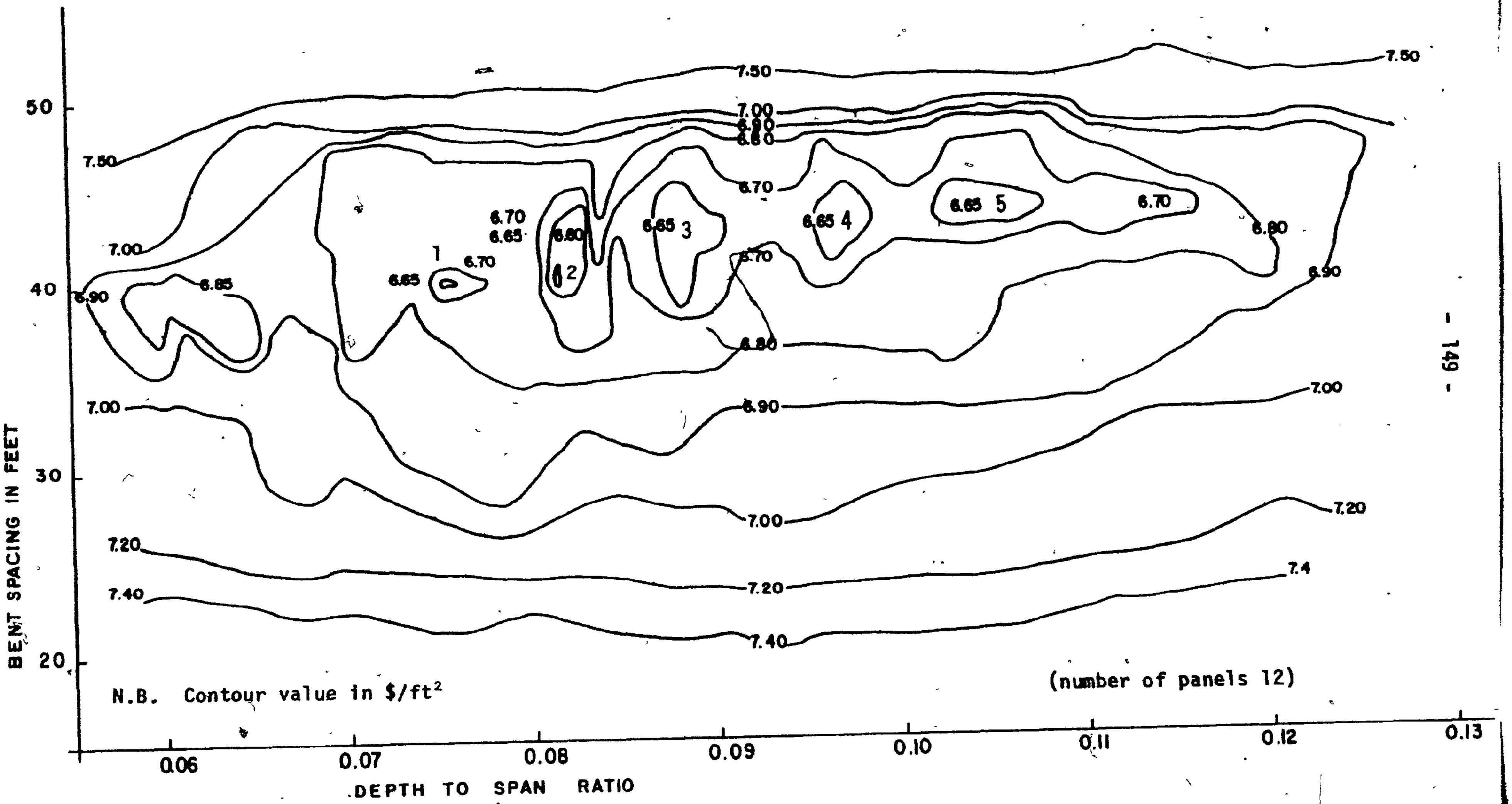


(a) Break Down of Total Cost For Optimal Points - General Cost Model.

(b) Break Down of Total Cost For Optimal points - Weight Related Cost Model.

truss spacing = 43.3333 ft.
number of panels = 12
depth to span ratio = .088154

Fig. 5.25 - BREAK DOWN OF THE TOTAL COST FOR AN OPTIMAL DESIGN ON THE BASIS OF GENERAL COST MODEL.



N.B. Contour value in $\$/ft^2$

(number of panels 12)

FIGURE 5.26: DESIGN SPACE FOR GENERAL COST MODEL

RUN NUMBER	k		ITERATION		STARTING POINT			α	CONSTRAINTS					
	CYCLE		CYCLE						x_2		x_3		x_4 *	
	1	2	1	2	x_2	x_3	x_4*		NPLB	NPUB	DSLB	DSUB	TRLB	TRUB
1w	3	-	18	-	14	.09	26.	1.3	14	14	.06	.12	20.	52.
2w	4	-	18	-	14	.09	26.	1.3	14	14	.06	.12	20.	52.
3w	5	-	18	-	14	.09	26.	1.3	14	14	.06	.12	20.	52.
4w	3	3	10	8	14	.09	26.	1.3	14	14	.06	.12	20.	52.
5w	4	4	10	8	14	.09	26.	1.3	14	14	.06	.12	20.	52.
6w	5	5	10	8	14	.09	26.	1.3	14	14	.06	.12	20.	52.
7w	3	-	18	-	14	.12	32.5	1.3	14	14	.06	.12	20.	52.
8w	3	-	18	-	14	.12	32.5	0.9	14	14	.06	.12	20.	52.
9w	3	-	18	-	14	.09	26.	0.9	14	14	.06	.12	20.	52.
10w	3	-	18	-	14	.09	26.	1.7	14	14	.06	.12	20.	52.
11w	4	4	10	8	14	.09	26.	0.9	14	14	.06	.12	20.	52.
12w	4	4	10	8	14	.09	26.	1.7	14	14	.06	.12	20.	52.
13w	4	4	10	8	14	.12	32.5	0.9	14	14	.06	.12	20.	52.
14w	4	4	10	8	14	.12	32.5	1.3	14	14	.06	.12	20.	52.
15w	4	4	10	8	14	.12	32.5	1.7	14	14	.06	.12	20.	52.

NOTE: for all runs, 0.5 difference tolerated - same random numbers for all runs.

* x_4 = bent spacing in feet.

TABLE 5.1: INPUT DATA FOR OPTIMIZATION RUN-
MINIMIZE WEIGHT OF THE STRUCTURAL SYSTEM

RUN NUMBER	CYCLE 1					CYCLE 2				
	OPTIMAL POINTS			OBJECTIVE FUNCTION	REMARKS	OPTIMAL POINTS			OBJECTIVE FUNCTION	REMARKS
	x_2	x_3	x_4	f(w)	*	x_2	x_3	x_4	f(w)	*
1w	14	.08795	22.61	.004617	No Improvement	-	-	-	-	NA
2w	14	.09102	21.67	.004576	NIT	-	-	-	-	NA
3w	14	.08917	21.67	.004545	NIT	-	-	-	-	NA
4w	14	.08795	22.61	.004617	No Improvement	14	.08795	22.61	.004617	NIT
5w	14	.09311	20.00	.004636	NIT	14	.08569	24.76	.004630	NIT
6w	14	.09028	21.67	.004614	NIT	14	.09028	21.67	.004614	NIT
7w	14	.09222	20.00	.004627	TOL	-	-	-	-	NA
8w	14	.10621	20.00	.004669	TOL	-	-	-	-	NA
9w	14	.09936	26.00	.004644	No Improvement	-	-	-	-	NA
10w	14	.09374	24.76	.004604	TOL	-	-	-	-	NA
11w	14	.09000	26.00	.004670	NIT	14	.09000	26.00	.004670	NIT
12w	14	.09361	20.00	.004640	NIT	14	.09361	20.00	.004640	NIT
13w	14	.09248	20.00	.004695	NIT	14	.08801	22.61	.004617	NIT
14w	14	.08169	21.67	.004605	No Improvement	14	.08169	21.67	.004605	NIT
15w	14	.11038	20.00	.004695	NIT	14	.10551	21.67	.004669	NIT

* Basis for search procedure termination

<u>TABLE 5.2</u>: OPTIMIZATION RUN - OBJECTIVE FUNCTION, MINIMIZE WEIGHT OF THE STRUCTURAL SYSTEM

RUN NUMBER	k		ITERATION		STARTING POINT			α	RANDOM NUMBER	CONSTRAINTS						REMARKS
	CYCLE		CYCLE		x_2	x_3	x_4			x_2		x_3		x_4		
	1	2	1	2						NPLB	NPUB	DSLB	DSUB	TRLB	TRUB	
1	4	-	18	-	10	10	26.	1.3	50	8	16	.06	.14	20.	52.	
2	5	-	18	-	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
3	6	-	18	-	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
4	4	4	8	10	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
5	4	4	10	8	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
6	5	5	8	10	10	.10	26.	1.3	50	8	15	.06	.14	20.	52.	
7	5	5	10	8	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
8	4	4	10	8	10	.10	26.	1.7	50	8	16	.06	.14	20.	52.	
9	4	4	10	8	10	.10	26.	1.3	75	8	16	.06	.14	20.	52.	
10	5	5	10	8	10	.10	26.	1.7	50	8	16	.06	.14	20.	52.	
11	5	5	10	8	10	.10	26.	1.3	75	8	16	.06	.14	20.	52.	
12	4	4	10	8	12	.10	26.	1.3	50	12	12	.06	.14	20.	52.	
13	5	5	10	8	12	.10	26.	1.3	50	12	12	.06	.14	20.	52.	
14	4	4	10	8	10	.10	26.	1.3	50	8	16	.06	.14	26.	40.	
15	5	5	10	8	10	.10	26.	1.3	50	8	16	.06	.14	26.	40.	
16	4	4	10	8	12	.082	40.	1.3	50	8	16	.06	.14	20.	52.	
17	5	5	10	8	12	.082	40.	1.3	50	8	16	.06	.14	20.	52.	*
18	5	5	10	8	12	.082	40.	1.3	50	12	12	.06	.14	20.	52.	*
19	4	4	10	8	10	.125	52.	1.3	50	8	16	.06	.14	20.	52.	**
20	5	5	10	8	10	.125	52.	1.3	50	8	16	.06	.14	20.	52.	**
21	4	-	18	-	10	.10	26.	1.3	50	10	14	.08	.12	26.	47.3	
22	4	4	10	8	10	.10	26.	1.3	50	10	14	.08	.12	26.	47.3	
23	4	4	10	12	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
24	5	5	10	12	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	
25	5	6	10	12	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.	

NOTE: For all runs, 0.5 percent difference tolerated.

* Starting point from one of the best designs

** Starting point from one of the worst designs

<u>TABLE 5.3: INPUT DATA FOR OPTIMIZATION RUNS - GENERAL COST MODEL</u>

RUN NUMBER	OPTIMAL POINTS					Optimal value of general cost \$/ft^2	REMARKS
	x_2	x_3	x_4	weight ton/ft^2	wt.rel. cost \$/ft^2		
1	12	.0971	43.33	.005045	6.3937	6.59377	No Improvement
2	12	.0972	43.33	.005046	6.3951	6.59494	NIT
3	12	.0975	43.33	.005048	6.3982	6.59767	NIT
4	12	.0971	43.33	.005045	6.3937	6.59377	NIT
5	12	.0971	43.33	.005045	6.3937	6.59377	NIT
6	14	.0814	40.00	.005260	6.5915	6.81106	NIT
7	12	.0910	47.27	.005423	6.6803	6.73421	NIT
8	12	.0754	40.00	.005191	6.4413	6.64050	NIT
9	12	.0829	43.33	.005219	6.4856	6.62874	NIT
10	12	.1043	43.33	.005036	6.4237	6.62846	NIT
11	12	.1023	43.33	.005084	6.4597	6.64943	NIT
12	12	.0971	43.33	.005045	6.3937	6.59377	NIT
13	12	.0942	43.33	.005217	6.5454	6.69136	NIT
14	12	.0600	40.00	.005590	6.7450	6.82940	NIT
15	12	.0826	28.89	.005094	6.4260	6.95267	NIT
16	12	.0820	40.00	.005133	6.4205	6.63965	NIT
17	12	.0820	40.00	.005133	6.4205	6.63965	NIT
18	12	.0820	40.00	.005133	6.4205	6.63965	NIT
19	12	.0843	37.14	.005116	6.4009	6.69905	NIT
20	14	.1113	47.27	.005357	6.7709	6.85976	NIT
21	12	.0959	40.00	.005100	6.4369	6.68310	TOL
22	12	.0959	40.00	.005100	6.4369	6.68310	TOL
23	12	.0971	43.33	.005045	6.3937	6.59377	NIT
24	12	.0910	47.27	.005423	6.6803	6.73421	NIT
25	12	.0910	47.27	.005423	6.6803	6.73421	NIT

<u>TABLE 5.4:</u> RESULTS FOR OPTIMIZATION RUNS -
GENERAL COST MODEL - CYCLE 1

RUN NUMBER	OPTIMAL POINTS					Optimal value of general cost $/ft^2	REMARKS
	x_2	x_3	x_4	weight ton/ft^2	wt.rel. cost $/ft^2		
1	-	-	-	-	-	-	NA
2	-	-	-	-	-	-	NA
3	-	-	-	-	-	-	NA
4	12	.0971	43.33	.005045	6.3937	6.59377	NIT
5	12	.0971	43.33	.005045	6.3937	6.59377	NIT
6	12	.0930	47.27	.005434	6.7024	6.75283	NIT
7	12	.0910	47.27	.005423	6.6803	6.73420	NIT
8	12	.0754	40.00	.005191	6.4413	6.64050	NIT
9	12	.0829	43.33	.005219	6.4856	6.62874	NIT
10	12	.1043	43.33	.005036	6.4237	6.62846	NIT
11	12	.1023	43.33	.005084	6.4597	6.64943	NIT
12	12	.0882	43.33	.005120	6.4184	6.59222*	NIT-optimal case
13	12	.0942	43.33	.005217	6.5454	6.69136	NIT
14	12	.0838	37.14	.005112	6.3945	6.69363	NIT
15	14	.0831	40.00	.005145	6.4886	6.74275	NIT
16	12	.0820	40.00	.005133	6.4205	6.63965	NIT
17	12	.0820	40.00	.005133	6.4205	6.63965	NIT
18	12	.0820	40.00	.005133	6.4205	6.63965	NIT
19	12	.08433	37.14	.005116	6.4009	6.69905	NIT
20	14	.0972	47.27	.005393	6.7307	6.80532	NIT
21	-	-	-	-	-	-	NA
22	12	.0897	40.00	.005105	6.4083	6.65114	NIT
23	12	.0971	43.33	.005045	6.3937	6.59377	NIT
24	12	.0886	43.33	.005186	6.4847	6.63859	NIT
25	12	.0880	40.00	.005091	6.3853	6.63260	NIT

TABLE 5.5: RESULTS FOR OPTIMIZATION RUNS - GENERAL COST MODEL - CYCLE 2

RUN NUMBER	K		ITERATION		STARTING POINT			α	RANDOM NUMBER	CONSTRAINTS					
	CYCLE		CYCLE							x_2		x_3		x_4	
	1	2	1	2	x_2	x_3	x_4			NPLB	NPUB	DSLB	DSUB	TRLB	TRUB
1	4	4	18	-	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.
2	5	5	18	-	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.
3	6	6	18	-	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.
4	4	4	10	12	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.
5	5	5	10	12	10	.10	26.	1.3	50	8	16	.06	.14	20.	52.
6	4	4	10	12	10	.10	26.	1.3	75	8	16	.06	.14	20.	52.
7	4	-	18	-	10	.10	26.	1.3	75	8	16	.06	.14	20.	52.
8	4	-	18	-	10	.10	26.	1.3	50	8	16	.06	.14	26.	40.

NOTE: For all runs, 0.5 percent difference tolerated.

TABLE 5.6: INPUT DATA FOR OPTIMIZATION RUNS - WEIGHT RELATED COST MODEL

RUN NUMBER	OPTIMAL POINTS FOR CYCLE 1					optimal value for weight rel.lost $\$/ft^2$	REMARKS
	x_2	x_3	x_4	weight ton/ft^2	general cost		
1	14	.0849	24.76	.004656	7.0423	6.11658	NIT
2	12	.1077	28.89	.004781	6.9026	6.25721	TOL
3	10	.1105	28.89	.004752	7.1805	6.28587	NIT
4	14	.0893	26.00	.004669	6.9864	6.13933	NIT
5	12	.1103	28.89	.004788	6.9230	6.27858	NIT
6	10	.1000	26.00	.004858	7.3729	6.31801	No Improvement
7	10	.1000	26.00	.004858	7.3729	6.31801	No Improvement
8	10	.1000	26.00	.004858	7.3729	6.31801	No Improvement

<u>TABLE 5.7:</u> RESULTS FOR OPTIMIZATION RUNS -
WEIGHT RELATED COST MODEL - CYCLE 1

RUN NUMBER	OPTIMAL POINTS FOR CYCLE 2					optimal value for weight rel.cost $\$/ft^2$	REMARKS
	x_2	x_3	x_4	weight ton/ft^2	general cost		
1	-	-	-	-	-	-	NA
2	-	-	-	-	-	-	NA
3	-	-	-	-	-	-	NA
4	14	.0893	26.00	.004669	6.9864	6.13933	NIT
5	14	.0923	20.00	.004638	7.4745	6.15716	NIT
6	14	.0966	24.76	.004624	7.0911	6.14929	NIT
7	-	-	-	-	-	-	NA
8	-	-	-	-	-	-	NA

TABLE 5.8: RESULTS FOR OPTIMIZATION RUNS - WEIGHT RELATED COST MODEL - CYCLE 2

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The potential exists for building construction cost savings if the design process can be better coordinated. Realization of such savings is essential if project profitability is to be maximized. To date, however, few tools exist to assist the designer to make tradeoffs between the various subsystems which comprise a building such that some objective function is optimized.

With respect to the foregoing need, two goals were selected for achievement in this thesis. They were:

(i) To develop a practical computerized design aid for the design of the foundation, structural and enclosure subsystems of light industrial type buildings in such a way as to permit tradeoffs to be made between the various subsystems in order to optimize overall system performance; and

(ii) To demonstrate the importance of careful formulation of the performance measure used for determining the optimal configuration of the system.

These goals have been met. A computer design package now exists which determines values for subsystem interface variables such that system performance is optimized and which also provides detailed designs for the foundation, bent and roof subsystems. These designs satsify all relevant code provisions. The user may operate the program in one of two modes:

(i) as an evaluation tool in which the designer specifies the values for the interface variables;

(ii) as an automated-design procedure in which values are selected for the interface variables such that either weight or cost is minimized.

For the second mode of operation, rather than treating the problem as one large optimization problem, it was decomposed into four subproblems and the solution of these subproblems was coordinated by a master program in which values of the interface variables were determined by Box's Complex Method. The procedure proved both efficient and effective in determining the optimum configuration for the system although no claim can be made that the global optimum is attained.

A significant contribution is seen to lie in the formulation of a general cost model which reflects the inputs of labour, equipment and material required for the fabrication and/or erection of each subsystem. This model is based on a detailed understanding of the sequence of operations required for the construction of each subsystem. The author was fortunate to obtain actual production rates from industry for many of these operations. Results derived from application of the general cost model were compared those developed using a weight or material related cost model which reflects current engineering office practice. The results obtained from an example problem demonstrated the potential for getting considerably different system configuration and cost, depending on the cost model used. For the problem considered, optimum values for the interface variables, bent spacing, number of panels and depth to span ratio were 43.33', 12 and 0.0882 respectively while optimum values for the weight related cost criterion were 24.76', 14 and 0.0849. The difference in cost for these two optima predicted by the general cost model was 6.8 percent or some $23,405 on a total cost of $342,795. This difference indicates the importance of selecting system configuration using an objective function which reflects the manner in which the subsystems of a building are actually constructed and costed.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Topics which could be treated in future work include:

(i) Addition of cladding and mechanical design and costing routines so as to provide a total system design package;

(ii) addition of design alternatives for each subsystem;

(iii) examination of other methods of subproblem solution coordination;

(iv) incorporation of optimization procedures to assist in the solution of subsystem design problems such as determining the optimal number of chord splices per truss,

(v) automated design procedures for structural system bracing and joint details; and

(vi) refinement of existing cost models by developing an improved understanding of the operations involved in the construction of each subsystem and by gathering actual field production rates for these operations.

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APPENDIX I

STUDY OF THE BENEFITS OF MEMBER GROUPING

ALTERNATIVE 1

Material	491260# @ 16.5¢/#	=	$81,060.00
Fabrication	2191 MH @ 14.50$/hr.	=	31,770.00
	Total	=	$112,830.00

Supply only - $460.00/ton

ALTERNATIVE 2

Material	394480# @ 16.5¢/#	=	$65,090.00
Fabrication	1772 MH @ 14.50$/hr.	=	25,694.00
	Total		$90,784.00

Supply only - $460.00/ton

ALTERNATIVE 3

Material	509960# @ 16.5¢/#	=	$84,143.00
Fabrication	3162 MH @ 14.50$/hr.	=	45,849.00
	Total		$129,992.00

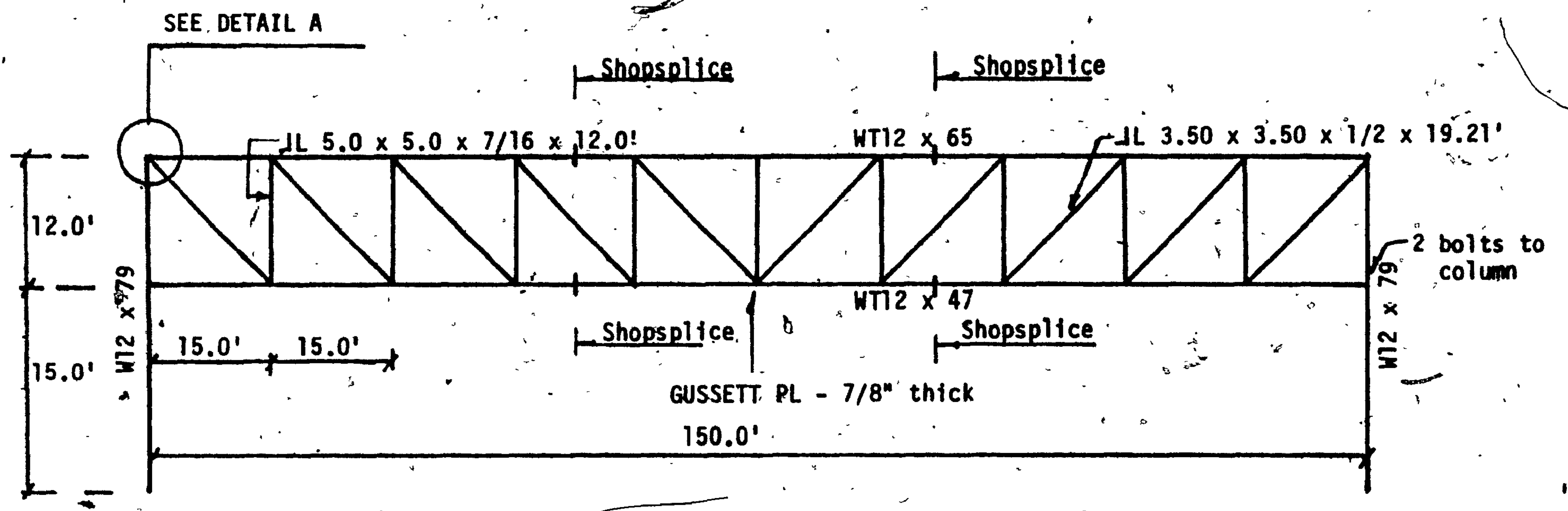
Supply only - $510.00/ton

ALTERNATIVE 4

Material	373600# @ 16.5¢/#	=	$61,644.00
Fabrication	2372 MH @ 14.50$/ton	=	34,394.00
	Total		$96,038.00

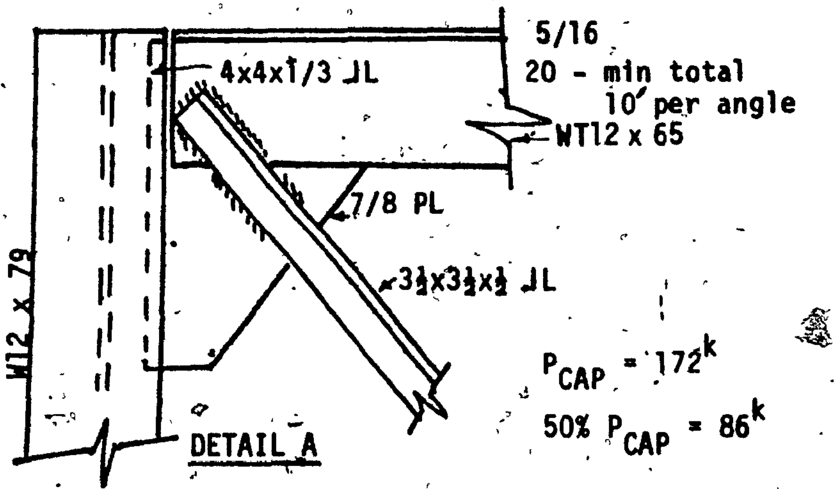
Supply only - $514.00/ton

SUMMARY SHEET



NB. Shopweld - E70xxelectrodes

Number of bays 20
Number of panels 10



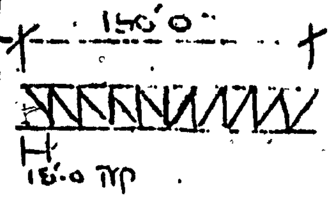
$P_{CAP} = 172^k$

$50\% \ P_{CAP} = 86^k$

ALTERNATIVE 1

T#1	MAIN MATERIAL							DETAIL MATERIAL						
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT
	12	TC	WT	65	150 0	1	9750	7/8	GUSS	PL				400
	12	BC	WT	47	150 0	1	7050							x 20
	5x5x7/16	VERT	L	28.6	12 0	9	3089							8000
	4½x4½x½	DIAG	L	22.2	19 3	10	4274							
							24163							
							x 20							
							483260							

DETAILS AND REMARKS



10 PANELS

491,260 #

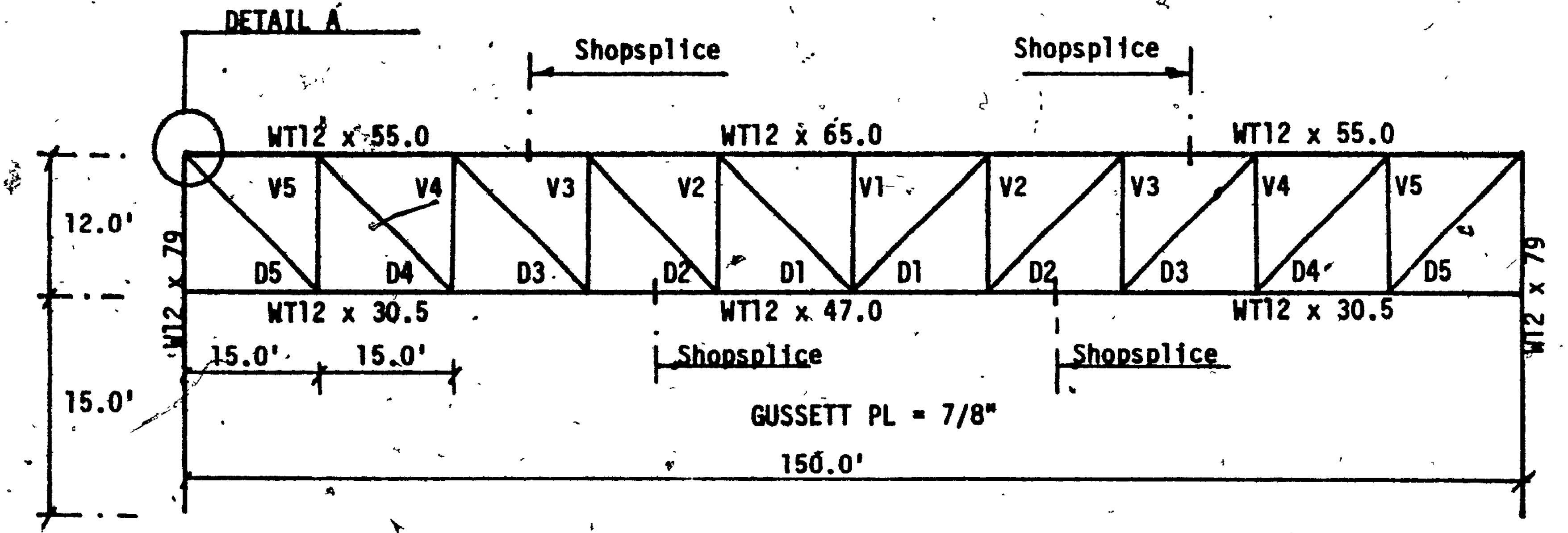
245.6 TONS.

6.92 MH/T

PEINTURE ~ 2 MH/T.

MAT'L ~ 16.5¢/#

WORKSHEET FOR ALTERNATIVE 1



V1 ⅃L 3.50 x 3.00 x 1/4 x 12.0'
V2 ⅃L 3.50 x 3.50 x 1/4 x 12.0'
V3 ⅃L 5.00 x 3.50 x 3/8 x 12.0'
V4 ⅃L 5.00 x 3.50 x 7/16 x 12.0'
V5 ⅃L 5.00 x 5.00 x 7/16 x 12.0'

D1 ⅃L 3.50 x 3.00 x 1/4 x 19.21'
D2 ⅃L 3.50 x 3.00 x 1/4 x 19.21'
D3 ⅃L 4.00 x 3.50 x 1/4 x 19.21'
D4 ⅃L 5.00 x 3.50 x 5/16 x 19.21'
D5 ⅃L 3.50 x 3.50 x 1/2 x 19.21'

NB.Shopweld - 5/16"
E70xxelectrodes

Number of bays 20
Number of panels 10

ALTERNATIVE 2

MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
12	TC	WT	55	37 6	2	4125	7/8	GU	PL				400	
12	TC	WT	65	75 0	1	4875							x 20	
12	BC	WT	30.5	52 6	2	3203							8000	
12	BC	WT	47	45 0	1	2115								
3½x3x¼	V₁	⅃L	10.8	12 0	1	130								10 PANELS
3½x3½x¼	V₂	⅃L	11.6	12 0	2	279								
5x3½x3/8	V₃	⅃L	20.8	12 0	2	500								
5x3½x7/16	V₄	⅃L	24.0	12 0	2	576								
5x5x7/16	V₅	⅃L	28.6	12 0	2	686								
✓ 3½x3x¼	D₁	⅃L	10.8	19 3	2	416								
✓ 3½x3x¼	D₂	⅃L	10.8	19 3	2	416								SAVING:
4x3½x¼	D₃	⅃L	12.4	19 3	2	477								T.C.: 750#
5x3½x5/16	D₄	⅃L	17.4	19 3	2	670								B.C. 1732#
3½x3½x½	D₅	⅃L	22.2	19 3	2	856								
						19,324								
						x 20								
						386,480								

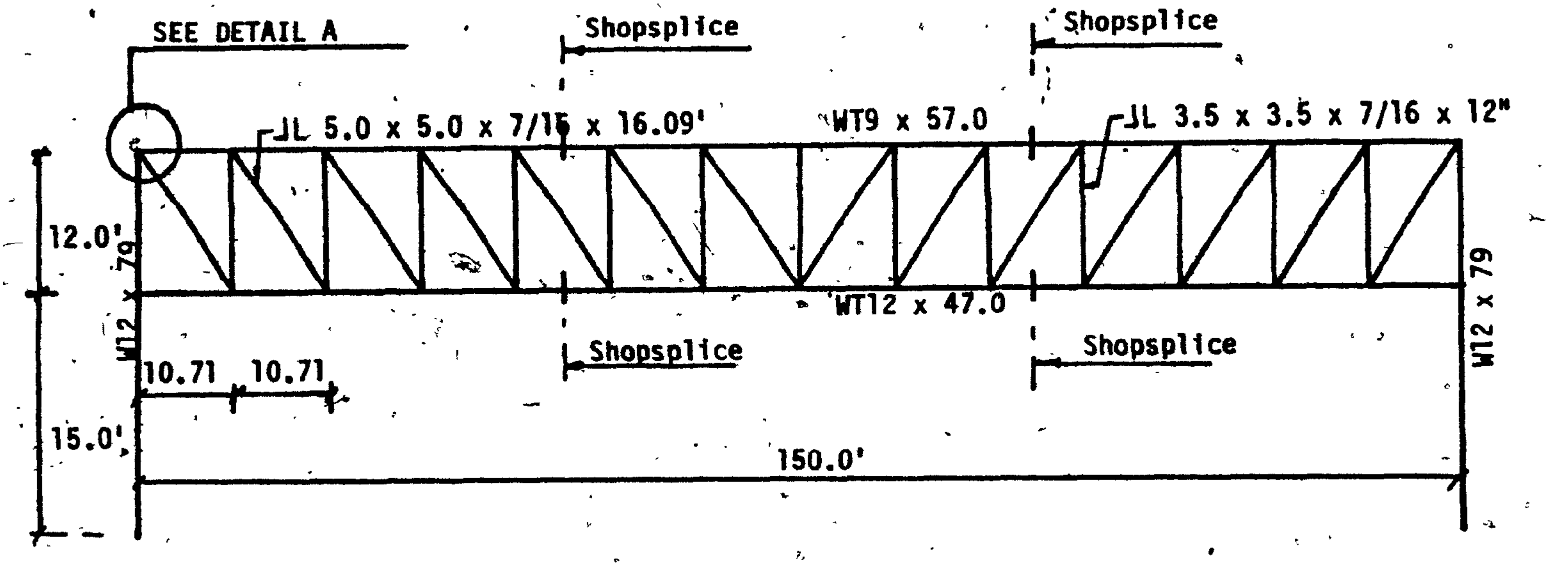
6.98 MH/T.

394,480#

PAINT: 2 MH/T.

197.3 TONS

WORKSHEET FOR ALTERNATIVE 2



Shopwelded ~ 5/16" ~ E70xx electrodes

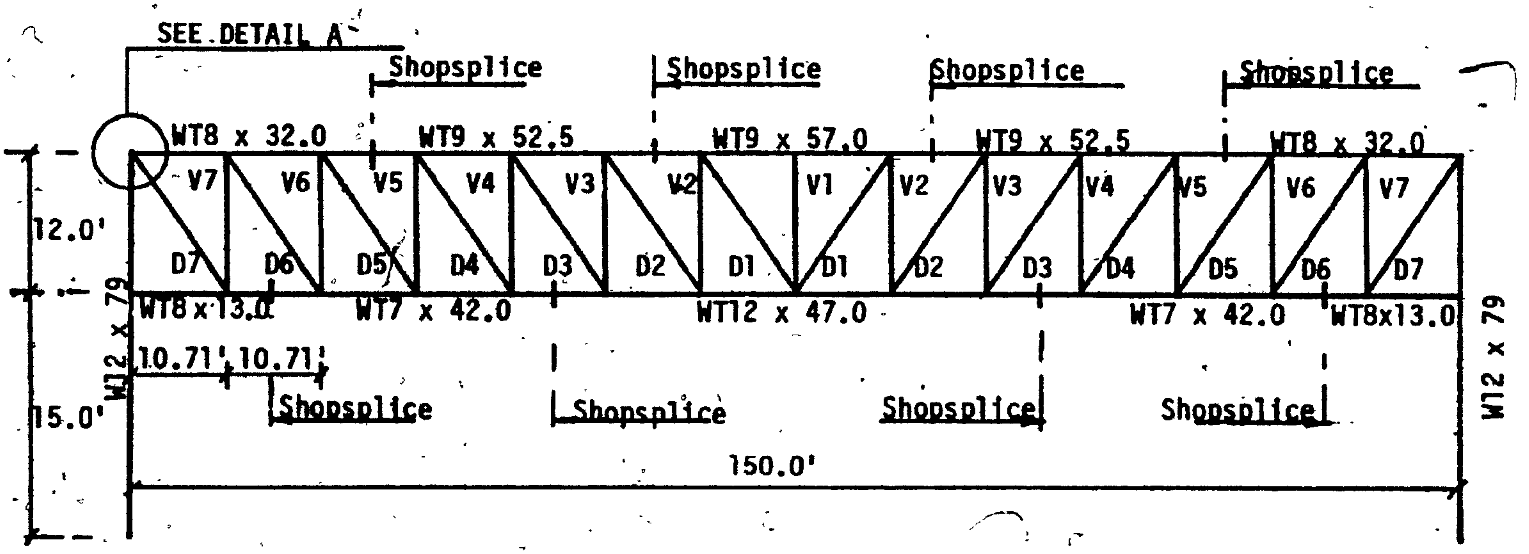
Number of bays 20

Number of panels 14

ALTERNATIVE 3

ALT 3	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
	9	TC	WT	57	15 0	1	8550							8000	
	12	BC	WT	47	15 0	1	7050								
	3½x3½x7/16	VERT	JL	19.6	12 0	13	3058								
	5x5x 7/16	DIAG	JL	28.6	16 1	14	6440								
							25098								
							x 20								
							501960								14 PANELS
															- 1½ PER SPLICE LESS
															509,960#
															255 TONS
															10.4 M/H/T.

WORKSHEET FOR ALTERNATIVE 3



V1 ⅃L 3.00 x 2.50 x 1/4 x 12.0'
V2 ⅃L 3.50 x 3.00 x 1/4 x 12.0'
V3 ⅃L 4.00 x 3.50 x 1/4 x 12.0'
V4 ⅃L 5.00 x 3.50 x 7/16 x 12.0'
V5 ⅃L 6.00 x 3.50 x 3/8 x 12.0'
V6 ⅃L 5.00 x 4.00 x 3/8 x 12.0'
V7 ⅃L 5.00 x 5.00 x 7/16 x 12.0'

D1 ⅃L 3.00 x 2.50 x 1/4 x 16.09'
D2 ⅃L 3.00 x 2.50 x 1/4 x 16.09'
D3 ⅃L 3.00 x 2.50 x 1/4 x 16.09'
D4 ⅃L 3.50 x 3.00 x 1/4 x 16.09'
D5 ⅃L 3.50 x 3.00 x 5/16 x 16.09'
D6 ⅃L 5.00 x 3.00 x 5/16 x 16.09'
D7 ⅃L 3.50 x 3.50 x 7/16 x 16.09'

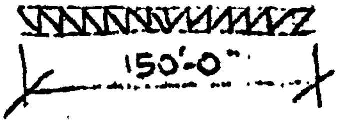
NB. Shopweld —
E70xxelectrodes

Number of bays 20
Number of panels 14

ALTERNATIVE 4

	MAIN MATERIAL							DETAIL MATERIAL						
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT
	8	TC	WT	32	26 9 7/16	2	1714	34	GUSS	PL				400
	9	TC	WT	52.5	32 1 11/16	2	3375							x20
	9	TC	WT	57	32 1 11/16	1	1832							8000
	8	BC	WT	13	16 0 13/16	2	418							
	7	BC	WT	42	32 1 11/16	2	2700							
	12	BC	WT	47	53 6 7/8	1	2518							
-	3x2½x¼	V1	JL	9.0	12 0	1	108							
X	3½x3x¼	V2	JL	10.8	12 0	2	259							
	4x3½x¼	V3	JL	12.4	12 0	2	298							
	5x3½x5/16	V4	JL	17.4	12 0	2	418							
	6x3½x3/8	V5	JL	23.4	12 0	2	562							
	5x5x3/8	V6	JL	24.6	12 0	2	590							
	5x5x3/8	V7	JL	24.6	12 0	2	646							
-	3x2½x¼	D1	JL	9.0	16 1	2	290							
-	3x2½x¼	D2	JL	9.0	16 1	2	290							
-	3x2½x¼	D3	JL	9.0	16 1	2	290							
X	3½x3x¼	D4	JL	10.8	16 1	2	348							
	3½x3x5/16	D5	JL	13.2	16 1	2	425							
	5x3x5/16	D6	JL	16.4	16 1	2	528							
	3½x3½x7/16	D7	JL	19.6	16 1	2	631							
							18280							
							x20							
							365,600							

DETAILS AND REMARKS



14 PANELS

373,600#

186.8 TONS

10.7 MH/T

WORKSHEET FOR ALTERNATIVE 4

APPENDIX II

STEEL PRICE STRUCTURE

Material Base Price and Extras

I - Base price = ¢16.00 /lb.

II - Extra

a) Item Quantity

QUANTITIES	EXTRA (¢/lb)
10,000 lbs and over	none
under 10,000 lbs to 6,000 lbs incl.	0.10
under 6,000 lbs to 4,000 lbs incl.	0.25
under 4,000 lbs to 2,000 lbs incl.	0.65
under 2,000 lbs to 1,000 lbs incl.	1.50
under 1,000 lbs	3.00

b) Loading

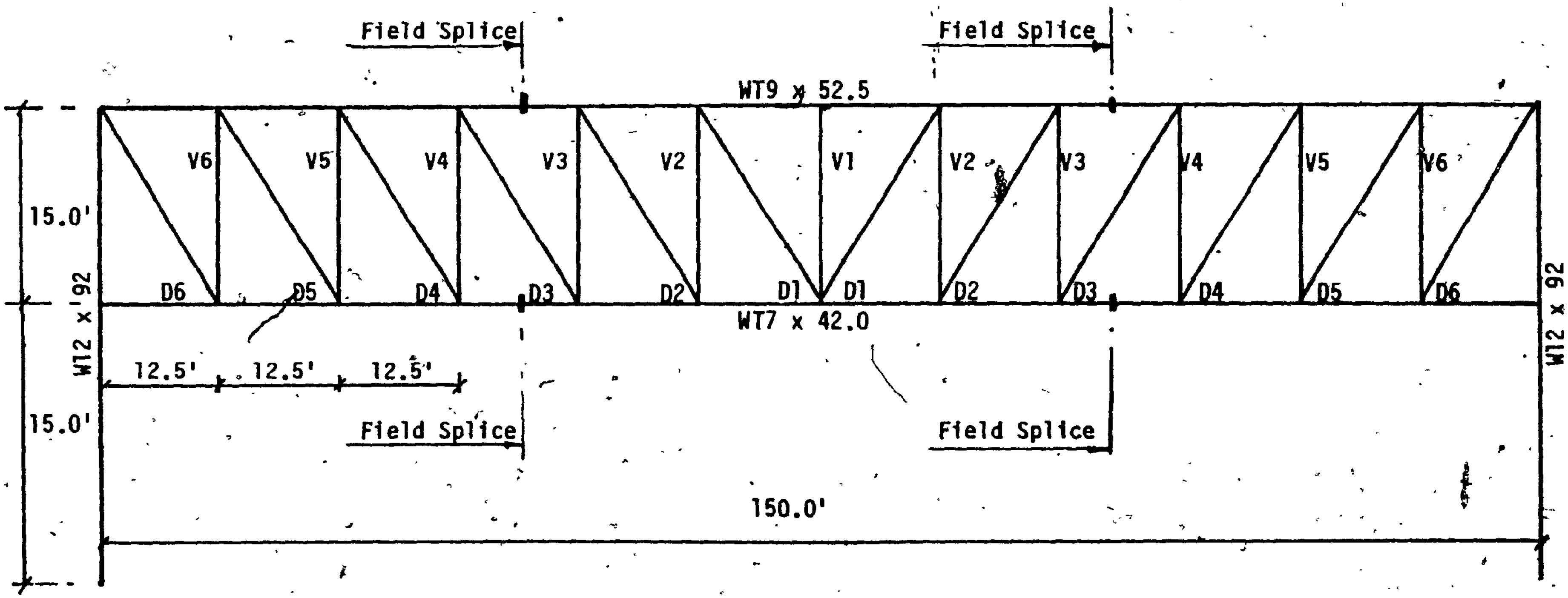
QUANTITIES	EXTRA (¢/lb)
10,000 lbs or over	None
under 10,000 lbs to 6,000 lbs incl.	0.10
under 6,000 lbs to 4,000 lbs incl.	0.15
under 4,000 lbs	0.20

APPENDIX III

FABRICATION LABOUR INPUT AS A FUNCTION OF TRUSS CONFIGURATION

	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
	TRUSS				FIG. 4										
T.C	WT	12		65	50'-0"	3	9750								
V1	L4x3½x5/16			7.7	15'-0"	2	231								
V2	L5x3½x3/8			10.4	15'-0"	4	624								
V3	L6x6x3/8			14.9	15'-0"	4	894								
V4	L6x6x½			19.6	15'-0"	4	1176								
D1	L4x3½x¼			6.2	24'-0"	4	595								
D2	L4x3½x¼			6.2	24'-0"	4	595								
D3	L4x4x5/16			8.2	24'-0"	4	787	FILLER PL'S						300	
D4	L5x3½x3/8			10.4	24'-0"	4	998	SPLICE			130		4	520	
L.C.	WT	8		39	50'-0"	3	5850	END CONN.			100		4	400	
							21500							1220	
							x 31							x 31	
							666500							37820	
	12 WF			COL'S	@		C.R.								-.67
	WF	12		92	30'-0"	62	171120	14		12L	71.4	1'-2"	62	5172	
															(3480) 1040

WORKSHEET FOR ALTERNATIVE 4



V1 ⅃L 4.00 x 3.50 x 1/4 x 15.0'
V2 ⅃L 4.00 x 3.50 x 5/16 x 15.0'
V3 ⅃L 5.00 x 3.50 x 7/16 x 15.0'
V4 ⅃L 5.00 x 5.00 x 7/16 x 15.0'
V5 ⅃L 6.00 x 6.00 x 7/16 x 15.0'
V6 ⅃L 6.00 x 6.00 x 9/16 x 15.0'

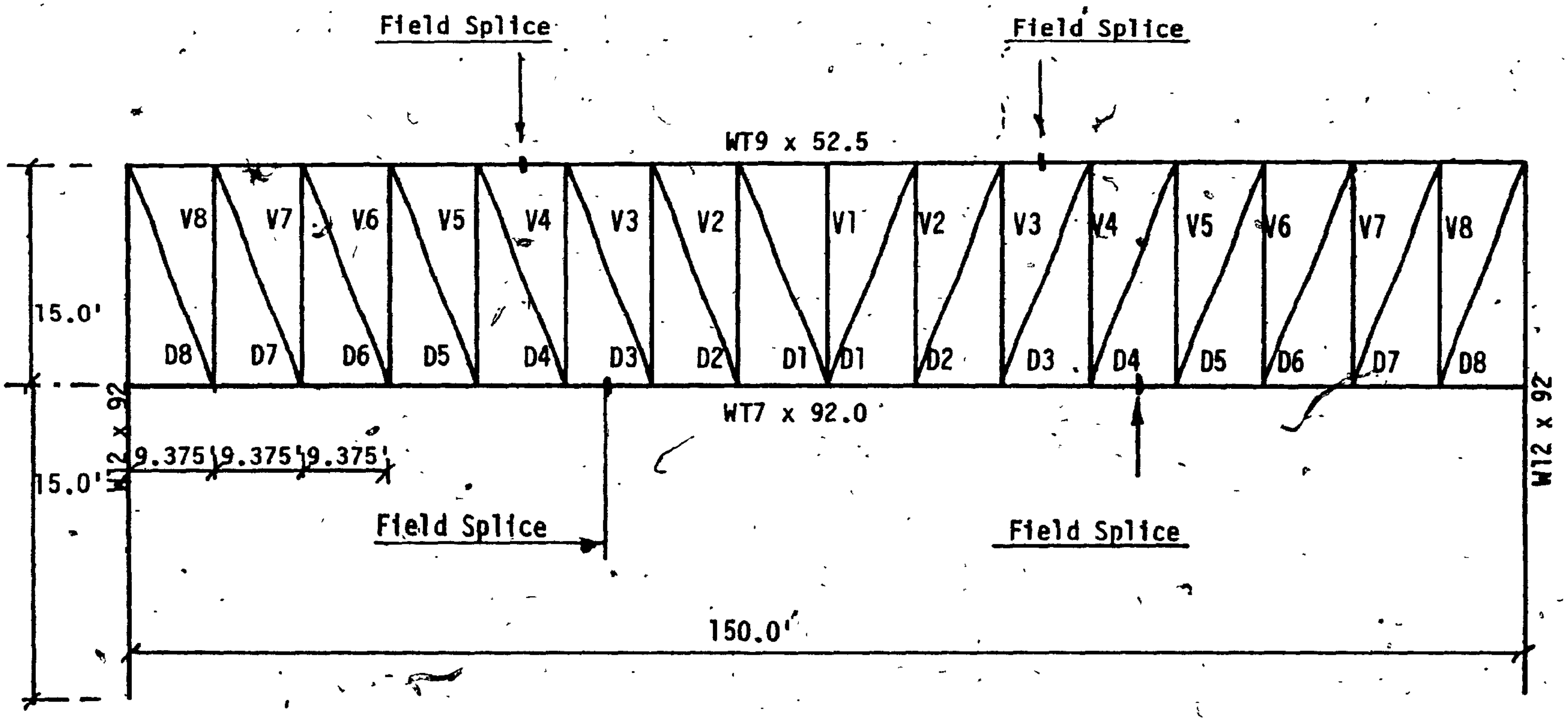
D1 ⅃L 3.50 x 3.00 x 1/4 x 19.53'
D2 ⅃L 3.50 x 3.00 x 1/4 x 19.53'
D3 ⅃L 3.50 x 3.00 x 1/4 x 19.53'
D4 ⅃L 3.50 x 3.00 x 5/16 x 19.53'
D5 ⅃L 5.00 x 3.00 x 5/16 x 19.53'
D5 ⅃L 4.00 x 3.00 x 7/16 x 19.53'

Bent Spacing 30.00 feet
Number of bents 31

ALTERNATIVE 5

	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
	TRUSS			1=	16.-	5									
T.C.	WT	9		52.5	50'-0"	3	7875	✓							
V1	L4×3½×	¼		6.2	15'-0"	2	186	✓							
V2	" ×	5/16		7.7	15'-0"	4	462	✓							
V3	L5×3½×	7/16		12	15'-0"	4	720	✓							
V4	L5×5×7/16			14.3	15'-0"	4	858								
V5	L6×6×	7/16		17.2	15'-0"	4	1032	✓							
V6	L6×6×	9/16		21.9	15'-0"	4	13[illegible]	✓							
D1	L3½×3×	¼		5.4	19'-6"	4	421	✓							
D2	"			"	19'-6"	4	421	✓							
D3	"			"	19'-6"	4	431	✓							
D4	" ×	5/16		6.6	19'-6"	4	515								
D5	L5×3×	5/16		8.2	19'-6"	4	640	FILLER	[illegible]					400	
D6	L4×3×	7/16		11.1	19'-6"	4	566	SPLICE			120		4	480	
L.C.	WT	7		42	50'-0"	3	6300	END CONN.			100		4	400	
							22031							1280	
							×31							×31	
							682961							39680	5.8
	12 WF COLS. & B. P.														
	WF	12		92	30'-0"	62	171120	14		1½	71.4	1'-2	62	5172	2450
															1040

WORKSHEET FOR ALTERNATIVE 5



V1 ⅃L 3.50 x 3.00 x 1/4 x 15.0'
V2 ⅃L 4.00 x 3.50 x 1/4 x 15.0'
V3 ⅃L 5.00 x 3.50 x 5/16 x 15.0'
V4 ⅃L 5.00 x 3.50 x 7/16 x 15.0'
V5 ⅃L 5.00 x 5.00 x 7/16 x 15.0'
V6 ⅃L 6.00 x 6.00 x 3/8 x 15.0'
V7 ⅃L 6.00 x 6.00 x 1/2 x 15.0'
V8 ⅃L 6.00 x 6.00 x 9/16 x 15.0'

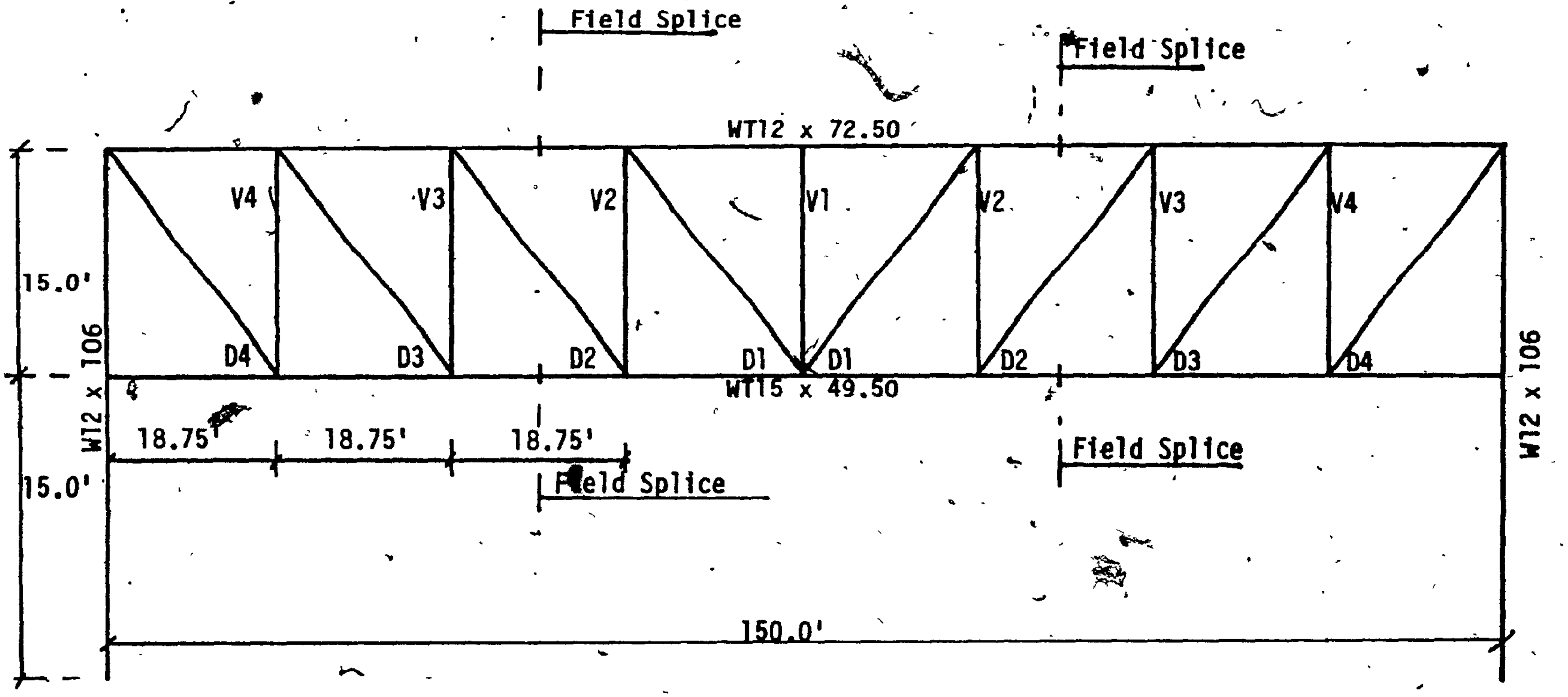
D1 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D2 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D3 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D4 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D5 ⅃L 3.00 x 2.50 x 5/16 x 17.69'
D6 ⅃L 3.00 x 3.00 x 3/8 x 17.69'
D7 ⅃L 5.00 x 3.00 x 5/16 x 17.69'
D8 ⅃L 4.00 x 3.50 x 3/8 x 17.69'

Bent spacing 30.00 feet
Number of bents 31

ALTERNATIVE 6

	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
	TRUSS.			FIG.		6									
T.C.	WT	9		52.5	50'-0"	3	7875	✓							
V1	L3½x3x	¼		5.4	15'-0"	2	162	✓							
V2	L4x3½	x¼		6.2	15'-0"	4	372	✓							
V3	L5x3½	x5/16		8.7	15'-0"	4	522	✓							
V4	L5x3½	x7/16		12	15'-0"	4	720	✓							
V5	L5x5x	7/16		14.3	15'-0"	4	858	✓							
V6	L6x6x	3/8		14.9	15'-0"	4	894	✓							
V7	L6x6x	½		19.6	15'-0"	4	1176	✓							
V8	L6x6x	9/16		21.9	15'-0"	4	1314	✓							
D1	L3x2½x¼			4.5	17'-8"	4	318	✓							
D2	"			"	17'-8"	4	318	✓							
D3	"			"	17'-8"	4	318	✓							
D4	"			"	17'-8"	4	318	✓							
D5	"	x5/16		5.6	17'-8"	4	396	✓							
D6	L5x3x	3/8		7.2	17'-8"	4	509	✓							
D7	L5x3x	5/16		8.2	17'-8"	4	580	FILLER PL'S						471	
D8	L4x3½x	3/8		9.1	17'-8"	4	643	SPLICE			120		4	480	
B.C.	WT	7		42	50'-0"	3	6300	END CONN.			100		4	400	
							23593							1351	
							x31							x31	
							731383							41881	5.73%
	Rf WF WF	12		COL'S 92	30'-0"	6" 62	R. FL. 171120	L4		1½	11.4	1'-2"	62	5180	3480 1240

WORKSHEET FOR ALTERNATIVE 6



V1 ⅃L 5.00 x 3.50 x 5/16 x 15.0'
V2 ⅃L 5.00 x 5.00 x 3/8 x 15.0'
V3 ⅃L 6.00 x 6.00 x 7/16 x 15.0'
V4 ⅃L 6.00 x 6.00 x 5/8 x 15.0'

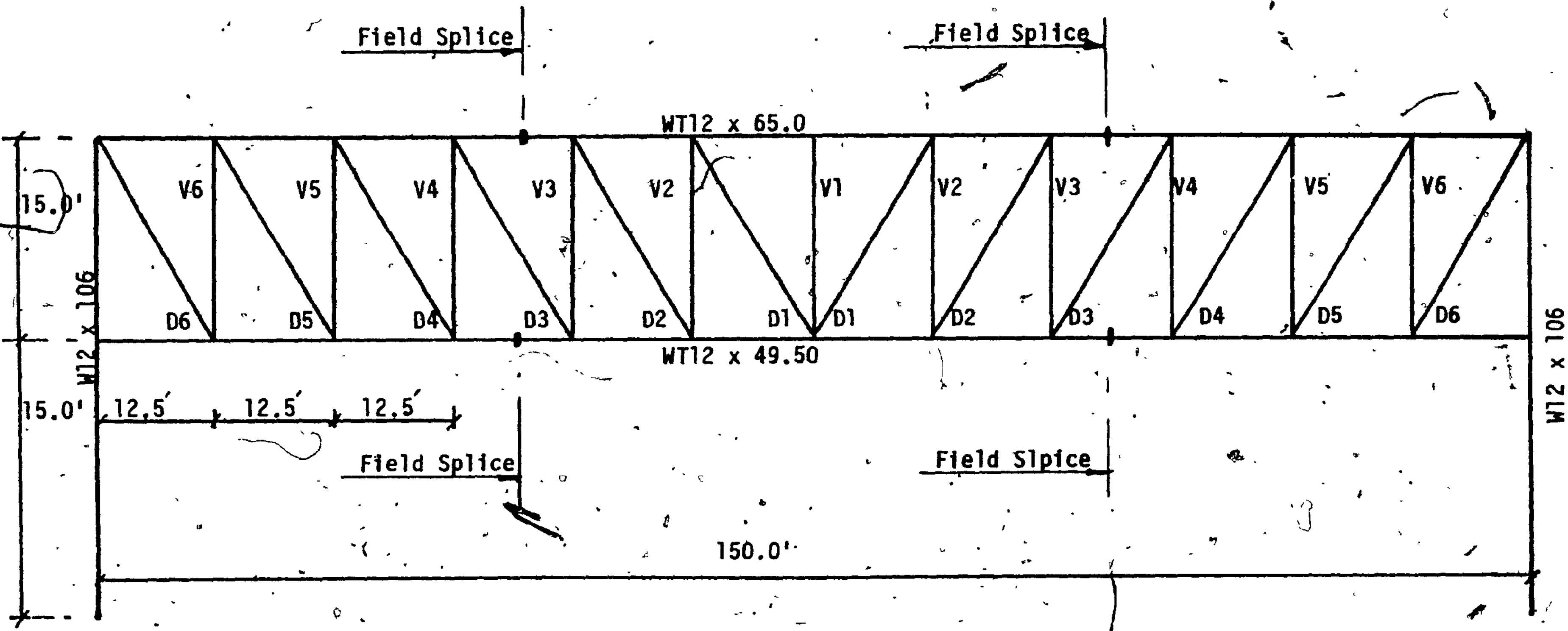
D1 ⅃L 4.00 x 3.50 x 1/4 x 24.01'
D2 ⅃L 4.00 x 3.50 x 1/4 x 24.01'
D3 ⅃L 5.00 x 3.50 x 3/8 x 24.01'
D4 ⅃L 5.00 x 5.00 x 7/16 x 24.01'

Bent spacing 37.50 feet
Number of bents 25

ALTERNATIVE 7

	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
		TK	15.)		FIG.	- 7									
T.C.	WT	12		72.5	50'-0"	3	10875	✓							
V1	L5x3½x	5/16		8.7	15'-0"	2	261	✓							
V2	L5x5x	3/8		12.3	15'-0"	4	738	✓							
V3	L6x6x	7/16		17.2	15'-0"	4	1032	✓							
V4	L6x6x	5/8		24.2	15'-0"	4	1452								
D1	L4x3½x	1/4		6.2	24'-0"	4	595	✓							
D2	"			"	24'-0"	4	595	✓							
D3	L5x2½x	3/8		10.4	24'-0"	4	998	FILLER	PLS					350	
D4	L5x5x	7/16		14.3	24'-0"	4	1373	SPLICE			150		4	600	
B.C.	WT	15		49.5	50'-0"	3	7425	END CONN.			100		4	400	
							25344							1350 ✓	
							X 25							X 25	
							633600 ✓							33750	5.32%
	12 WF			20	L3	4	B.R.								
	WF	12		106	30'-0"	50	159600	14		½ PL	71.4	1'-2	50	4177	2000 1000

WORKSHEET FOR ALTERNATIVE 7



V1 ⅃L 4.00 x 3.50 x 1/4 x 15.0'
V2 ⅃L 5.00 x 3.50 x 5/16 x 15.0'
V3 ⅃L 5.00 x 5.00 x 3/8 x 15.0'
V4 ⅃L 6.00 x 6.00 x 7/16 x15.0'
V5 ⅃L 6.00 x 6.00 x 9/16 x 15.0'
V6 ⅃L 8.00 x 8.00 x 1/2 x 15.0'

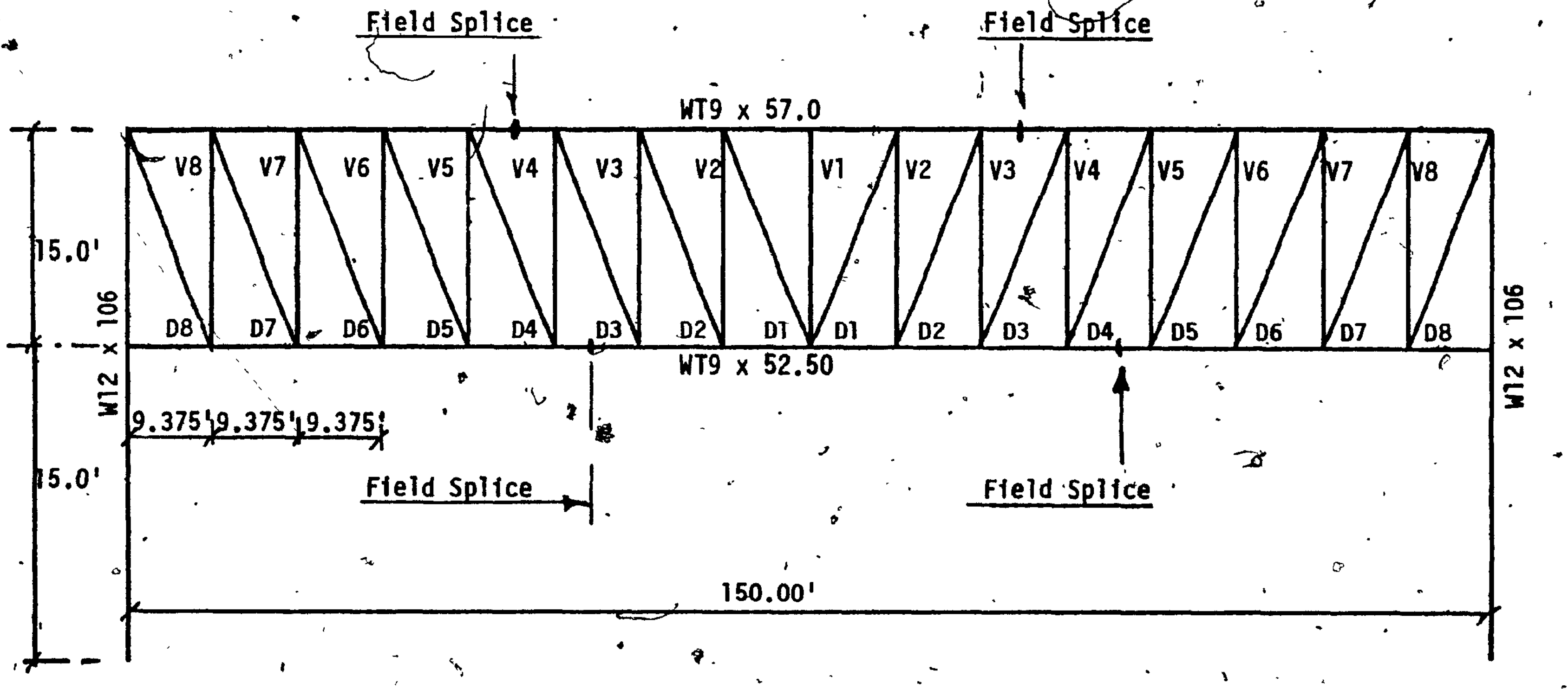
D1 ⅃L 3.50 x 3.00 x 1/4 x 19.53'
D2 ⅃L 3.50 x 3.00 x 1/4 x 19.53'
D3 ⅃L 3.50 x 3.50 x 1/4 x 19.53'
D4 ⅃L 3.50 x 3.00 x 3/8 x 19.53'
D5 ⅃L 3.50 x 3.00 x 1/2 x 19.53'
D6 ⅃L 5.00 x 5.00 x 3/8 x 19/53'

Bent spacing 37.50 feet
Number of bents 25

ALTERNATIVE 8

	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
	Truss Fig - 8														
T.C.	WT	12		65	50'-0"	3	9750								
V1	L4x3½x	¼		6.2	15'-0"	1	93								
V2	L5x3½x	5/16		8.7	15'-0"	4	522								
V3	L5x5x	3/8		12.3	15'-0"	4	738								
V4	L6x6x	7/16		17.2	15'-0"	4	1032								
V5	L6x6x	9/16		21.9	15'-0"	4	1314								
V6	L8x8x	½		26.4	15'-0"	4	1584								
D1	L3½x3	x¼		5.4	19'-6"	4	421								
D2	"			"	19'-6"	4	421								
D3	L3½x3½	x¼		5.8	19'-6"	4	452								
D4	L3½x3	x3/8		7.9	19'-6"	4	616								
D5	L4x3½x	½		11.9	19'-6"	4	928	FILLER PLS						450	
D6	L5x5x	3/8		12.3	19'-6"	4	960	SPLICE			140		4	360	
B.C.	WT	15		49.5	50'-0"	3	7425	END conn			100		4	400	
							26256							1410	
							x25							x25	
							656400							35250	
															5-378
	12 WF			COLS	w/ B.P.										
	WF	12		106	30'-0"	50	159000	14		PL	71.4	1'-2"	50	4177	3000 3000

WORKSHEET FOR ALTERNATIVE 8



V1 ⅃L 4.00 x 3.00 x 1/4 x 15.0'
V2 ⅃L 4.00 x 3.50 x 5/16 x 15.0'
V3 ⅃L 6.00 x 3.50 x 3/8 x 15.0'
V4 ⅃L 5.00 x 5.00 x 7/16 x 15.0'
V5 ⅃L 6.00 x 6.00 x 7/16 x 15.0'
V6 ⅃L 6.00 x 6.00 x 1/2 x 15.0'
V7 ⅃L 6.00 x 6.00 x 9/16 x 15.0'
V8 ⅃L 8.00 x 8.00 x 1/2 x 15.0'

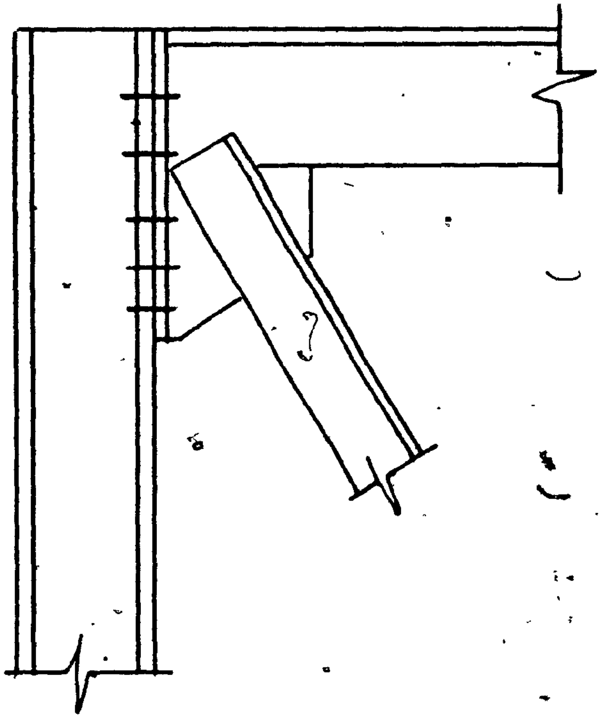
D1 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D2 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D3 ⅃L 3.00 x 2.50 x 1/4 x 17.69'
D4 ⅃L 3.50 x 3.00 x 1/4 x 17.69'
D5 ⅃L 3.00 x 3.00 x 3/8 x 17.69'
D6 ⅃L 3.00 x 3.00 x 7/16 x 17.69'
D7 ⅃L 4.00 x 3.00 x 7/16 x 17.69'
D8 ⅃L 4.00 x 4.00 x 7/16 x 17.69'

Bent spacing 37.50 feet
Number of bents 25

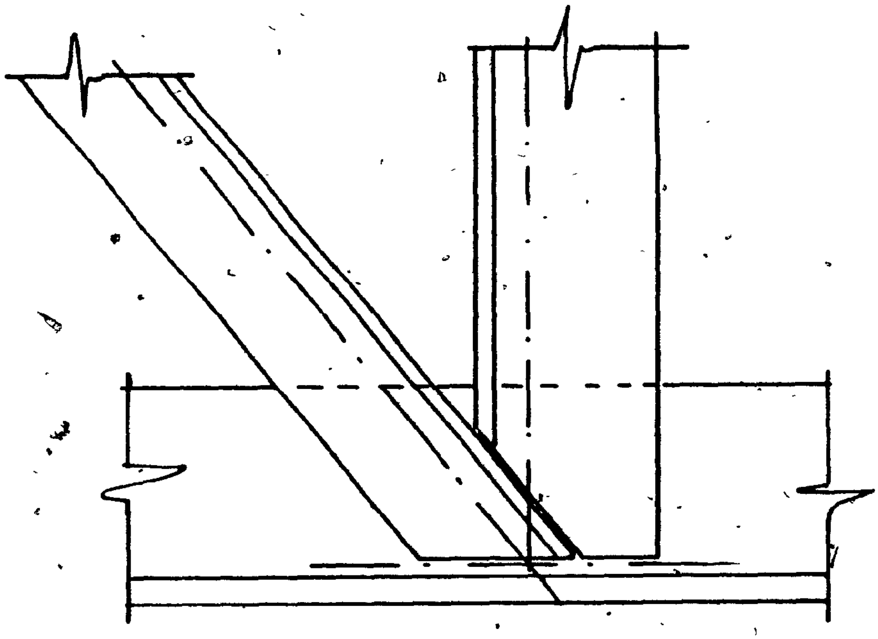
ALTERNATIVE 9

	MAIN MATERIAL							DETAIL MATERIAL							DETAILS AND REMARKS
	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	SECTION	TYPE	SHAPE	UNIT WT.	LENGTH	PCS.	WEIGHT	
	TRUSS			FIG-9											
T.C	WT	9		57	50'-0"	3	8550								
V1	L4x3x	1/4		5.8	15'-0"	2	174								
V2	L4x3½	x5/16		7.7	15'-0"	4	462								
V3	L6x3½	x3/8		11.7	15'-0"	4	702								
V4	L5x5x	7/16		14.3	15'-0"	4	858								
V5	L6x6x	7/16		17.2	15'-0"	4	1032								
V6	L6x6x	1/2		19.6	15'-0"	4	1176								
V7	L6x6x	9/16		21.9	15'-0"	4	1314								
V8	L8x8x	1/2		26.4	15'-0"	4	1584								
D1	L3x2½x	1/4		4.5	17'-8"	4	318								
D2	L3x2½x	1/4		4.5	17'-8"	4	318								
D3	"			4.5	17'-8"	4	318								
D4	L3½x3x	1/4		5.4	17'-8"	4	382								
D5	L3x3x	3/8		7.2	17'-8"	4	510								
D6	L3x3x	1/2		9.4	17'-8"	4	664								
D7	L4x3x	1/2		11.1	17'-8"	4	785	FILLER	1'S					570	
D8	L4x4x	7/16		11.3	17'-8"	4	799	SPLICE		-	140		4	560	
B.C1	WT	9		52.5	50'-0"	3	7875	END CONN.			100		4	400	
							27821							1530	
							X 25							X 25	
							695525							38250	
															5.49%
	12 WF			COL'S	@ B.C.										
	WF	12		106	30'-0"	50	159000	14		PL	71.4	1'-2"	50	4177	4000 1000

WORKSHEET FOR ALTERNTAIVE 9



(a) SCHEMATIC OF TYPICAL CONNECTION OF TRUSS TO WF COLUMN



(b) SCHEMATIC OF TYPICAL CONNECTION OF CHORD TO WEBS

JOINT DETAILS

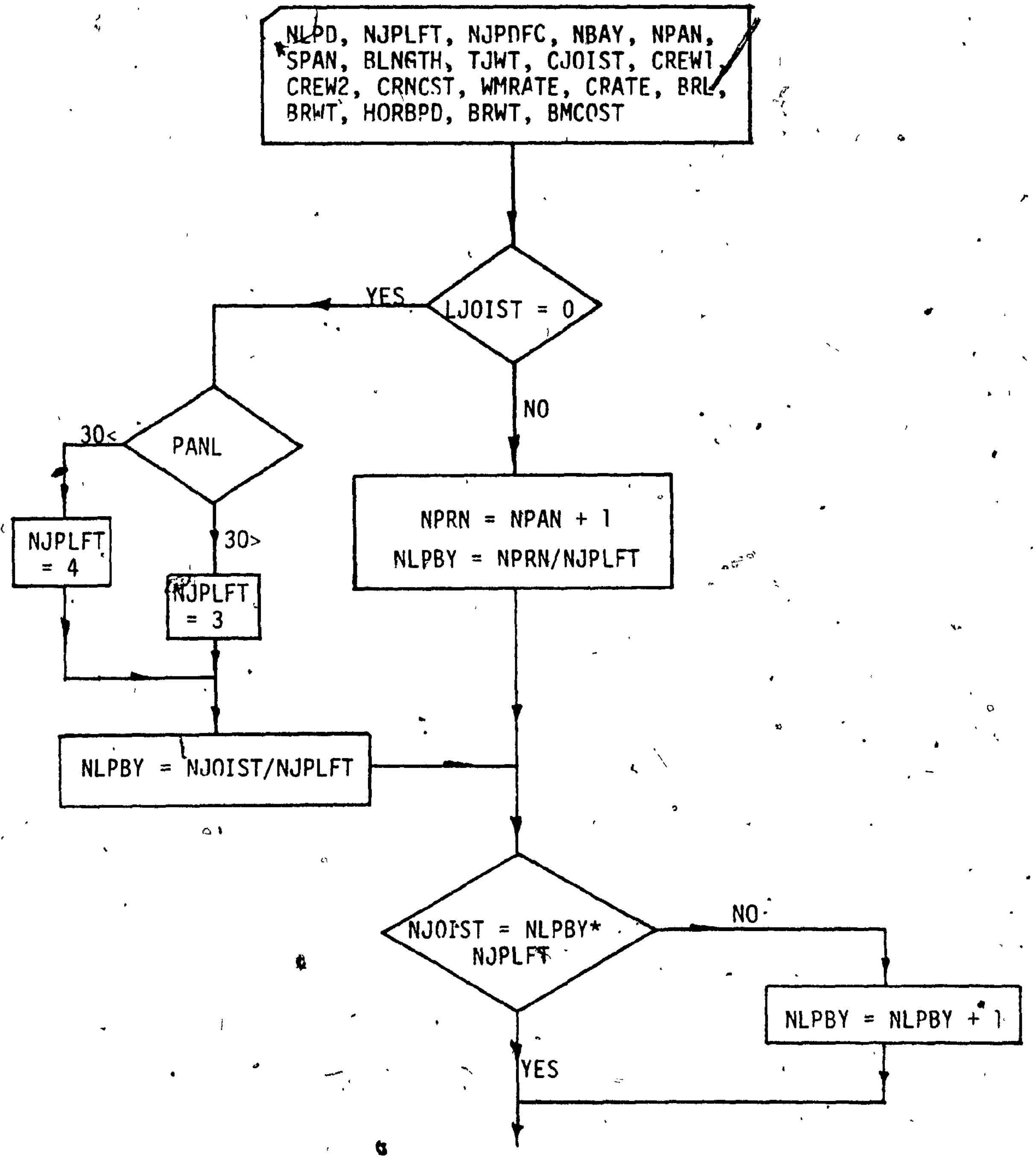
APPENDIX IV.

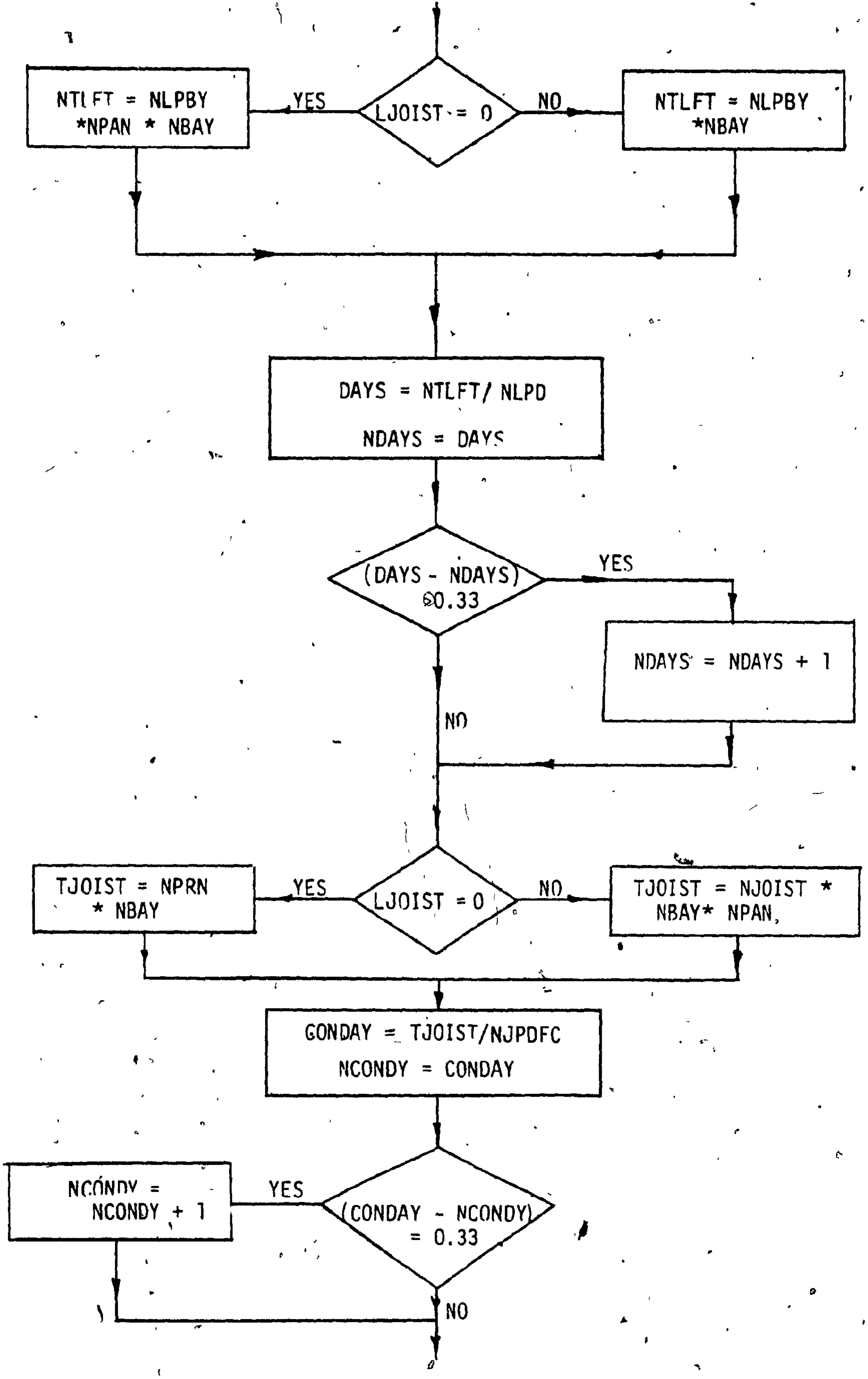
GENERAL COST MODEL FOR ROOF SYSTEM

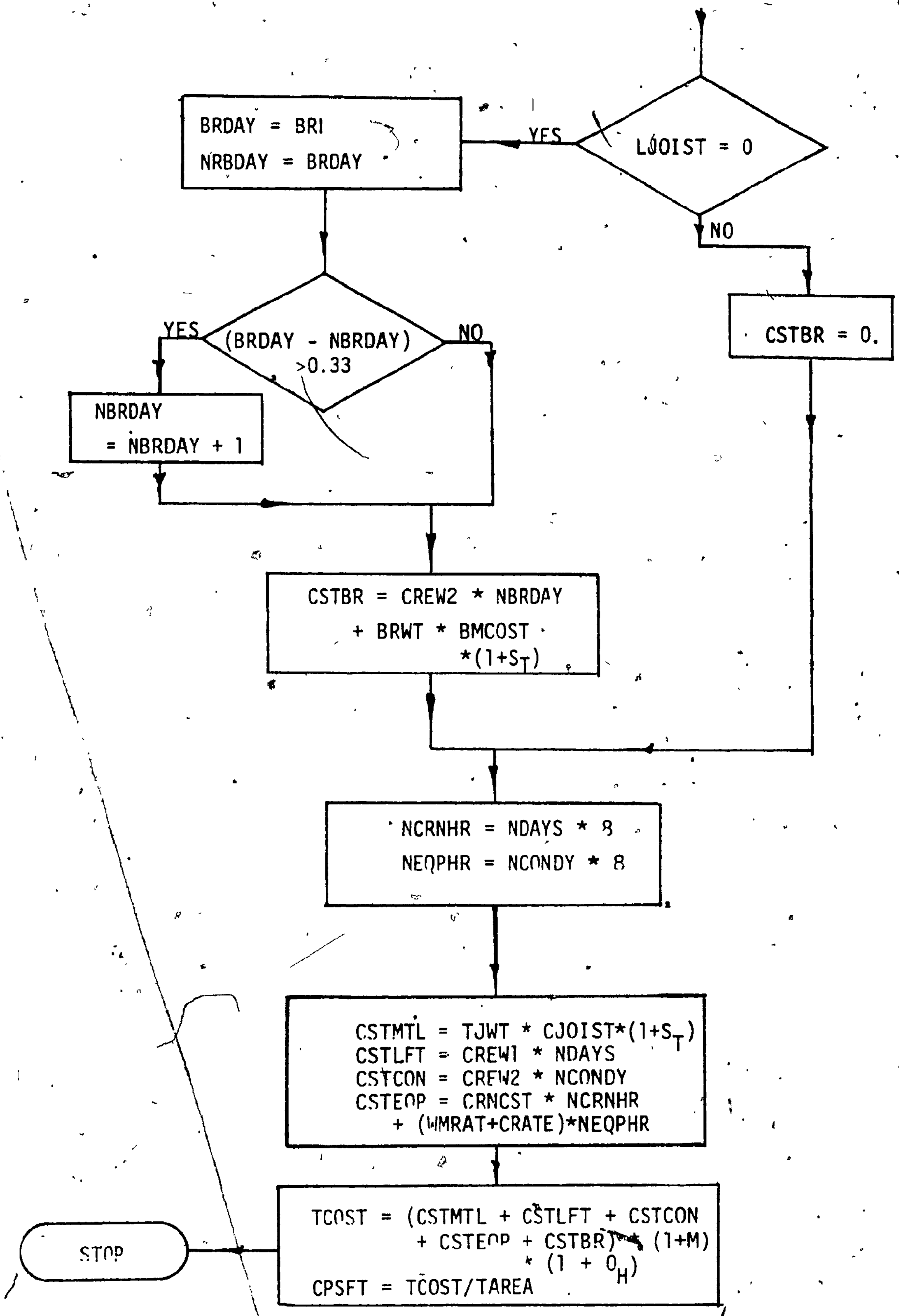
APPENDIX IV

General Cost Model for Roof System

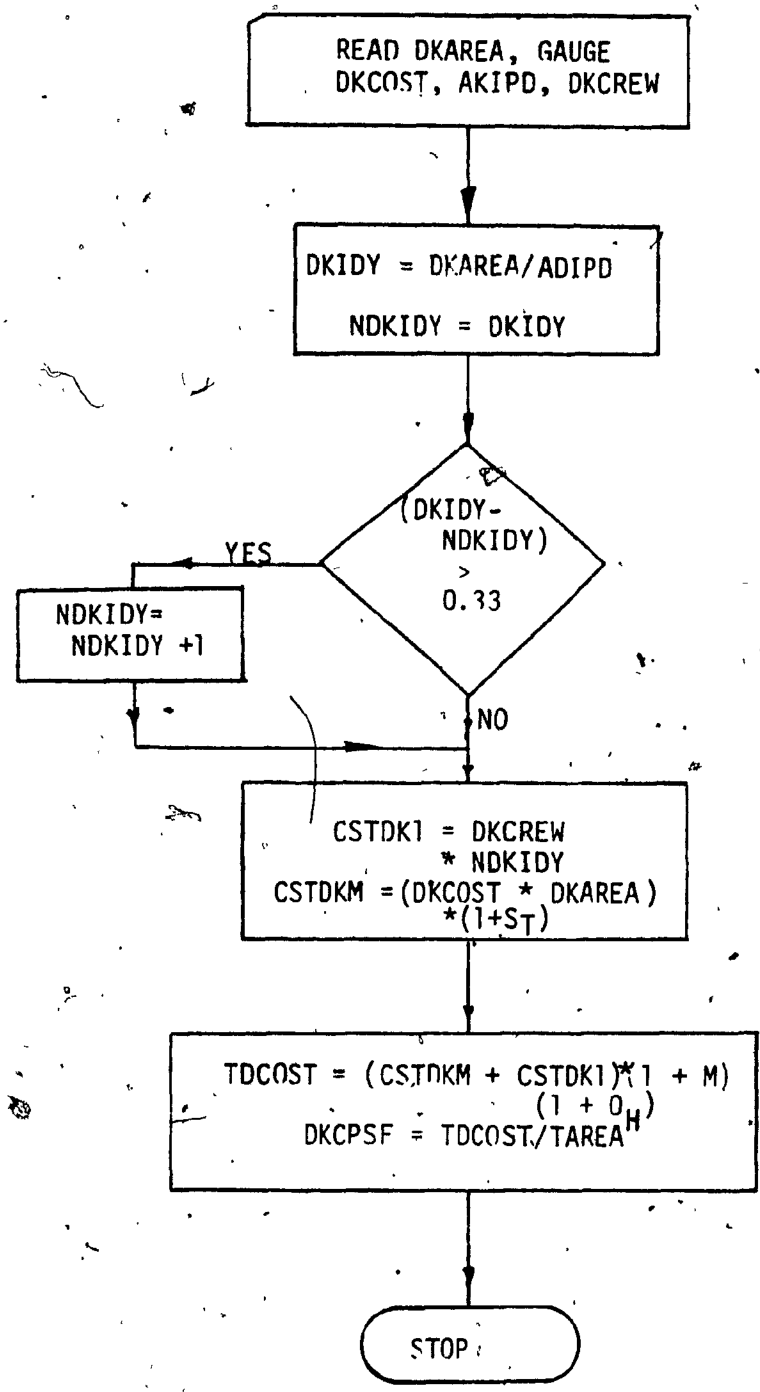
A. Flow Chart for Determination of Purlin and Joist Cost




NTLFT = NLPBY
*NPAN * NBAY
YES
LJOIST = 0
NO
NTLFT = NLPBY
*NBAY
DAYS = NTLFT/ NLPD
NDAYS = DAYS
(DAYS - NDAYS)
≥0.33
YES
NDAYS = NDAYS + 1
NO
TJOIST = NPRN
* NBAY
YES
LJOIST = 0
NO
TJOIST = NJOIST *
NBAY* NPAN,
CONDAY = TJOIST/NJPDFC
NCONDY = CONDAY
NCONDY =
NCONDY + 1
YES
(CONDAY - NCONDY)
= 0.33
NO


LJOIST = 0
YES
NO
BRDAY = BRI
NRBDAY = BRDAY
(BRDAY - NBRDAY) >0.33
YES
NO
NBRDAY = NBRDAY + 1
CSTBR = 0.
CSTBR = CREW2 * NBRDAY + BRWT * BMCOST *(1+S_T)
NCRNHR = NDAYS * 8
NEQPHR = NCONDY * 8
CSTMTL = TJWT * CJOIST*(1+S_T)
CSTLFT = CREW1 * NDAYS
CSTCON = CREW2 * NCONDY
CSTEQP = CRNCST * NCRNHR + (WMRAT+CRATE)*NEQPHR
TCOST = (CSTMTL + CSTLFT + CSTCON + CSTEQP + CSTBR) * (1+M) * (1 + O_H)
CPSFT = TCOST/TAREA
STOP

B. Flow Chart for Determination of Decking Cost



C. DEFINITION OF FLOW CHART TERMS

NLPD = No. of lifts per day

NJPLFT = No. of joists per lift

NJPDFC = No. of joists per day for connection

NBAY = No. of bays

NPAN = No. of structural steel truss panels

TJWT = Total purlins or joists weight

CREW1 = Rate of crew (4.5 persons) for lifting

CREW2 = Rate of crew (2.5 persons) for connections

CRNCST = Crane cost per hour including crane operator and oiler

WMRATE = Rate for welding machine

CRATE = Rate for compressor

CJOIST = Unit cost of purlin or joist

NPRN = No. of purlins per bay

NJOIST = No. of joists between two purlins

NLPBY = No. of lifts per bay

DAYS = No. of days required for lifting of purlins or joists

NTLFT = Total lifts

PANL = Joists length

TJOIST = Total purlins or joists

NCONDY = No. of days required for connection of purlins or joists

BRL = Total linear feet of bridging

HORBPB = Horizontal bridging per day in linear feet

NBRDAY = Total days required for bridging
BRWT = Total weight of bridging material
BMCOST = Cost of bridging material per linear feet
CSTBR = Total cost for bridging
NCRNHR = Crane hours required
NEQPHR = Equipment hours required
CSTMTL = Cost of material
CSTLFT = Cost for lifting of purlins or joists
CSTCON = Cost for the connection of material
CSTEQP = Equipment cost
TCOST = Total cost
CPSFT = Cost per ft^2 of purlin or joist
DKAREA = Total decking area
GAUGE = Decking gauge
DKCOST = Unit cost of decking
ADIPD = Unit area of decking installed per day
NDKIDY = Number of decking installation days
CSTDKI = Cost of installation of decking
CSTDKM = Decking material cost
DKCPSF = Decking cost per ft^2

and M, S_T and O_H are explained in Chapter 4.

D. Determination of Roof System Cost using General Cost Model - An Example

(i) Purlin Cost

Given data:

NPAN = 10

NPRN = 11

NBAY = 16

SPCAING = 32.5ft

NJPLFT = 1

NLPD = 55

NJPDFC = 33

CJOIST = $0.26/lbs.

CREW1 = $63.36/hr

CRNCST = $85.00/hr.

WMRATE = $ 2.00/hr.

CRATE = $ 1.75/hr.

TAREA = 52000 ft^2

M = 0.075

S_T = 0.08

O_H = 0.20

CREW2 = $35.20/hr.

TJWT = 13*32.5 * 16*11 = 74360.0 lbs.

NLPBY = 11/1 = 11

BTLFT = 11 * 16 = 176

DAYS = 176/55 = 3.2

NDAYS = 3

TJOIST = 11 * 16 = 176

CONDY = 176/33 = 5.33

NCONDY = 6

NCRNHR = 3 * 8 = 24 hrs.

NEQPHR = 6 * 8 = 48 hrs.

CSTMTL = 0.26*74360.0* 1.08 = $20880.29

CSTLFT = 8 * 63.36 * 3 = $1520.64

CSTCON = 8*35.20*6 = $1689.60

CSTEQP = 85.0*24 + (2.00 + 1.75)48 = $2220.00

TCOST = (20880.29 + 1520.64 + 1689.60 + $2220.00) *
(1.075)(1.20) = $33940.58

CPSFT = 33940.58/52000.00 = $0.653/ft^2

(ii) <u>Joist Cost</u>

Given data:

NJOIST	=	4	BRL	=	10400 ft
PANL	=	10.0 ft.	NORBPD	=	1200Lft/day
NJPLFT	=	4 (for PANL < 30')	BRWT	=	21008.0 lbs.
NJPDFC	=	80	BMCOST	=	0.1455
CJOIST	=	$0.25/lb.			

TJWT = 4*10*16*4*10 = 25600.0

NLPBY = 4/4 = 1

NTLFT = 10*16 = 160

DAYS = 160/55 = 2.9

NDAYS = 3

TJOIST = 4 * 10*16 = 640

CONDY = 640/80 = 8

NCONDY = 8

BRDAY = 10400/1200 = 8.667

NBRDAY = 9

CSTBR = 8 * 35.20*9 + 21008*0.1455*1.08 = $5835.60

NCRNHR = 8 * 3 = 24 hrs.

NEQPHR = 8*8 = 64 hrs.

CSTMTL = 0.25*25600.0*1.08 = $6912.00

CSTLFT = 8*63.36 * 3 = $1520.64

CSTCON = 8 * 35.20 * 8 = $2252.80

CSTEQP = 85.0*24 + (2.00 + 1.75) 64 = $2280.00

TCOST = (6912.00 + 1520.64 + 2252.80 + 2280.00 +
5835.60)(1.075)(1.20) = $24253.34

CPSFT = 24253.34/52000.00 = %0.466/ft^2

(iii) <u>Decking Cost</u>

Given Data:

DKAREA = 54600 ft^2

GAUGE = 20

DKCOST = $0.47/$ft^2$

ADIPD = 5160 ft^2/day

DKCREW = $70.4/hr.

DKIDY = 54600/5160 = 10.58

NDKIDY = 11

CSTDKI = 11*8*70.4 = $6195.20

CSTDKM = 0.47*54600*1.08 = $27714.96

TDCOST = (6195.20 + 27714.96)(1.075)(1.20) = \$43744.11

DKCPSF = 43744.11/52000.= \$0.841/ft^2

Cost per SFT of roof system = cost per SFT of purlins + cost per SFT of joist + cost per SFT of decking

= 0.653 + 0.466 + 0.841

= \$1.960/ft^2

APPENDIX V

EXHAUSTIVE SEARCH RESULTS

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	12646.15	210750.48	88933.99	99175.20	411505.82	7.91357	.00558
8	.07	12646.15	205238.51	88933.99	102374.40	409193.05	7.86910	.00542
8	.08	12646.15	195865.14	88933.99	105573.60	403018.88	7.75036	.00513
8	.09	12646.15	191349.56	88933.99	108772.80	401702.50	7.72505	.00499
8	.10	12646.15	190385.91	88933.99	111972.00	403938.05	7.76804	.00497
8	.11	12646.15	188673.56	88933.99	115171.20	405424.90	7.79663	.00492
8	.12	12646.15	188846.96	88933.99	118370.40	408797.50	7.86149	.00493
10	.06	12646.15	206210.31	94468.86	99175.20	412500.52	7.93270	.00537
10	.07	12646.15	206879.99	94468.86	102374.40	416369.40	8.00710	.00539
10	.08	12646.15	193846.64	94468.86	105573.60	406535.25	7.81799	.00499
10	.09	12646.15	191606.11	94468.86	108772.80	407493.92	7.83642	.00492
10	.10	12646.15	189995.51	94468.86	111972.00	409082.52	7.86697	.00488
10	.11	12646.15	190371.47	94468.86	115171.20	412657.69	7.93572	.00490
10	.12	12646.15	190963.57	94468.86	118370.40	416448.99	8.00863	.00492
12	.06	12646.15	205813.37	73460.40	99175.20	391095.11	7.52106	.00519
12	.07	12646.15	206890.32	73460.40	102374.40	395371.26	7.60329	.00523
12	.08	12646.15	195432.65	73460.40	105573.60	387112.79	7.44448	.00488
12	.09	12646.15	191979.28	73460.40	108772.80	386858.62	7.43959	.00476
12	.10	12646.15	192996.68	73460.40	111972.00	391075.22	7.52068	.00480
12	.11	12646.15	193649.20	73460.40	115171.20	394926.95	7.59475	.00483
12	.12	12646.15	193906.26	73460.40	118370.40	398383.20	7.66122	.00484
14	.06	12646.15	207944.12	71423.48	99175.20	391188.95	7.52286	.00503
14	.07	12646.15	207755.81	71423.48	102374.40	394199.84	7.58077	.00503
14	.08	12646.15	198144.68	71423.48	105573.60	387787.91	7.45746	.00473
14	.09	12646.15	198838.34	71423.48	108772.80	391680.77	7.53232	.00476
14	.10	12646.15	199778.15	71423.48	111972.00	395819.78	7.61192	.00479
14	.11	12646.15	197201.45	71423.48	115171.20	396442.29	7.62389	.00472
14	.12	12646.15	198712.36	71423.48	118370.40	401152.39	7.71447	.00477
16	.06	12646.15	211310.69	75127.95	99175.20	398259.98	7.65885	.00511
16	.07	12646.15	204158.28	75127.95	102374.40	394306.78	7.58282	.00490
16	.08	12646.15	201097.08	75127.95	105573.60	394444.78	7.58548	.00480
16	.09	12646.15	200946.44	75127.95	108772.80	397493.34	7.64410	.00480
16	.10	12646.15	203355.63	75127.95	111972.00	403101.73	7.75196	.00489
16	.11	12646.15	204152.28	75127.95	115171.20	407097.59	7.82880	.00492
16	.12	12646.15	204776.06	75127.95	118370.40	410920.56	7.90232	.00495

GENERAL COST MODEL RESULTS - TRUSS SPACING 20.00 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	10749.90	190332.60	91051.70	99175.20	391309.41	7.52518	.00570
8	.07	10749.90	178091.42	91051.70	102374.40	382267.42	7.35130	.00534
8	.08	10749.90	173707.91	91051.70	105573.60	381083.12	7.32852	.00521
8	.09	10749.90	170213.24	91051.70	108772.80	380787.65	7.32284	.00511
8	.10	10749.90	165016.19	91051.70	111972.00	378789.79	7.28442	.00495
8	.11	10749.90	163485.38	91051.70	115171.20	380458.19	7.31650	.00491
8	.12	10749.90	167012.75	91051.70	118370.40	387184.76	7.44586	.00504
10	.06	10749.90	186608.66	97854.39	99175.20	394388.15	7.58439	.00557
10	.07	10749.90	174933.66	97854.39	102374.40	385912.35	7.42139	.00522
10	.08	10749.90	171226.72	97854.39	105573.60	385404.61	7.41163	.00511
10	.09	10749.90	169655.72	97854.39	108772.80	387032.81	7.44294	.00507
10	.10	10749.90	162813.52	97854.39	111972.00	383389.81	7.37288	.00486
10	.11	10749.90	165700.77	97854.39	115171.20	389476.27	7.48993	.00496
10	.12	10749.90	166859.99	97854.39	118370.40	393834.68	7.57374	.00501
12	.06	10749.90	186181.38	77786.95	99175.20	373893.43	7.19026	.00540
12	.07	10749.90	182265.43	77786.95	102374.40	373176.68	7.17647	.00529
12	.08	10749.90	170651.75	77786.95	105573.60	364762.20	7.01466	.00494
12	.09	10749.90	168287.70	77786.95	108772.80	365597.35	7.03072	.00487
12	.10	10749.90	166641.48	77786.95	111972.00	367150.32	7.06058	.00483
12	.11	10749.90	166588.90	77786.95	115171.20	370296.95	7.12110	.00483
12	.12	10749.90	169321.71	77786.95	118370.40	376228.96	7.23517	.00491
14	.06	10749.90	184309.15	74119.99	99175.20	368354.24	7.08374	.00510
14	.07	10749.90	182376.36	74119.99	102374.40	369620.65	7.10809	.00504
14	.08	10749.90	174343.33	74119.99	105573.60	364786.83	7.01513	.00480
14	.09	10749.90	170236.69	74119.99	108772.80	363879.39	6.99768	.00467
14	.10	10749.90	168463.46	74119.99	111972.00	365305.36	7.02510	.00463
14	.11	10749.90	169044.27	74119.99	115171.20	369085.37	7.09780	.00465
14	.12	10749.90	174643.65	74119.99	118370.40	377883.95	7.26700	.00485
16	.06	10749.90	188544.40	77017.85	99175.20	375487.35	7.22091	.00525
16	.07	10749.90	184768.67	77017.85	102374.40	374910.82	7.20982	.00514
16	.08	10749.90	177421.09	77017.85	105573.60	370762.44	7.13005	.00492
16	.09	10749.90	173096.30	77017.85	108772.80	369636.85	7.10840	.00479
16	.10	10749.90	173955.75	77017.85	111972.00	373695.50	7.18645	.00482
16	.11	10749.90	175578.98	77017.85	115171.20	378517.94	7.27919	.00488
16	.12	10749.90	178046.45	77017.85	118370.40	384184.59	7.38817	.00497

GENERAL COST MODEL RESULTS - TRUSS SPACING 26.00 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	10689.52	171843.38	96919.87	99175.20	378627.96	7.28131	.00575
8	.07	10689.52	162094.61	96919.87	102374.40	372078.39	7.15535	.00548
8	.08	10689.52	157781.82	96919.87	105573.60	370964.80	7.13394	.00535
8	.09	10689.52	153976.13	96919.87	108772.80	370358.31	7.12228	.00525
8	.10	10689.52	151261.71	96919.87	111972.00	370843.09	7.13160	.00518
8	.11	10689.52	151212.44	96919.87	115171.20	373993.02	7.19217	.00519
8	.12	10689.52	147995.61	96919.87	118370.40	373975.39	7.19183	.00509
10	.06	10689.52	178281.03	101938.03	99175.20	390083.78	7.50161	.00592
10	.07	10689.52	163109.99	101938.03	102374.40	378111.94	7.27138	.00550
10	.08	10689.52	151994.28	101938.03	105573.60	370195.42	7.11914	.00517
10	.09	10689.52	151554.06	101938.03	108772.80	372954.40	7.17220	.00517
10	.10	10689.52	149886.07	101938.03	111972.00	374485.61	7.20165	.00513
10	.11	10689.52	149576.54	101938.03	115171.20	377375.29	7.25722	.00513
10	.12	10689.52	148177.92	101938.03	118370.40	379175.86	7.29184	.00509
12	.06	10689.52	176271.36	84917.07	99175.20	371053.15	7.13564	.00571
12	.07	10689.52	163885.74	84917.07	102374.40	361866.73	6.95898	.00536
12	.08	10689.52	154839.28	84917.07	105573.60	356019.47	6.84653	.00510
12	.09	10689.52	154774.14	84917.07	108772.80	359153.52	6.90680	.00511
12	.10	10689.52	152230.03	84917.07	111972.00	359808.61	6.91940	.00504
12	.11	10689.52	151349.79	84917.07	115171.20	362127.57	6.96399	.00502
12	.12	10689.52	154216.18	84917.07	118370.40	368193.17	7.08064	.00511
14	.06	10689.52	178325.09	83955.98	99175.20	372145.79	7.15665	.00560
14	.07	10689.52	163855.24	83955.98	102374.40	360875.14	6.93991	.00519
14	.08	10689.52	155243.64	83955.98	105573.60	355462.74	6.83582	.00494
14	.09	10689.52	157538.33	83955.98	108772.80	360956.64	6.94147	.00503
14	.10	10689.52	156281.84	83955.98	111972.00	362899.35	6.97883	.00499
14	.11	10689.52	155362.16	83955.98	115171.20	365178.87	7.02267	.00497
14	.12	10689.52	160156.15	83955.98	118370.40	373172.06	7.17639	.00513
16	.06	10689.52	177917.65	88476.64	99175.20	376259.01	7.23575	.00566
16	.07	10689.52	166773.28	88476.64	102374.40	368313.85	7.08296	.00535
16	.08	10689.52	160693.40	88476.64	105573.60	365433.16	7.02756	.00519
16	.09	10689.52	160895.32	88476.64	108772.80	368834.28	7.09297	.00520
16	.10	10689.52	159856.23	88476.64	111972.00	370994.39	7.13451	.00518
16	.11	10689.52	159921.87	88476.64	115171.20	374259.24	7.19729	.00519
16	.12	10689.52	164077.49	88476.64	118370.40	381614.05	7.33873	.00532

GENERAL COST MODEL RESULTS - TRUSS SPACING 32.50 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	9717.21	175712.99	100075.41	99175.20	384680.81	7.39771	.00606
8	.07	9717.21	160313.74	100075.41	102374.40	372480.76	7.16309	.00566
8	.08	9717.21	147628.30	100075.41	105573.60	362994.51	6.98066	.00532
8	.09	9717.21	143145.52	100075.41	108772.80	361710.94	6.95598	.00520
8	.10	9717.21	142309.01	100075.41	111972.00	364073.63	7.00142	.00520
8	.11	9717.21	140017.79	100075.41	115171.20	364981.61	7.01888	.00514
8	.12	9717.21	137473.95	100075.41	118370.40	365636.97	7.03148	.00507
10	.06	9717.21	160594.82	107968.41	99175.20	377455.64	7.25876	.00569
10	.07	9717.21	155922.33	107968.41	102374.40	375982.35	7.23043	.00557
10	.08	9717.21	150331.33	107968.41	105573.60	373590.55	7.18443	.00542
10	.09	9717.21	145495.12	107968.41	108772.80	371953.54	7.15295	.00531
10	.10	9717.21	140422.33	107968.41	111972.00	370079.95	7.11692	.00515
10	.11	9717.21	141022.14	107968.41	115171.20	373878.97	7.18998	.00519
10	.12	9717.21	141734.62	107968.41	118370.40	377790.64	7.26520	.00522
12	.06	9717.21	162027.99	84208.38	99175.20	355128.77	6.82940	.00559
12	.07	9717.21	153080.71	84208.38	102374.40	349380.69	6.71886	.00535
12	.08	9717.21	150295.90	84208.38	105573.60	349795.08	6.72683	.00528
12	.09	9717.21	143352.86	84208.38	108772.80	346051.24	6.65483	.00511
12	.10	9717.21	144126.02	84208.38	111972.00	350023.60	6.73122	.00514
12	.11	9717.21	144519.55	84208.38	115171.20	353616.33	6.80031	.00516
12	.12	9717.21	140910.82	84208.38	118370.40	353206.80	6.79244	.00506
14	.06	9717.21	164207.27	86261.06	99175.20	359360.74	6.91078	.00558
14	.07	9717.21	153911.60	86261.06	102374.40	352264.27	6.77431	.00530
14	.08	9717.21	151638.22	86261.06	105573.60	353190.09	6.79212	.00525
14	.09	9717.21	146470.33	86261.06	108772.80	351221.40	6.75426	.00512
14	.10	9717.21	145228.83	86261.06	111972.00	353179.10	6.79191	.00509
14	.11	9717.21	145882.53	86261.06	115171.20	357032.00	6.86600	.00512
14	.12	9717.21	146884.90	86261.06	118370.40	361233.57	6.94680	.00516
16	.06	9717.21	166409.60	91346.80	99175.20	366648.81	7.05094	.00573
16	.07	9717.21	156590.89	91346.80	102374.40	360029.30	6.92364	.00547
16	.08	9717.21	154791.27	91346.80	105573.60	361428.87	6.95056	.00543
16	.09	9717.21	150056.44	91346.80	108772.80	359893.25	6.92102	.00533
16	.10	9717.21	148500.39	91346.80	111972.00	361536.39	6.95262	.00529
16	.11	9717.21	147619.25	91346.80	115171.20	363854.46	6.99720	.00527
16	.12	9717.21	149427.17	91346.80	118370.40	368861.58	7.09349	.00533

GENERAL COST MODEL RESULTS - TRUSS SPACING 40.00 FEET

NFANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CFSFT $/SFT	WFSFT T/SFT
8	.06	9260.80	189542.41	108174.52	99175.20	406152.93	7.81063	.00677
8	.07	9248.81	148838.29	108174.52	102374.40	368636.03	7.08915	.00574
8	.08	9260.80	144278.58	108174.52	105573.60	367287.51	7.06322	.00568
8	.09	9260.80	142599.48	108174.52	108772.80	368807.60	7.09245	.00564
8	.10	9260.80	137025.14	108174.52	111972.00	366432.46	7.04678	.00550
8	.11	9260.80	131681.29	108174.52	115171.20	364287.81	7.00553	.00535
8	.12	9260.80	134597.00	108174.52	118370.40	370402.72	7.12313	.00544
10	.06	9260.80	188079.27	109544.89	99175.20	406060.16	7.80885	.00665
10	.07	9260.80	149627.35	109544.89	102374.40	370807.45	7.13091	.00572
10	.08	9260.80	142006.22	109544.89	105573.60	366385.51	7.04588	.00552
10	.09	9260.80	145013.15	109544.89	108772.80	372591.64	7.16522	.00561
10	.10	9260.80	138395.57	109544.89	111972.00	369173.26	7.09949	.00544
10	.11	9260.80	135297.71	109544.89	115171.20	369274.61	7.10143	.00536
10	.12	9260.80	137231.32	109544.89	118370.40	374407.42	7.20014	.00542
12	.06	9260.80	184623.99	88703.79	99175.20	381763.77	7.34161	.00644
12	.07	9260.80	151824.40	88703.79	102374.40	352163.38	6.77237	.00564
12	.08	9260.80	150612.9[illegible]	88703.79	105573.60	354151.15	6.81060	.00562
12	.09	9260.80	141120.51	88703.79	108772.80	347857.89	6.68957	.00537
12	.10	9260.80	140340.[illegible]	88703.79	111972.00	350276.79	6.73609	.00535
12	.11	9260.80	139679.70	88703.79	115171.20	352815.48	6.78491	.00534
12	.12	9260.80	139179.12	88703.79	118370.40	355514.11	6.83681	.00534
14	.06	9260.80	181272.39	89978.84	99175.20	379687.23	7.30168	.00632
14	.07	9260.80	161120.90	89978.84	102374.40	362734.93	6.97567	.00584
14	.08	9260.80	153096.18	89978.84	105573.60	357909.42	6.88287	.00564
14	.09	9260.80	141838.91	89978.84	108772.80	349851.34	6.72791	.00534
14	.10	9260.80	143920.84	89978.84	111972.00	355132.47	6.82947	.00541
14	.11	9260.80	140476.77	89978.84	115171.20	354887.61	6.82476	.00532
14	.12	9260.80	143322.53	89978.84	118370.40	360932.56	6.94101	.00541
16	.06	9260.80	183691.19	97349.09	99175.20	389476.28	7.48993	.00650
16	.07	9260.80	155978.92	97349.09	102374.40	364963.22	7.01852	.00583
16	.08	9260.80	156313.68	97349.09	105573.60	368497.17	7.08648	.00585
16	.09	9260.80	144972.84	97349.09	108772.80	360355.54	6.92991	.00555
16	.10	9260.80	145751.03	97349.09	111972.00	364332.92	7.00640	.00558
16	.11	9260.80	142324.64	97349.09	115171.20	364105.73	7.00203	.00549
16	.12	9260.80	146781.14	97349.09	118370.40	371761.43	7.14926	.00563

GENERAL COST MODEL RESULTS - TRUSS SPACING 47.27 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	8966.67	185262.73	130856.77	99175.20	424261.36	8.15887	.00683
8	.07	8966.67	162659.74	130856.77	102374.40	404857.58	7.78572	.00634
8	.08	8966.67	149161.07	130856.77	105573.60	394558.11	7.58766	.00602
8	.09	8966.67	138003.59	130856.77	108772.80	386599.82	7.43461	.00574
8	.10	8966.67	133228.64	130856.77	111972.00	385024.08	7.40431	.00562
8	.11	8966.67	128564.07	130856.77	115171.20	383558.71	7.37613	.00550
8	.12	8966.67	123912.93	130856.77	118370.40	382106.76	7.34821	.00538
10	.07	8966.67	162839.16	148969.51	102374.40	423149.73	8.13749	.00660
10	.08	8966.67	144631.99	148969.51	105573.60	408141.76	7.84888	.00616
10	.09	8966.67	134196.41	148969.51	108772.80	400905.38	7.70972	.00589
10	.10	8966.67	134343.41	148969.51	111972.00	404251.58	7.77407	.00591
10	.11	8966.67	130762.26	148969.51	115171.20	403869.63	7.76672	.00581
10	.12	8966.67	130327.80	148969.51	118370.40	406634.37	7.81989	.00581
12	.06	8966.67	180371.35	142643.87	99175.20	431157.08	8.29148	.00714
12	.07	8966.67	157461.30	142643.87	102374.40	411446.23	7.91243	.00663
12	.08	8966.67	147087.93	142643.87	105573.60	404272.07	7.77446	.00638
12	.09	8966.67	134880.99	142643.87	108772.80	395264.32	7.60124	.00607
12	.10	8966.67	137876.22	142643.87	111972.00	401458.76	7.72036	.00616
12	.11	8966.67	133218.89	142643.87	115171.20	400000.62	7.69232	.00604
12	.12	8966.67	132723.93	142643.87	118370.40	402704.86	7.74432	.00603
14	.06	8966.67	182064.79	152279.23	99175.20	442485.90	8.50934	.00726
14	.07	8966.67	149555.70	152279.23	102374.40	413176.00	7.94569	.00651
14	.08	8966.67	142161.01	152279.23	105573.60	408980.52	7.86501	.00633
14	.09	8966.67	137743.17	152279.23	108772.80	407761.87	7.84157	.00622
14	.10	8966.67	137043.60	152279.23	111972.00	410261.51	7.88964	.00621
14	.11	8966.67	136873.79	152279.23	115171.20	413290.89	7.94790	.00622
14	.12	8966.67	133925.36	152279.23	118370.40	413541.66	7.95272	.00615
16	.06	8966.67	184254.72	166478.73	99175.20	458875.32	8.82453	.00757
16	.07	8966.67	149252.92	166478.73	102374.40	427072.71	8.21294	.00676
16	.08	8966.67	144635.46	166478.73	105573.60	425654.46	8.18566	.00665
16	.09	8966.67	142229.74	166478.73	108772.80	426447.94	8.20092	.00660
16	.10	8966.67	137323.25	166478.73	111972.00	424740.64	8.16809	.00647
16	.11	8966.67	139253.66	166478.73	115171.20	429870.26	8.26674	.00654
16	.12	8966.67	136562.85	166478.73	118370.40	430378.65	8.27651	.00647

GENERAL COST MODEL RESULT - TRUSS SPACING 52.00 FEET

NFANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CRSFT $/SFT	WPSFT T/SFT
8	.06	8425.27	182881.52	65824.10	99175.20	356306.09	6.85204	.00558
8	.07	8425.27	174161.88	65824.10	102374.40	350785.65	6.74588	.00542
8	.08	8425.27	159131.03	65824.10	105573.60	338954.00	6.51835	.00513
8	.09	8425.27	151684.62	65824.10	108772.80	334706.79	6.43667	.00499
8	.10	8425.27	149997.31	65824.10	111972.00	336218.68	6.46574	.00497
8	.11	8425.27	147205.33	65824.10	115171.20	336625.91	6.47358	.00492
8	.12	8425.27	147133.74	65824.10	118370.40	339753.51	6.53372	.00493
10	.06	8425.27	171773.13	65921.70	99175.20	345295.29	6.64029	.00537
10	.07	8425.27	172706.46	65921.70	102374.40	349427.82	6.71977	.00539
10	.08	8425.27	151824.65	65921.70	105573.60	331745.22	6.37972	.00499
10	.09	8425.27	148077.89	65921.70	108772.80	331197.66	6.36919	.00492
10	.10	8425.27	145259.74	65921.70	111972.00	331578.71	6.37651	.00488
10	.11	8425.27	145853.54	65921.70	115171.20	335371.71	6.44946	.00490
10	.12	8425.27	146478.22	65921.70	118370.40	339195.59	6.52299	.00492
12	.06	8425.27	167184.36	60238.09	99175.20	335022.91	6.44275	.00519
12	.07	8425.27	168759.38	60238.09	102374.40	339797.13	6.53456	.00523
12	.08	8425.27	150364.32	60238.09	105573.60	324601.27	6.24233	.00488
12	.09	8425.27	144535.90	60238.09	108772.80	321972.06	6.19177	.00476
12	.10	8425.27	146114.61	60238.09	111972.00	326749.96	6.28365	.00480
12	.11	8425.27	147214.71	60238.09	115171.20	331049.27	6.36633	.00483
12	.12	8425.27	147223.96	60238.09	118370.40	334257.72	6.42803	.00484
14	.06	8425.27	166627.07	56747.53	99175.20	330975.07	6.36491	.00503
14	.07	8425.27	166212.67	56747.53	102374.40	333759.87	6.41846	.00503
14	.08	8425.27	150667.66	56747.53	105573.60	321414.06	6.18104	.00473
14	.09	8425.27	151582.44	56747.53	108772.80	325528.04	6.26015	.00476
14	.10	8425.27	152907.95	56747.53	111972.00	330052.76	6.34717	.00479
14	.11	8425.27	148942.57	56747.53	115171.20	329286.58	6.33243	.00472
14	.12	8425.27	151059.29	56747.53	118370.40	334602.49	6.43466	.00477
16	.06	8425.27	167956.78	59089.87	99175.20	334647.12	6.43552	.00511
16	.07	8425.27	156477.61	59089.87	102374.40	326367.15	6.27629	.00490
16	.08	8425.27	151423.68	59089.87	105573.60	324512.43	6.24062	.00480
16	.09	8425.27	150955.69	59089.87	108772.80	327243.63	6.29315	.00480
16	.10	8425.27	154654.84	59089.87	111972.00	334141.98	6.42581	.00489
16	.11	8425.27	155933.73	59089.87	115171.20	338620.08	6.51192	.00492
16	.12	8425.27	156888.84	59089.87	118370.40	342774.38	6.59182	.00495

WEIGHT RELATED COST MODEL RESULTS - TRUSS SPCAING 20.00 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	7275.42	181527.57	72273.04	99175.20	360251.23	6.92791	.00570
8	.07	7275.42	162978.12	72273.04	102374.40	344900.99	6.63271	.00534
8	.08	7275.42	156115.79	72273.04	105573.60	341237.86	6.56227	.00521
8	.09	7275.42	150526.88	72273.04	108772.80	338848.15	6.51631	.00511
8	.10	7275.42	142296.25	72273.04	111972.00	333816.71	6.41955	.00495
8	.11	7275.42	139757.89	72273.04	115171.20	334477.56	6.43226	.00491
8	.12	7275.42	144473.63	72273.04	118370.40	342392.50	6.58447	.00504
10	.06	7275.42	172995.46	73737.00	99175.20	353183.09	6.79198	.00557
10	.07	7275.42	155105.23	73737.00	102374.40	338492.06	6.50946	.00522
10	.08	7275.42	149148.44	73737.00	105573.60	335734.47	6.45643	.00511
10	.09	7275.42	146580.55	73737.00	108772.80	336365.78	6.46857	.00507
10	.10	7275.42	135552.07	73737.00	111972.00	328536.50	6.31801	.00486
10	.11	7275.42	140078.67	73737.00	115171.20	336262.30	6.46658	.00496
10	.12	7275.42	141066.20	73737.00	118370.40	340449.03	6.54710	.00501
12	.06	7275.42	169387.47	67850.69	99175.20	343688.78	6.60940	.00540
12	.07	7275.42	163321.68	67850.69	102374.40	340822.20	6.55427	.00529
12	.08	7275.42	145195.29	67850.69	105573.60	325895.00	6.26721	.00494
12	.09	7275.42	141319.96	67850.69	108772.80	325218.87	6.25421	.00487
12	.10	7275.42	138605.97	67850.69	111972.00	325704.08	6.26354	.00483
12	.11	7275.42	138424.98	67850.69	115171.20	328722.29	6.32158	.00483
12	.12	7275.42	141887.53	67850.69	118370.40	335384.04	6.44969	.00491
14	.06	7275.42	163606.16	62603.38	99175.20	332660.16	6.39731	.00510
14	.07	7275.42	160493.33	62603.38	102374.40	332746.53	6.39897	.00504
14	.08	7275.42	147955.77	62603.38	105573.60	323408.18	6.21939	.00480
14	.09	7275.42	141373.52	62603.38	108772.80	320025.13	6.15433	.00467
14	.10	7275.42	138411.16	62603.38	111972.00	320261.97	6.15888	.00463
14	.11	7275.42	139225.21	62603.38	115171.20	324275.22	6.23606	.00465
14	.12	7275.42	147340.65	62603.38	118370.40	335589.85	6.45365	.00485
16	.06	7275.42	167052.97	65726.50	99175.20	339230.10	6.52366	.00525
16	.07	7275.42	161223.64	65726.50	102374.40	336599.96	6.47308	.00514
16	.08	7275.42	149664.45	65726.50	105573.60	328239.97	6.31231	.00492
16	.09	7275.42	142819.97	65726.50	108772.80	324594.70	6.24221	.00479
16	.10	7275.42	144077.06	65726.50	111972.00	329050.99	6.32790	.00482
16	.11	7275.42	146545.45	65726.50	115171.20	334718.58	6.43690	.00488
16	.12	7275.42	149662.25	65726.50	118370.40	341034.58	6.55836	.00497

WEIGHT RELATED COST MODEL RESULTS - TRUSS SPACING 26.00 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	7670.04	172258.56	79705.04	99175.20	358808.83	6.90017	.00575
8	.07	7670.04	158065.20	79705.04	102374.40	347814.67	6.68874	.00548
8	.08	7670.04	151597.42	79705.04	105573.60	344546.10	6.62589	.00535
8	.09	7670.04	145734.76	79705.04	108772.80	341882.63	6.57467	.00525
8	.10	7670.04	141138.66	79705.04	111972.00	340485.73	6.54780	.00518
8	.11	7670.04	141017.60	79705.04	115171.20	343563.87	6.60700	.00519
8	.12	7670.04	135901.35	79705.04	118370.40	341646.82	6.57013	.00509
10	.06	7670.04	179042.72	81266.60	99175.20	367154.55	7.06066	.00592
10	.07	7670.04	157176.75	81266.60	102374.40	348487.79	6.70169	.00550
10	.08	7670.04	140368.57	81266.60	105573.60	334878.80	6.43998	.00517
10	.09	7670.04	139636.09	81266.60	108772.80	337345.52	6.48741	.00517
10	.10	7670.04	136512.77	81266.60	111972.00	337421.39	6.48887	.00513
10	.11	7670.04	135968.38	81266.60	115171.20	340076.21	6.53993	.00513
10	.12	7670.04	133677.20	81266.60	118370.40	340984.23	6.55739	.00509
12	.06	7670.04	173998.89	76732.07	99175.20	357576.19	6.87647	.00571
12	.07	7670.04	155927.65	76732.07	102374.40	342704.15	6.59046	.00536
12	.08	7670.04	142311.38	76732.07	105573.60	332287.08	6.39014	.00510
12	.09	7670.04	141760.74	76732.07	108772.80	334935.63	6.44107	.00511
12	.10	7670.04	137720.53	76732.07	111972.00	334094.63	6.42490	.00504
12	.11	7670.04	136277.46	76732.07	115171.20	335850.76	6.45867	.00502
12	.12	7670.04	140629.88	76732.07	118370.40	343402.38	6.60389	.00511
14	.06	7670.04	174578.23	74315.08	99175.20	355738.55	6.84113	.00560
14	.07	7670.04	153527.03	74315.08	102374.40	337886.55	6.49782	.00519
14	.08	7670.04	140544.78	74315.08	105573.60	328103.50	6.30968	.00494
14	.09	7670.04	143628.57	74315.08	108772.80	334386.50	6.43051	.00503
14	.10	7670.04	141532.18	74315.08	111972.00	335489.31	6.45172	.00499
14	.11	7670.04	140038.77	74315.08	115171.20	337195.09	6.48452	.00497
14	.12	7670.04	147438.72	74315.08	118370.40	347794.24	6.68835	.00513
16	.06	7670.04	171718.65	78999.76	99175.20	357563.65	6.87622	.00566
16	.07	7670.04	155434.55	78999.76	102374.40	344478.76	6.62459	.00535
16	.08	7670.04	146021.95	78999.76	105573.60	338265.35	6.50510	.00519
16	.09	7670.04	146294.52	78999.76	108772.80	341737.12	6.57187	.00520
16	.10	7670.04	144643.82	78999.76	111972.00	343285.63	6.60165	.00518
16	.11	7670.04	144725.17	78999.76	115171.20	346566.17	6.66473	.00519
16	.12	7670.04	151037.39	78999.76	118370.40	356077.59	6.84765	.00532

WEIGHT RELATED COST MODEL RESULTS - TRUSS SPACING 32.50 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WFSFT T/SFT
8	.06	7068.17	188127.39	81634.89	99175.20	376005.65	7.23088	.00606
8	.07	7068.17	167840.44	81634.89	102374.40	358917.91	6.90227	.00566
8	.08	7068.17	150147.75	81634.89	105573.60	344424.41	6.62355	.00532
8	.09	7068.17	143583.88	81634.89	108772.80	341059.74	6.55884	.00520
8	.10	7068.17	141976.74	81634.89	111972.00	342651.80	6.58946	.00520
8	.11	7068.17	138472.34	81634.89	115171.20	342346.60	6.58359	.00514
8	.12	7068.17	134503.45	81634.89	118370.40	341576.91	6.56879	.00507
10	.06	7068.17	166337.70	84172.43	99175.20	356753.49	6.86064	.00569
10	.07	7068.17	159898.52	84172.43	102374.40	353513.51	6.79834	.00557
10	.08	7068.17	152125.49	84172.43	105573.60	348939.69	6.71038	.00542
10	.09	7068.17	144792.28	84172.43	108772.80	344805.68	6.63088	.00531
10	.10	7068.17	137604.35	84172.43	111972.00	340816.95	6.55417	.00515
10	.11	7068.17	137960.38	84172.43	115171.20	344372.18	6.62254	.00519
10	.12	7068.17	139016.00	84172.43	118370.40	348627.00	6.70437	.00522
12	.06	7068.17	166494.73	78000.83	99175.20	350738.92	6.74498	.00559
12	.07	7068.17	154070.14	78000.83	102374.40	341513.53	6.56757	.00535
12	.08	7068.17	150100.27	78000.83	105573.60	340742.87	6.55275	.00528
12	.09	7068.17	139616.72	78000.83	108772.80	333458.52	6.41266	.00511
12	.10	7068.17	140791.57	78000.83	111972.00	337832.56	6.49678	.00514
12	.11	7068.17	141292.90	78000.83	115171.20	341533.09	6.56794	.00516
12	.12	7068.17	135796.78	78000.83	118370.40	339236.17	6.52377	.00506
14	.06	7068.17	167657.32	78706.97	99175.20	352607.66	6.78092	.00558
14	.07	7068.17	153391.57	78706.97	102374.40	341541.10	6.56810	.00530
14	.08	7068.17	150201.82	78706.97	105573.60	341550.56	6.56828	.00525
14	.09	7068.17	142355.61	78706.97	108772.80	336903.55	6.47891	.00512
14	.10	7068.17	140414.65	78706.97	111972.00	338161.79	6.50311	.00509
14	.11	7068.17	141398.66	78706.97	115171.20	342345.00	6.58356	.00512
14	.12	7068.17	142858.80	78706.97	118370.40	347004.34	6.67316	.00516
16	.06	7068.17	168821.58	83977.23	99175.20	359042.18	6.90466	.00573
16	.07	7068.17	155265.26	83977.23	102374.40	348685.06	6.70548	.00547
16	.08	7068.17	152812.62	83977.23	105573.60	349431.62	6.71984	.00543
16	.09	7068.17	145682.05	83977.23	108772.80	345500.25	6.64424	.00533
16	.10	7068.17	143414.37	83977.23	111972.00	346431.77	6.66215	.00529
16	.11	7068.17	142036.94	83977.23	115171.20	348253.54	6.69718	.00527
16	.12	7068.17	144774.93	83977.23	118370.40	354190.73	6.81136	.00533

WEIGHT RELATED COST MODEL RESULTS - TRUSS SPACING 40.00 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	6841.37	209183.93	92025.27	99175.20	407225.77	7.83126	.00677
8	.07	6825.15	159123.54	92025.27	102374.40	360348.36	6.92978	.00574
8	.08	6841.37	153197.19	92025.27	105573.60	357637.44	6.87764	.00568
8	.09	6841.37	150868.39	92025.27	108772.80	358507.84	6.89438	.00564
8	.10	6841.37	142979.40	92025.27	111972.00	353818.04	6.80419	.00550
8	.11	6841.37	135133.30	92025.27	115171.20	349171.14	6.71483	.00535
8	.12	6841.37	139333.05	92025.27	118370.40	356570.10	6.85712	.00544
10	.06	6841.37	206223.90	89390.14	99175.20	401630.62	7.72367	.00665
10	.07	6841.37	158861.37	89390.14	102374.40	357467.28	6.87437	.00572
10	.08	6841.37	148391.43	89390.14	105573.60	350196.54	6.73455	.00552
10	.09	6841.37	152628.73	89390.14	108772.80	357633.04	6.87756	.00561
10	.10	6841.37	143259.49	89390.14	111972.00	351463.00	6.75890	.00544
10	.11	6841.37	138821.89	89390.14	115171.20	350224.60	6.73509	.00536
10	.12	6841.37	141617.00	89390.14	118370.40	356218.91	6.85036	.00542
12	.06	6841.37	201007.32	83075.90	99175.20	390099.79	7.50192	.00644
12	.07	6841.37	160284.37	83075.90	102374.40	352576.04	6.78031	.00564
12	.08	6841.37	158683.93	83075.90	105573.60	354174.80	6.81105	.00562
12	.09	6841.37	145557.17	83075.90	108772.80	344247.24	6.62014	.00537
12	.10	6841.37	144487.27	83075.90	111972.00	346376.53	6.66109	.00535
12	.11	6841.37	143541.14	83075.90	115171.20	348629.61	6.70442	.00534
12	.12	6841.37	142859.92	83075.90	118370.40	351147.59	6.75284	.00534
14	.06	6841.37	195762.51	84562.82	99175.20	386341.90	7.42965	.00632
14	.07	6841.37	171085.82	84562.82	102374.40	364864.41	7.01662	.00584
14	.08	6841.37	160611.80	84562.82	105573.60	357589.59	6.87672	.00564
14	.09	6841.37	145004.42	84562.82	108772.80	345181.41	6.63810	.00534
14	.10	6841.37	148014.23	84562.82	111972.00	351390.42	6.75751	.00541
14	.11	6841.37	143080.01	84562.82	115171.20	349655.40	6.72414	.00532
14	.12	6841.37	147176.14	84562.82	118370.40	356950.73	6.86444	.00541
16	.06	6841.37	197248.31	90613.86	99175.20	393878.75	7.57459	.00650
16	.07	6841.37	162836.49	90613.86	102374.40	362666.13	6.97435	.00583
16	.08	6841.37	163384.54	90613.86	105573.60	366413.38	7.04641	.00585
16	.09	6841.37	147887.04	90613.86	108772.80	354115.07	6.80991	.00555
16	.10	6841.37	149050.18	90613.86	111972.00	358477.42	6.89380	.00558
16	.11	6841.37	144160.22	90613.86	115171.20	356786.65	6.86128	.00549
16	.12	6841.37	150639.16	90613.86	118370.40	366464.79	7.04740	.00563

WEIGHT RELATED COST MODEL RESULTS - TRUSS SPACING 47.27 FEET

NPANL	DSR	FCOST $	BCOST $	RCOST $	CCOST $	TCOST $	CPSFT $/SFT	WPSFT T/SFT
8	.06	6673.81	204256.80	98879.62	99175.20	408985.43	7.86510	.00683
8	.07	6673.81	179177.86	98879.62	102374.40	387105.70	7.44434	.00634
8	.08	6673.81	162760.74	98879.62	105573.60	373887.78	7.19015	.00602
8	.09	6673.81	148205.15	98879.62	108772.80	362531.38	6.97176	.00574
8	.10	6673.81	141754.03	98879.62	111972.00	359279.46	6.90922	.00562
8	.11	6673.81	135209.68	98879.62	115171.20	355934.31	6.84489	.00550
8	.12	6673.81	128447.18	98879.62	118370.40	352371.01	6.77637	.00538
10	.07	6673.81	178130.32	109810.54	102374.40	396989.07	7.63441	.00660
10	.08	6673.81	155541.48	109810.54	105573.60	377599.43	7.26153	.00616
10	.09	6673.81	141581.22	109810.54	108772.80	366838.38	7.05458	.00589
10	.10	6673.81	141862.26	109810.54	111972.00	370318.61	7.12151	.00591
10	.11	6673.81	136863.86	109810.54	115171.20	368519.41	7.08691	.00581
10	.12	6673.81	136207.01	109810.54	118370.40	371061.76	7.13580	.00581
12	.06	6673.81	196694.08	114795.09	99175.20	417338.17	8.02573	.00714
12	.07	6673.81	170341.39	114795.09	102374.40	394184.68	7.58047	.00663
12	.08	6673.81	157397.77	114795.09	105573.60	384440.27	7.39308	.00638
12	.09	6673.81	141124.74	114795.09	108772.80	371366.43	7.14166	.00607
12	.10	6673.81	145389.58	114795.09	111972.00	378830.47	7.28520	.00616
12	.11	6673.81	138897.47	114795.09	115171.20	375537.56	7.22188	.00604
12	.12	6673.81	138275.49	114795.09	118370.40	378114.78	7.27144	.00603
14	.06	6673.81	197435.38	121161.88	99175.20	424446.27	8.16243	.00726
14	.07	6673.81	159148.33	121161.88	102374.40	389358.43	7.48766	.00651
14	.08	6673.81	149599.36	121161.88	105573.60	383008.65	7.36555	.00633
14	.09	6673.81	143646.68	121161.88	108772.80	380255.17	7.31260	.00622
14	.10	6673.81	142782.51	121161.88	111972.00	382590.20	7.35750	.00621
14	.11	6673.81	142607.35	121161.88	115171.20	385614.24	7.41566	.00622
14	.12	6673.81	138492.25	121161.88	118370.40	384698.35	7.39805	.00615
16	.06	6673.81	198684.53	132092.80	99175.20	436626.34	8.39666	.00757
16	.07	6673.81	157418.43	132092.80	102374.40	398559.44	7.66460	.00676
16	.08	6673.81	151469.00	132092.80	105573.60	395809.21	7.61172	.00665
16	.09	6673.81	148362.68	132092.80	108772.80	395902.09	7.61350	.00660
16	.10	6673.81	141788.21	132092.80	111972.00	392526.82	7.54859	.00647
16	.11	6673.81	144534.71	132092.80	115171.20	398472.52	7.66293	.00654
16	.12	6673.81	140858.86	132092.80	118370.40	397995.87	7.65377	.00647

WEIGHT RELATED COST MODEL RESULTS - TRUSS SPACING 52.00 FEET