FINAL REPORT

KNOWLEDGE BASED EXPERT SYSTEM FOR RATING FLORIDA BRIDGES
VOLUME I

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16. Abstract

The report presents the development of a prototype knowledge based expert system (REX1 and REX2 - **R**ating **EX**pert) for analysis and rating of highway bridges. The different bridge types considered are solid slab, voided slab, double-T, and segmental box girders. The system REX-1 utilizes the grillage analogy using space frame idealization for analysis of all bridge types except segmental box bridges. The rating of segmental box bridges is carried out in system REX-2 based on plane frame idealization. The system is designed to be user-friendly and requires minimal computer knowledge; it is entirely menu driven and easily workable. Data pertaining to standard bridge cross-sections have been stored in a database for easy access by the system. A rule-based module provides load and resistance factors based on the structural reliability concepts. Utilizing the grillage analogy eliminated the need for distribution factors in determining the live load effect. Segmental box bridge is checked for serviceability conditions, in which the time-dependent force effects, such as creep and shrinkage of concrete and relaxation of steel, are considered in the system resulting from stage-by-stage construction. Typical bridge types are chosen for illustration of rating using the system REX.

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SUMMARY

The report presents the development of a prototype knowledge based expert systems (REX-1 and REX-2 **R**ating **Ex**pert) for rating of highway bridges. Bridges are being subjected to an ever increasing. volume of heavy truck traffic, and a growing number of exceptional live loads such as heavy construction equipment, military vehicles, etc. This together with the effects of normal wear and tear, has made the assessment of bridge load carrying capacity a vital step in efficient bridge management.

The objective of this project is to develop a knowledge based expert system (REX - **R**ating **EX**pert) for automation of the process of analysis and rating of highway bridges. The development of REX system has been made in two phases. During the first phase, the system REX-1 was developed to include solid slab, voided slab AASHTO girder and slab and T-beam bridges. The segmental box bridge rating and time-dependent stresses were included in the system REX-2 during the second phase development. The system utilizes the grillage analogy using space frame idealization for analysis of all the bridge: types except; segmental box bridges, which are idealized` using plane frame elements.

The prototype system is designed to be user-friendly and requires minimal computer knowledge; it is entirely menu driven and easily workable. The tedious and mistake prone task of bridge idealization and calculation of the corresponding section properties has been automated. Mundane tasks such as the processing: of: large outputs and calculation of the rating-factors are now-performed by the` computer. The REX system has a built-in database containing a wide array of data pertaining to standard bridge cross sections, such as AASHTO girders, voided slab: units, etc. A rule-based module provides the-reliability based load factors. These factors - are intended to represent conditions existing based on field ' data obtained from a variety of locations using weigh-in-motion and other data gathering methods. Illustrative examples for typical bridge

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LIST OF SYMBOLS

$A, \bar{A}$	=	area of transformed and of age-adjusted transformed sections
A_c	=	area of concrete at the cross-section considered
$B, \bar{B}$	=	first moment of area of transformed section and of age-adjusted transformed section
c	=	depth of compression zone in a fully-cracked section
c_b	=	distance from centroidal axis of section to extreme bottom fiber
c_t	=	distance from centroidal axis of section to extreme top fiber
D	=	nominal dead load effect
$E, \bar{E}$	=	modulus of elasticity and age-adjusted elasticity modulus
e	=	eccentricity of the prestressing force in the concrete section measured from the centroid of the section; linear extension of a member
f_{ct}	=	strength of concrete in tension
G	=	shear modulus
$I, \bar{I}$	=	moment of area of transformed section and of age-adjusted transformed section; impact factor
I_x	=	moment of inertia in the longitudinal direction
I_y	=	moment of inertia in the transverse direction
J_g	=	girder torsional inertia
J_x	=	torsional inertia in the longitudinal direction
J_y	=	torsional inertia in the transverse direction
K	=	torsional coefficient
L	=	nominal live load effect; length of member
L_x	=	length of the longitudinal grillage member
L_y	=	length of the transverse grillage member

M	=	bending moment
M_1	=	primary moment due to prestressing
MAB_{zm}	=	moment applied by joint A to a member AB which is +ve clockwise about the z-axis of the member
M_2, M_s	=	secondary moment due to support reaction
M_d	=	moment due to dead load
M_l	=	moment due to live load
M_t	=	total moment
N	=	normal force
n	=	a factor to account for shear strains in the member stiffness matrix
P	=	prestressing force
P_y	=	center to center distance of circular voids
Q_m	=	twisting moment in a space frame member
R	=	reaction / downward force
RF	=	the rating factor
R_n, M_n	=	nominal resistance
r	=	radius of gyration of cross-section
S_b	=	section modulus with respect to extreme bottom fiber
S_t	=	section modulus with respect to extreme top fiber
s	=	crack spacing
T_m	=	axial tension force in a member
t	=	time; thickness of grillage element
t_v	=	diameter of circular voids
y	=	coordinate of any fiber, measured downwards from a reference point O; center of pressure;
β	=	shape factor used to account for shear deflections in the plane member flexibility matrix

β_1 , β_2	=	coefficients 0.5 or 1 as specified below Eq. (31)
γ	=	slope of stress diagram
γ_D	=	dead load factor
γ_L	=	live load factor
δ	=	deflection
Δ	=	increment or decrement
ε	=	normal strain
$\Delta\sigma_{pr}$, $\Delta\bar{\sigma}_{pr}$	=	intrinsic and reduced relaxation of prestressed steel
ν	=	poisson's ratio
σ	=	stress
ϕ	=	creep coefficient; capacity reduction factor
ϕAB	=	angle of rotation at the end A of a member AB relative to the line through A and B.
θ	=	the end slope
χ	=	aging coefficient
χ_r	=	relaxation reduction factor
ψ	=	curvature (slope of strain diagram)

Subscripts

c, ps, ns	=	concrete, prestressed and nonprestressed steel
cs	=	shrinkage of concrete
o	=	initial time
O	=	reference point

CHAPTER 1

INTRODUCTION

19.1 INTRODUCTION

The bridge engineer responsible for operating and maintaining bridges on a modern roadway system is continually faced with a task of evaluating the load carrying capacity of existing bridges. These bridges have been constructed to meet a wide range of different design criteria which can result: in a large variation in live load capacities. Several other factors *such as* changing: live load configurations, structural modifications; deterioration, and, actual load frequencies are continually altering the conditions at *each* bridge. The existing.bridges :need to be evaluated with due consideration to both safety and serviceability, which: should be highly dependent on the bridge location, :functional classification of highway system, expected vehicle types and configurations, multiple presence of 'vehicles, peak loads, etc.

Knowledge based expert systems have been applied successfully to diagnosis problems. Expert systems have also been developed for fault detection, prediction, interpretation, monitoring, planning; and design problems. They use the :knowledge and inference procedures of human: experts to solve ill-structured problems. This is in contrast to a conventional computer program which is 'algorithmic in nature; using.- precisely defined logical formulae and data. The largest :portion of expert system studies' has: been in the--areas. of pavements and :traffic. Expert systems can capture currently residing knowledge in a particular domain and make it available to bridge engineers through knowledge-based tutorials. They can automate mundane and repetitive tasks such as bridge analysis, design, rating and management and provide ready access to information in manuals and codes. Knowledge-based expert systems can emulate expert colleagues to advise engineers in solving difficult problems.

1. 2 OBJECTIVE-AND SCOPE

This project presents the development of the expert system (REX - Rating EXpert) for automation of the process of analysis and strength determination of highway bridges. This utilizes the expert system technology together with the ` methods of" analysis in the bridge evaluation process. The different bridge types considered are solid slab, voided slab, AASHTO girder and slab, double-T beams and segmental box girders:

Chapter 2 reviews different methods for bridge analyses, evaluation. processes and expert system applications in engineering.

Chapter -3 presents the basic expert system architecture and expert system shells With their characteristic -features. The criteria for the choice¯ of EXSYS, the expert :system tool chosen for this study, are discussed along with knowledge representation in:EXSYS.

Chapter 4 discusses the relevant concepts in the analyses, the: cross sectional properties of different bridge types for space frame idealization, bridge load carrying capacity evaluation, and load and resistance factors:

Chapter 5 describes the construction and service load stresses in segmental box bridges taking into account the time-dependent creep and shrinkage effects.

Chapter 6 elaborates the design of the prototype rating expert system (REX) including the knowledge base system; the analysis and rating modules for different bridge types and the output-modules.

Chapter 7 presents illustrative examples for different bridge types:

The summary and conclusions are presented in Chapter. 8.

CHAPTER 2

LITERATURE REVIEW

21 INTRODUCTION

A Knowledge Based Expert System (**KBES**) is an intelligent computer program that uses the knowledge and inference procedures of human experts to solve difficult problems. A conventional computer program is, on the' contrary, algorithmic in nature, using precisely defined, logical formulae and data. Only; a few state transportation agencies have a significant experience in expert systems, whereas, most- have expertise in developing and using conventional programs:

Bridge analysis and evaluation have realized great strides in recent years. Higher levels of analysis and more realistic evaluations are achievable through the use of ` computers. Considerable work has been carried out in the development of expert systems since their inception; in the 1960's. The following sections discuss the various methods of bridge analysis: and applications of expert systems in the field of civil engineering.

2 2 BRIDGE ANALYSIS

The word analysis implies the conceptual breaking up of a whole into parts so that one can have an insight into the complete entity. In the context of bridges, analysis refers to force analysis, a process of determining the distribution of force effects or responses, such as deflections and bending moments, in the various components of the structure. Methods of transverse load distribution analysis of highway bridges range in sophistication from the -overly simplified American Association of State Highway and Transportation Officials (AASHTO) methods to highly complex finite element :methods [1]. Whereas the AASHTO methods are simple and conservative, the finite element methods require complex programs and are costly and. prone to common errors: These: various methods, both AASHTO and refined, are surveyed in the following sections.

Within a span of approximately 30 years, from roughly 1950 to 1980, the science of bridge analysis has undergone major change. Following the advent of the digital computer, and the consequent development of analytical techniques based upon its use, the bridge designer has available today a number of powerful analytical tools in the so-called refined methods of analysis [2]:

2.2.1 AASHTO

AASHTO's Standard Specifications for Highway ,Bridges, is the guide for most bridge design in the United states. Many of the provisions in the specifications are based on empirical studies. A typical specification states that the distribution of wheel loads in longitudinal beams carrying concrete deck on I-beam stringers or prestressed concrete girders-. on one lane of traffic is S/7.0 (for S<14') [3]. A principal assumption underlying the analysis methods of AASHTO is that bridges of a given type all behave similarly with respect to their live load distribution properties [2].

2.2.2 Finite Difference Method

In the method of finite differences, a slab is first divided into a grid. At each station in the grid, a linear equation relating the transverse deflections at a group of neighboring stations is formed. Simultaneous solution of these equations provides the value of deflection and in turn the moments can be determined [4].

2.2.3 Finite Element Method

In the: finite. element method, the deflected surface is represented approximately by piece--wise. continuous, algebraic interpolation functions. A slab to be analyzed by the finite element method is first divided by a grid of mesh lines. Either the method of virtual work, or the minimization of total energy, is then used to form a set of linear simultaneous equations involving the displacements as the unknowns. Independent sets of 'stiffness' equations relating nodal forces to displacements are established and solved for deflections and moments and: forces are then determined from the known displacements [4]. This method is capable of representing all types of bridge superstructures [2].

Finite strip method is a particular case of the finite element method in which the element is in the form of a strip extending, in the case of a bridge from abutment, to abutment. By using this method a bridge superstructure can be idealized as a three-dimensional assembly of strips [1]. This method requires less computation and is, therefore, more economical.

2.2.4 Grillage Analogy

The term Grillage Analogy is used', to describe the analysis of slabs using one dimensional beams which are subjected to loads acting in the direction perpendicular to the plane of the assembly [1]. The flexural and torsional stiffnesses of the grillage members are determined, so that a close approximation of the behavior of the slab is obtained [4]. The stiffness method of analysis is used in the grillage analogy.

2.2.5 Semicontinuum Idealization

The semicontinuum idealization is a special case of the grillage analogy [1]. It can be used on most bridges where the longitudinal bending and torsional rigidities are, discrete and identifiable (i.e. webs or girders) and' the transverse bending and torsional rigidities are spread uniformly along the length of` the bridge. This leads to an idealization of a discrete: number of one dimensional longitudinal beams and a transverse medium in which the number of beams approaches infinity.

2.3 BRIDGE EVALUATION

Evaluation of a bridge involves determining its load carrying capacity by taking into account cross section, material: properties, and structure geometry. A more detailed evaluation can consider effects of deterioration. The bridge assessment can be performed through actual field testing using a rating vehicle or by using analysis methods and computer techniques.

2.3.1 Significance

Rating of bridges has become a major concern due to the large number of deficient bridges, economics, and changing live loads (in particular, heavier loads). In addition, the availability of more sophisticated analyses, other than the conservative approach used in design, enables a more realistic picture of bridge behavior. Realizing this `behavior aids as a guidance in establishing realistic allowable load limits on a particular bridge and may save an otherwise 'healthy' bridge from costly replacement:

2.3.2 Methods of Rating

"The problem in bridge evaluation is that: there is no current design practice" [5]. Various methodologies are used in conducting bridge testing'; and evaluation. These- vary from state to state and country to country. Translating the results: of bridge load tests into bridge load ratings depends on the type of test performed (diagnostic or proof), the analysis method employed (allowable stress, load factor, or load and resistance factor (LRFD)), and the structural characteristics of the bridge tested [6]. In addition, the load and resistance factor method as described by AASHTO may be considered [3].

Five rating schemes corresponding to the allowable stress, load factor, sufficiency, inventory and operating, and load and resistance factor methods are discussed below. The rating factor indicates the portion of the rating vehicle loading allowed on the bridge. A rating factor in excess of 1.0 indicates that the span is satisfactory for the rating load used, whereas a rating factor less than 1.0 indicates the span is not adequate for the rating load used.

The methods presented can be used to evaluate the bridge with respect to flexural strength, shear strength, fatigue, or cracking. The general relationship for determining the rating factors is as follows:

Rating factor for flexure:

$$RF = \frac{M_n - M_{DP}}{M_L} \qquad \text{...... (2.1)}$$

where

RF = the rating factor considering flexure.

M_n = nominal flexural strength

M_{DP} = factored girder moment due to all load cases

M_L = total factored girder moment due to live load with impact.

Rating factor for shear strength:

$$RF = \frac{V_n - V_{DP}}{V_L} \qquad \text{......(2. 2)}$$

where

RF = the rating factor considering shear.

R_n = nominal shear strength.

R_{DP} = shear strength due to all load cases

V_L = total factored shear due to live load with impact.

Rating factor for fatigue:

$$RF = \frac{f_A}{f_{rL}} \qquad \text{....(2. 3)}$$

where

RF = the rating factor considering fatigue.

f_A = allowable stress range.

f_{rL} = range between maximum tensile stress and minimum stress in straight reinforcement steel due to live load cases.

Rating factor for cracking:

$$RF = \frac{\sigma_A - \sigma_{DP}}{\sigma_L} \qquad ....(2.4)$$

where

RF = the rating factor considering cracking.

σ_A = allowable tensile stress which varies with $\sqrt{f'_c}$ and the type of rating.

σ_{DP} = stress at bottom of girder due to dead load and prestressing forces.

σ_L = stress at bottom of girder due to live load.

2.3.2.1 Allowable Stress Method

The load rating equation based on the allowable stress method [6] is:

$$RF = \frac{C - D}{K_1 L_R (1 + I)} \qquad ....(2.5)$$

where

RF = is the rating factor, which, when multiplied by the rating vehicle, gives the rating of the structure.

C = is the capacity of the member at operating level for the load effect being evaluated. The capacity of the member should be based on design drawings or specification values or the results of material strength tests.

D = theoretical dead load effect on the member.

L_R = theoretical live load effect on the member due to the rating vehicle.

I = impact factor based on AASHTO "Standard Specifications for Highway Bridges".

K_1 = adjustment factor which takes into consideration the results of the load test and the manner in which the results were obtained.

$$= \frac{100}{A_1\left(\frac{L_T}{L_M}\right)}$$

where

L_T = calculated theoretical test load effect on the member.

L_M = the measured test load effect on the member.

A_1 = coefficient to take into consideration load path redundancy, dead load to live load ratio, reliability of testing, and ability to determine the difference between observed and theoretical response.

2.3.2.2 Load Factor Method

The load rating equation for the load factor method [6] is:

$$RF = \frac{C - X_D D}{K_2 X_L L_R (1 + I)} \qquad \text{....(2. 6)}$$

where

RF, D, L_R, and I are as defined in Eqn. 2.1.

C = is the capacity of the member at operating level for the load effect being evaluated. This capacity should be calculated in accordance with the strength provisions of the AASHTO Design Specifications. The capacity of the member should be based on physical conditions at the time of the load test and the results of material strength tests for F_y or f'_c.

X_D = the load factor for the dead load effect on the member.

X_L = the load factor for the live load effect on the member due to the rating vehicle.

K_2 = adjustment factor which takes into consideration the results of the load test and other relevant factors.

$$= \frac{100}{A_2\left(\frac{L_T}{L_M}\right)}$$

where

L_T = calculated theoretical test load effect on the member.

L_M = the measured test load effect on the member.

A_1 = coefficient to take into consideration load path redundancy, dead load to live load ratio, reliability of testing, and ability to determine the difference between observed and theoretical response, and frequency of inspection and evaluation.

2.3.2.3 Sufficiency Rating

The sufficiency rating presented in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's* Bridges is *a* method *of* evaluating data by calculating *four* separate factors *to* obtain a *numeric value* which is indicative of bridge sufficiency to remain in service [7]. The resulting sufficiency rating is *a* qualitative *appraisal* where 100 percent *would* represent an entirely sufficient bridge and zero-percent would represent; an entirely insufficient bridge. A summary of the sufficiency rating factors and the sufficiency rating are shown in Figure 2.1.

2.3.2.4 Inventory and Operating Rating

The present method of evaluation provided in the *Manual* for: *Maintenance Inspection of Bridges* calls for each highway bridge to be rated at two levels [8]. The- first or upper level is referred to as the operating rating. The operating rating *provides* the absolute: maximum permissible live load the structure may carry. The second or lower level is referred to as the inventory rating. The inventory rating *provides* the live load that a structure can carry for an indefinite period of time.

The following general expressions will determine the ratings of the structure:

inventory strength analysis:

$$\phi R_n = 1.3D + 1.3\left(\frac{5}{3}\right)(RF)L(1+I) \qquad \text{....(2.7)}$$

or

$$RF = \frac{\phi R_n - 1.3D}{1.3\left(\frac{5}{3}\right)L(1+I)} \qquad \text{....(2.8)}$$

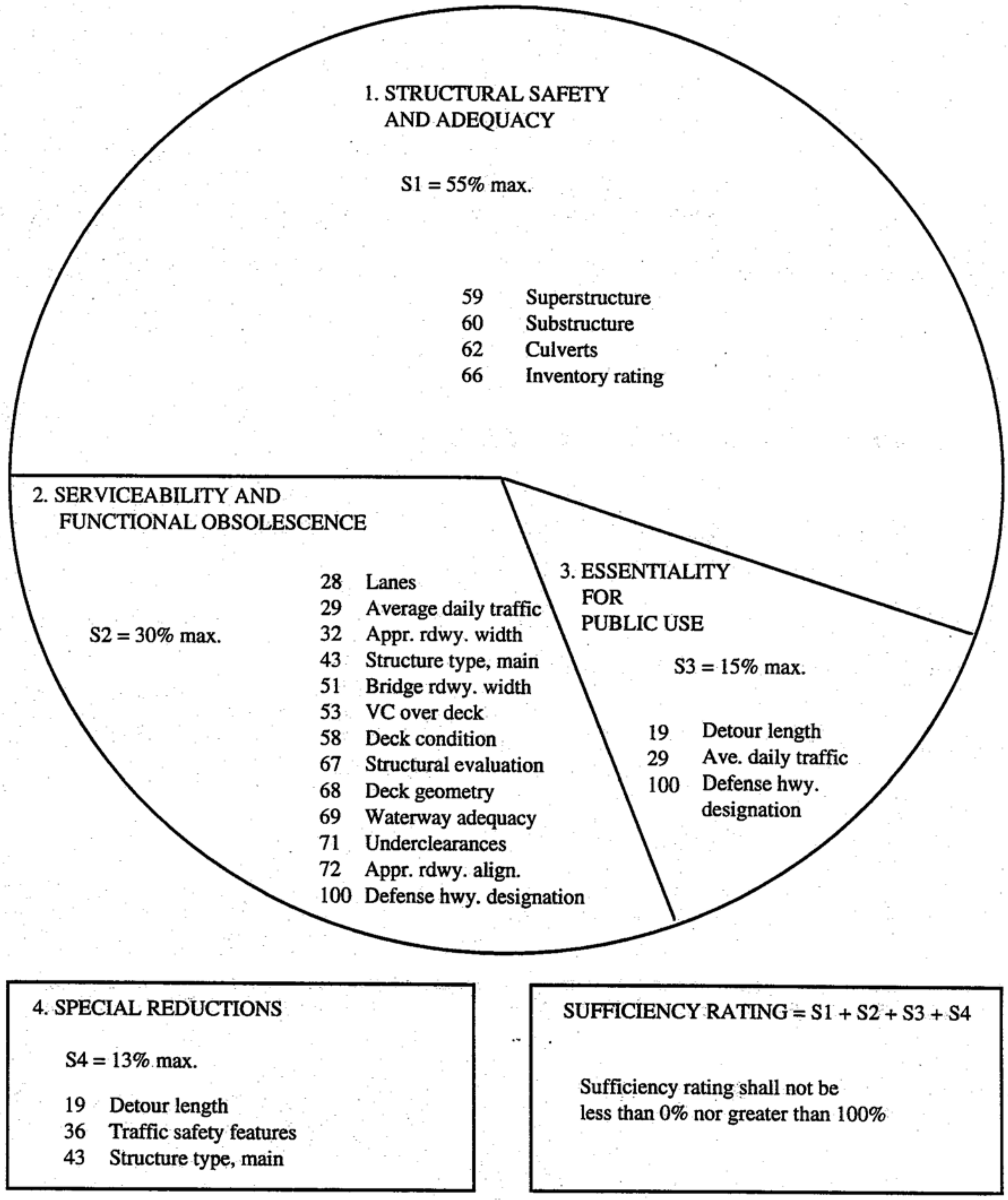


Figure 2.1 Summary of sufficiency rating [7]

operating strength analysis:

$$\phi R_n = 1.3D + 1.3(RF)L(1+I) \qquad \text{....(2. 9)}$$

or

$$RF = \frac{\phi R_n - 1.3D}{1.3L(1+I)} \qquad \text{....(2. 10)}$$

The *Manual for Maintenance Inspection of Bridges* stipulates that both conditions be satisfied in the rating of any section.

2.3.2.5 Load and Resistance Factor Method

The load rating equation for the load and resistance factor method [3,5] is:

$$RF = \frac{\phi R_n - \gamma_D D}{\gamma_L L(1+I)} \qquad \text{....(2. 11)}$$

where

RF = the rating factor

ϕ = the capacity reduction factor

R_n = the nominal resistance

γ_D = the dead load factor

D = the nominal dead load effect

γ_L = the live load factor

L = the nominal dead load effect

I = the impact factor

The selection *of* the load factors are based on structural reliability methods which eliminate the present AASHTO inventory and operating levels of evaluation.

Structural:: reliability method expresses safety in terms of a measure of the probability that the capacity will exceed- the - extreme load that may occur- during the inspection interval. Structural reliability theory is *now* being used to formulate safety checking equations throughout the world. In this procedure safety is expressed in terms of the safety index (beta), which is the number of standard deviations (depends on uncertainties) contained in the expected margin of safety (depends on the load and resistance factors).These safety indices correlate closely to the risk- or probability - that a bridge member loading *will* exceed its corresponding strength *or* capacity. Whereas the present AASHTO procedure leads to markedly different ratings by state agencies for the, same situation, the evaluation based on structural reliability theory aspires to provide a more rational, heterogeneous criteria for evaluation.

The rating based on reliability procedures depends on the load and resistance factors selected. These, in turn, depend on site traffic volume and potential truck overweight conditions, girder analysis used, observed deck smoothness, inspection effort and maintenance. All selections are intended to lead to the same reliability level because the factors were calibrated based on review of truck; data from weigh-in-motion (WIM) analysis studies, bridge tests, and strength studies [5]: .

Unlike the ratings put forth in the *Manual* for *Maintenance Inspection '* of Bridges, the rating based on structural reliability methods provides a means for accounting for the actual condition of the structure and quantifying other important factors that might be considered in the rating process.

2.4 BRIDGE MANAGEMENT [9]

Bridge management represents the end result following bridge evaluation. Many agencies responsible for bridges in the U.S. and abroad have been actively involved in the development of operating bridge management systems (BMSs) [10]. Following the catastrophic bridge collapse at Point Pleasant, W. VA, in 1967 a systematic approach to bridge inventory, rating, and posting programs were initiated.

The data base forms the basis for any BMS. The purpose of the data base is to identify first, all bridges for the BMS, and then be able to review, edit, and/or print related bridge information. It contains information relative to the bridge identification, structure type and material, age and service, geometric data, environment, navigation data, classification, condition, appraisal, load rating and posting, proposed improvements, and inspections.

The Pennsylvania Department of Transportation (Penn' DOT) implemented an operational BMS in 1987 [10]. It integrated several- data bases-containing bridge data into one data base with approximately 400 data elements. This BMS includes a priority ranking procedure based :upon minimum acceptable and desirable levels of service and the Federal Sufficiency Rating. It can provide cost estimating for maintenance/rehabilitation/replacement alternatives. North Carolina and Indiana along with other states are pursuing development of BMSs.

2.5 COMPUTER-AIDED BRIDGE CAPACITY RATING AND EVALUATION [11]

Several computer-aided analysis systems are available as a tool in determining the safe load carrying capacity of bridges. These systems are quite useful in determining the initial inventory and operating ratings of bridges.

2.5.1 Microcomputer Bridge Rating (BROOM)

The microcomputer software system; BROOM, was developed by the Center for Transportation Research,- New Mexico State University, through the - Rural Technology Assistance Program (RTAP) with funding through the Federal Highway Administration (FHWA). The system is user friendly and menu driven and runs on most microcomputers and analyses bridge superstructures for simple spans and up to three continuous spans. The material types include timber, voided concrete slabs, reinforced concrete beams or slabs, prestressed concrete AASHTO types, and steel girders of uniform or variable stiffnesses. The input data accepts uniform cross sections or variable section properties at the tenth point of each span.

The live load vehicle can have -a maximum of four axles with axle weights and spacing specified by the user or the user may choose any one of the standard live load vehicles - H, HS; Type 3, Type 3S2 or Type 3-3 trucks described in: the; AASHTO *Manual for Maintenance Inspection of Bridges [8].* The analysis of the bridge superstructure is two dimensional, where the wheel load distribution on the bridge is taken as he AASHTO wheel load distribution or a distribution chosen by the user. The bridge structure may be either composite or non composite.

The output includes the dead load, live load, and live load plus impact values for shear, moment, and deflection, at the tenth point of each span and: the corresponding stresses. The stress programs also compute the safe- load capacity for the bridge based on the stress analysis and the "allowable stresses"- chosen by the user. The user can quickly analyze any bridge for varying conditions once the data files have been generated. For example, a deteriorated or damaged bridge can easily be reevaluated based on the extent of the deterioration or damage.

2.5.2 Timber Bridge Rating Analysis (TIMBRE)

The Center for Transportation Research, New Mexico State University, developed the microcomputer program, TIMBRE, for the Rural Technology Assistance Program (RTAP) of the Louisiana State University [121 for analysis and rating timber highway bridges which are common on local road systems. The program has the capabilities to rate a timber bridge containing decay in one or more beams, in the. pile cap, or in any one of its piles, and would also consider timber bridges with missing parts or unevenly spaced parts. The program will handle bridge systems with upto three spans, fifty beams per span, and nine piles per bent. Live loads may be the standard H15 truck defined by AASHTO [8] or the "Louisiana truck".

The superstructure data includes; truck type, number of lanes; deck width and type, plank and beam dimensions, number of spans and lengths, beam spacings, dimensions and locations of decayed or damaged areas. The substructure data includes number of piles, pile cap dimensions, pile spacings, and dimensions, number and location of decayed or damaged piles, dimensions and locations of decayed or damaged areas:

The program analyzes the superstructure and- substructure based on the cross-sectional properties and the rating vehicle. The :output includes inventory and operating ratings for the . critical member of each span based on the shear and bending of the critical beam and for the deck. The inventory and operating ratings for the substructure are also determined in terms of the shear and bending of the pile caps and the capacity of the piles for each bent and abutment.

2.5.3 Bridge Rating and Analysis (BRASS)

A computerized method of determining the inventory and operating ratings was developed by Wyoming Highway Department sponsored by the Federal Highway Administration; (FHWA) [13]. The structural data: in the input include information from the "as constructed" plans and/or design file, the structural loading and the condition rating of the structural members, span length, cross-section dimensions, material properties, and structure type, e.g., rigid frame, slant leg, or continuous beam. The system also includes bridge design, deck design and review, girder section design. and review, and structural analysis.

2.5.4- Analysis- and Rating of Bridges (:BARS)

The BARS system was developed by the Control Data Corporation to perform inventory and operating ratings, postings, special permit analysis and analysis for bridge design. The structure: types include decking, stringers, floor beams, girders, and trusses. The, material types, which may be used in the analysis includes structural steels, reinforced and prestressed concrete and composite girder deck- system. The analysis is based on methods outlined in. the AASHTO specifications.

2.5.5 Bridge Analysis and Design (GRANDE)

The BRANDE system [14] was developed primarily to analyze the grid system of bridge superstructure and; rigid- frames -associated with either the superstructure or substructure.- It is designed based .on an elastic analysis, but a plastic analysis -is also available for behavioral studies of steel bridges. The basic geometric systems which are incorporated include the 'right and skew grids for bridge: superstructures and a general configuration for grids of frames of either superstructures or substructures.- Other desirable features include potential for inputting variable member properties, various support conditions with three to six degrees of freedoms per joint and an internal units conversion. Load types include concentrated loads on both joints and members, uniform loads, support settlements, and a deck load distribution approximation.

The output from BRANDE comprises of bending moments, torsion, shear, and axial forces at the member ends in addition to joint displacements and rotations. The user can opt for specifying part or all of the output for selected members, joints, or the entire structure.

2.5.6 >Reinforced Concrete Bridge Design (RCBD)

The prototype RCBD (Reinforced Concrete - Bridge - Design) ES [15] for selecting a reinforced concrete bridge was developed by using the VP-Expert development tool. RCBD is a rule - based ES that has more than 100 rules in its knowledge base. There are 12 different; types of bridges for the goal variables and: eight dependent variables for the bridge: span length, loading, soil condition, traffic condition, aesthetics, construction, completion time,, and maintenance (Table 2.1). Table 2.2 describes the ranges of variable SPAN LENGTH, which varies from very short to very long.

Table 2.1 RCBD knowledge base variables

Goal variables	Dependent variables
RC slab bridge	Span length
T- beam bridge	(e.g., very short, short,
RC box girder bridge	medium long,
Post tensioned slab bridge	very long)
Precast slab bridge	Loading
Post tensioned girder bridge	Soil condition
Precast girder and box bridge	Traffic
Rigid - frame bridge	Aesthetics
Arch bridge	Construction
Truss bridge	Time
Suspension bridge	Maintenance
Cable - stayed bridge	

Table 2.2 Variable span ranges

Ranges of Variable Span	Length (ft)
Very short	0 - 49
Short	50 - 199
Medium	200 - 599
Long	600 - 999
Very long	1000 ft or more

Typical rules in the knowledge base of **RCBD** are shown below:

ACTION

FIND Bridge

RULE 1

IF	Span length	= Short, and
	Loading	= Medium, or
	Loading	= Light, and
	Soil condition	= Normal

THEN Bridge = Reinforced concrete T-beams

RULE 2

IF	Span length	= Very long, and
	Loading	= Heavy, and
	Soil condition	= Excellent, and
	Aesthetics	= Very attractive
THEN	Bridge	= Cable-stayed bridge

A typical run consultation for RCBD is presented in Table 2.3.

Table 2.3 Sample of RCBD expert system interactive consultation

kb: **RCBD**. kbs loaded Welcome to the world of concrete bridges **RCBD** is an expert system to provide advice for bridge selection What is the value of SPAN-LENGTH ? Very short Short Medium Long Very long What is the value of LOADING ? Light Medium Heavy How is the SOIL CONDITION ? Normal Good Excellent The Bridge Selection is Cable- Stayed Bridge

2.5.7 Bridge Capacity Analysis (BRDG.CAP)

BRDG.CAP is a computer system developed to analyze steel girder bridges with localized flange losses or cracks in the girders [16]. Evaluation of such bridges for the safe load carrying capacity is a major concern for highway agencies. BRDG.CAP considers the redundant or secondary load paths which are normally not considered in the design or capacity analysis of bridges. Typical steel stringer bridges are rather highly redundant structures. The girders are continuously connected to a common concrete deck and to each other with strong diaphragms and bracing. This system considers the multigirder bridge system, its reserve capacity, and the secondary load paths present in these structures. Of the several bridges: analyzed, when no defect was present the bridges exhibited a large reserve capacity strength, on the average of five or six times an HS20 truck loading. When a girder' is damaged, the load is redistributed by the slab and diaphragms to the other girders, without further damage to the defective girder.

2:6:8 Bridge Routef-Evaluation (OVLOAD)

The computer program OVLOAD [17] has the capability of automatically checking potential overload situations against the capacity of every bridge along a proposed route. It consists of the main program which receives input data, reads stored data on bridges, determines whether or not a bridge is on the requested route, makes a comparison between the safe load capacity and- the required: capacity :via equivalent loading, and prints information on inadequate bridges. The three subroutines compute the equivalent HS loading for a given overweight vehicle on each:: particular bridge:

2.5.9 Computer Program for Bridge Analysis and Rating (BARE)

BAR6 [18] is an enhanced version of the Bridge Analysis and Rating computer program developed by the Pennsylvania'.. Department of Transportation to aid bridge engineers in analyzing-. a highway bridge to determine its load carrying capacity and estimate its' fatigue life. This can: analyze a simple span reinforced concrete T-beam-bridge or a slab bridge, a simple span prestressed concrete bridge; comprising of I-beams or box beams, or plank beams and a simple or continuous span steel bridge comprising of a deck, stringers, floorbeams, and girders or trusses. It can also analyze girders with in-span hinges and cantilever trusses. Computed values include reactions, moments, shears, truss member forces, stresses, deflections, rating factors, influence line. ordinates for various effects- at different sections and an estimated fatigue life of a steel girder or a truss. The structural and rating._- analysis are performed in accordance with the

AASHTO *Manual for Maintenance* Inspection of Bridges using the working stress method, whereas the fatigue life analysis is performed in accordance with the Pennsylvania Department of Transportation Design Manual Part 4.

2.6 EXPERT SYSTEMS IN STRUCTURAL ENGINEERING

Potential applications of artificial intelligence in structural engineering design and detailing were first proposed by Fenves and Noravbhoompipat [19]. Two expert; systems applied to structural engineering are discussed below.

26.1 SACON

SALON, an acronym for Structural Analysis CONsultant, is an expert system that aids the user in preparing the data for a large finite element program, MARL. It can take up to one year to master the use of MARL. SALON was developed to speed the process of familiarizing engineers with capabilities of the MARL program. It provides consultation on the best modeling approach for structural analysis programs. SALON uses a backward-chaining production rule approach, provided by EMYCIN, an expert system shell derived from MYCIN. The rules are, written in Interlisp language. The SALON expert system was, developed by a collaborative effort between the Heuristic Programming Project at Stanford University and the MARL Analysis: Research Corporation [20].

2.6.2 FACS

FRCS, an acronym for Flexible Automated Conversion System, is an expert system for guiding the creation of useful airframe models for finite element analysis. FEM techniques are difficult to use dn designing airframe structural systems due to the length of time required to generate analysis models manually. The basic approach was to supply, the computer with more than just the geometric description of the airframe model as is normally done in CAD systems, by including information such as manuals for analysis and modeling and expert knowledge.

The six components of the system are as follows:

i) geometry extractor: converts the geometric definition- of the user into a formatted model that can be used in the remaining components

i) classifier: decides the types of each discretized element in the geometric model that are to be used and conglomerates dimensional information on that segment from the geometric definition

iii) rule maintenance, system: rule base for the expert knowledge and inference rules

iv) inference engine: uses the rule base to choose the method with which to model the separate discredited elements of the geometry model

v) application. routine: performs, conversion of the model into generic finite element parameters according- to the method decided by the inference engine

vi) finite element translator: converts the generic representation of the application routine into :the syntax of the expected FEM package-,to be used in analysis:

The FAGS expert system was developed by B. Gregory and M. Shepard at Rensselaer University [21].

2.7 EXPERT SYSTEM APPLICATIONS TO BRIDGE ANALYSIS

"The procedure for rating of existing structures shall' require a careful evaluation of many complex and often conflicting factors in the continuing effort to extend the useful life of our highway bridges and safeguard the motoring public." [8]. One of the first programs for the rating of highway bridges utilizing expert system techniques was developed by Celal N. Kostem at Lehigh University [20;21]. This system and a few others are discussed below.

2.7.1 AASHTO Bridge Rating System

In this expert system two systems were developed in parallel. Each uses a significant database to store the expert knowledge important in the bridge design. The knowledge includes AASHTO bridge rating provisions, extensive data on overload of prestressed concrete highway bridges, and heuristics essential to decision making strategies. The database is structured in twodimensional spreadsheet format and the system designed for a forward-chaining process: within this database. Both systems contain in-core linear and nonlinear finite element modelers. The systems search the database for a bridge_ rating-(i.e. AASHTO, past cases, grillage analogy). If there is dissatisfaction with the rating, the finite element algorithms are triggered and the bridge is treated as a new design problem.

The two expert. systems represent two levels of development. In both systems, the inference process begins after initial input of the problem data. According to a user specified method of rating, the system responds with a conclusion according to that method. The expert system was developed by Celal N. Kostem at Lehigh University [20,21].

2.7.2 BRUFEM

BRUFEM, an acronym for Bridge Rating system Using Finite Element Modeling, performs bridge ratings. The system consists of three programs:

i) a preprocessor that develops a finite element model from a relatively small amount of input data about the geometry and stiffness parameters of the bridge

ii) a finite element. program, SIMPAL, to solve the model created by the preprocessor

ii) a post-processor that uses output from the finite element program and does the bridge rating based on the appropriate service level or strength criteria.

The system prepares a model for use by the finite element program SHVIPAL and from these results the bridge rating' is calculated [22].

2.7.3 KYBAS

KYBAS, an acronym for KentuckY Bridge Analysis System, was developed as a prototype framework to examine the use of artificial intelligence for highway girder bridge analysis and design.

The system is rule-based using the expert system shell, CLIPS, in a VAX environment. The rules are divided into the following five independent groups:

i) SUPERSTR: superstructure recommendation

ii) SUBSTR: substructure recommendation (under development)

iii) GEOMETRY: finite element analysis mesh -generation

iv) FORCES: analysis force vector generator recommendation

v) COST: preliminary cost-estimate (under development).

An initial rule, simple in nature starts the execution of the system. In GEOMETRY, the rules- in the input block are executed to obtain the bridge geometry, the system then :designs the mesh, and an input file is created. The finite element model is then invoked. Curbs and diaphragms are taken into account. In SUPERSTR, KYBAS will recommend the number of spans, bridge width, number of girders, AASHTO girder types, diaphragms, and :their related position. The FORCE rule group generates the necessary force vector. Each rule group can be executed independently, [22,231.

2.7.4 Bridge Rating Expert System

A bridge rating expert system was developed to a practical stage using Prolog-KABA, a treatment system for the prolog language, and its extension tool WING:

The system has two regions and seven main components. The <Process 1> region performs the inference process based on the input data and the inference result is output. The <Process2> region retrieves the knowledge, required for the: inference process from the knowledge base.

The concept of a membership function for the - fuzzy set theory was applied. Expert knowledge was' obtained from bridge rating experts via a questionnaire. The questionnaires content related the causes of deterioration to the various functions of a bridge, such as load carrying capacity, durability, and= serviceability expressed in a global hierarchical model. This process= quantified the expert knowledge and this knowledge is, in turn, converted into a membership function.

The inference mechanism uses fuzzy set theory in conjunction with forward reasoning followed by backward reasoning to infer goals and subgoals. The system determines and combines - membership functions at each subgoal to determine the condition (degree of soundness) of the bridge as viewed from the load carrying capability,. durability, and the serviceability of the target bridge, the final goal. The system was -developed at Kobe and Kyoto Universities in Japan [24].

The review of literature on expert systems in civil engineering shows that this is a viable and befitting approach to solve engineering problems. Knowledge based expert system advances have shown promise in standardizing the results' of analysis and evaluation and through automation provide a means of greatly reducing human error. The expert system proposed for the rating of bridges in this study can, therefore provide an efficient tool, in the, capacity evaluation of existing: and new bridges.

2.7.5 Bridge Design Expert System (BDES)

The Bridge Design Expert System (BDES) was- constructed [25] to explore the applications of expert systems to the design of bridge superstructures of short to medium spans. Figure 2.2 shows the steps in the bridge design process. The design space (Figure 2.3) represents all possible -bridge superstructure designs. Examples. of structural steel and prestressed superstructures included in the design. space of BDES are shown in Figure 2.2. The design space shown illustrates a treelike structure in which levels of the tree correspond to different design characteristics. Design space represents factual knowledge in, the knowledge base since the different .designs in the design, space are typically used standard designs.

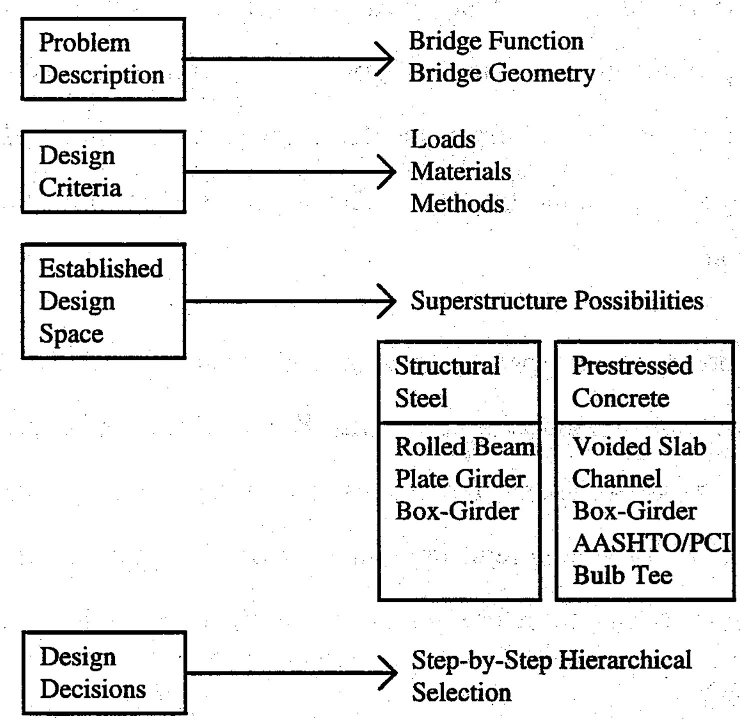


Figure 2.2 Design procedure

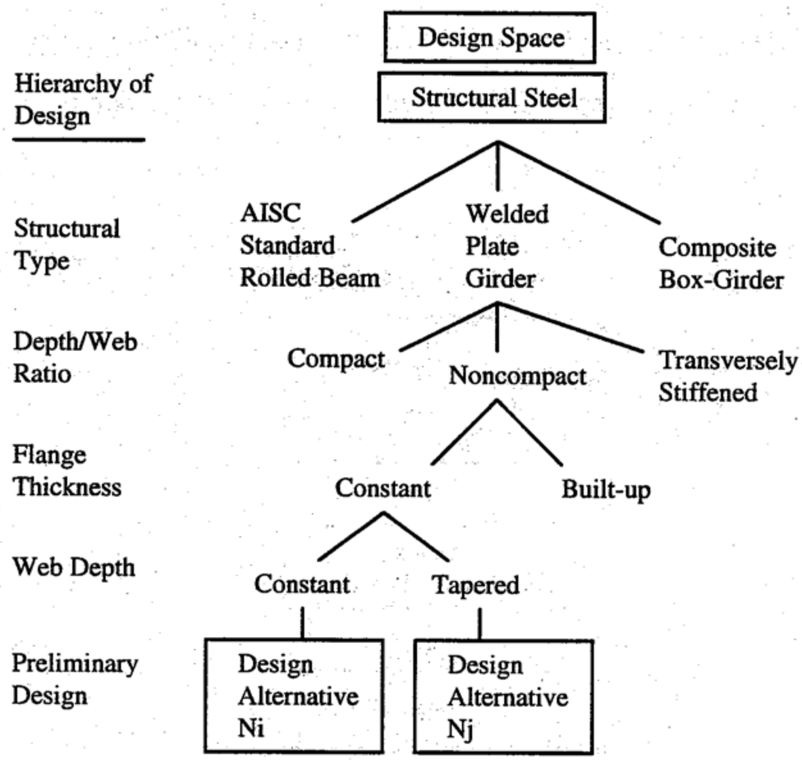


Figure 2.3 Design space

The design decisions , in the design process (Figure 2.4) include selecting a set of feasible design alternatives, sizing the members in the :alternatives, and comparing the alternatives to select a preliminary design. A step involving structural analysis is quite useful, which plays an important role in the design decisions. Heuristics knowledge, which includes rules of thumb, good judgment, and plausible reasoning governs decisions about appropriate selections. Typical rules include decisions to choose between`: steel or prestressed-concrete; among a compact, noncompact, or stiffened web; or between a constant or built - up :flange section:

BDES is highly user interactive with graphic capabilities to aid in input and output. The system requires the bridge geometry as minimal input. Graphic output displays various cross sections to illustrate clearly the designs generated by BDES. Figure 2.5 shows: a graphic output bridge geometry. Figure 2.6 shows the design recommendation generated by BDES corresponding to the geometry displayed in Figure 2.5. A graphic output of the girder cross sections for this design is shown in Figure 2.7

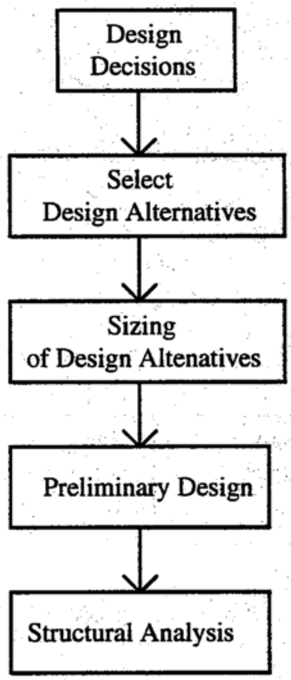


Figure 2.4 Design decisions

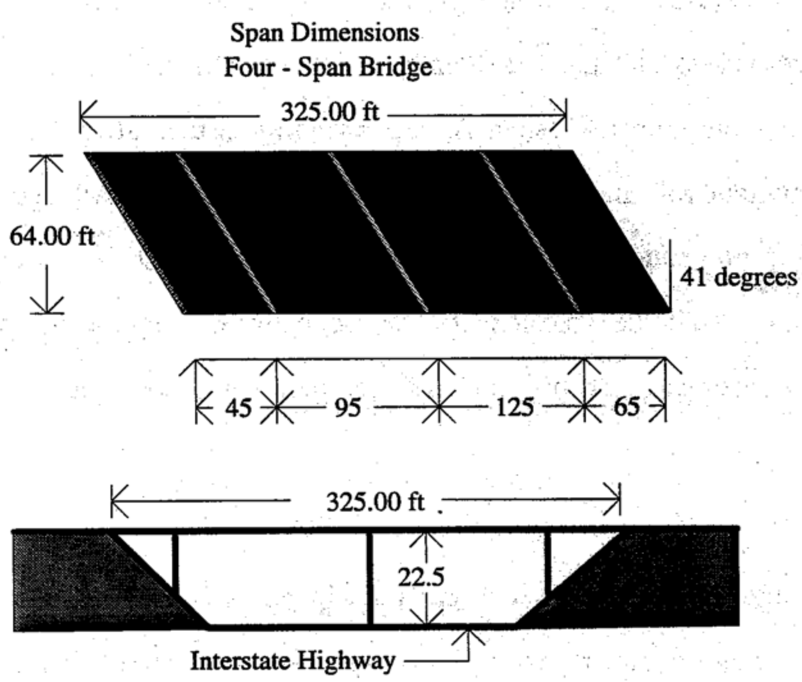


Figure 2.5 Bridge geometry

Superstructure Characteristics						
Material Type	Girder Type	Span Type	Length	Web	Flange	Depth
Structural Steel	Plate Girder	Simple Span 2	125 ft	Compact	Built-Up	Constant

Preliminary Design Data								
Girder Spacing	No. of Girders	Top Flange Plate		Web Plate		Bottom Flange Plate	
		Width	Thickness	Depth	Thickness	Width	Thickness
12.50 ft	5	11-3/4 in.	1-1/8 in.	60 in.	1-1/16 in.	16-3/16 in.	1-1/8 in.

Flange Build-Up					
Width	Bottom Flange	Length	Width	Top Flange Thickness	Length
11-3/4 in.	1/2 in.	56.3 ft	11-3/4 in.	1/2 in.	56.3 ft

Figure 2.6 Preliminary design alternative

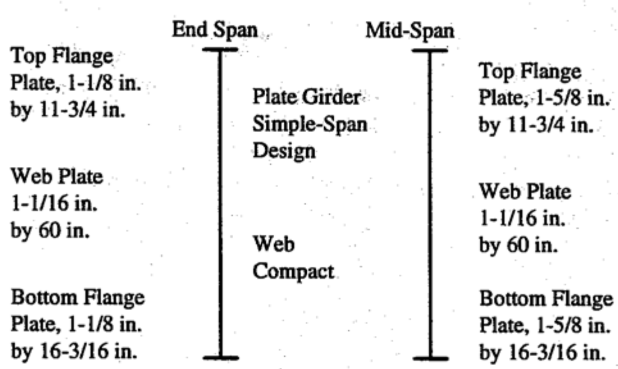


Figure 2.7 Girder cross section

2.8 Expert System for Determining the Disposition of Older Bridges (DOBES)

The expert system DOBES [26] is designed to make recommendations for bridge management as to the proper courses of action that should betaken, with regard to older highway bridges. The possible five basic options are: rehabilitation, improvement, replacement, abandonment, and routine maintenance. Based on an extensive set of rules, criteria, and procedures as currently used by bridge engineers, this expert system offers a computerized approach that should reduce the time needed to evaluate the older bridges yearly as well as to provide consistent basis for decision making.

CHAPTER 3

EXPERT SYSTEMS

3.1 INTRODUCTION

Knowledge-based expert systems (KBES) are identified by their method of representing and processing domain-specific, problem-solving knowledge. Thus the purpose of knowledge representation is to organize required information in a form such that the expert system can readily, access it for making decisions, planning;. analyzing, scenes, recognizing, objects and situations, drawing; conclusions. and other cognitive functions.

In order to solve complex problems encountered in artificial intelligence, one needs both a large amount of knowledge and some mechanisms for manipulating that knowledge to create solutions to new problems [27]. Methods of representing knowledge include the use of logic, rules, frames and semantic nets. These methods are well documented in published literature, among Rich and Knight (1991), Buchanan and Duda (1982), and Walters and Nielson (1988). Rule-based expert system, the most popular method and the method adopted for this study is detailed in this chapter along with expert -system architecture and the expert system shell EXSYS.

3.2 RULE-BASED KNOWLEDGE REPRESENTATION

Most *rule-based systems* can be classified as. production systems. The core idea of these tools is that the domain knowledge is represented in the form of modular rules known as production rules. The first part of the rule, called the antecedent, expresses a situation or premise while the second part, called the consequent, states a particular action or conclusion that applies if the situation or premise is true. The most common forms of production rules are of these formats:

ANTECEDENT	→	CONSEQUENT
SITUATION	→	ACTION
PREMISE	→	CONCLUSION

The first or left-hand part of the rule is a statement with the prefix IF. The second or right-hand part of the rule is a statement with the prefix THEN. The action, consequence or conclusion stated in the THEN part is valid and becomes part of the context, if the IF part of the rule is true or meets certain conditions. Production rules are by far the most popular and' widespread means of converting human knowledge into a format suitable for symbolic representation in a computer.

A set of production rules forms a production system to define some domain knowledge accurately, and this results in the solution of sub problem by inference, which is the clue of the final solution. For example, a set of production rules maybe of the form:

(abc)	→	(de)
(df)	→	(g)
(ghij)	→	(k)

These rules imply that if a, b, and c are true,d and e are fired. By using d which is obtained from the previous rule and f, new consequent g is generated, etc.

3.3 BASIC EXPERT SYSTEM: ARCHITECTURE

The three basic components of an expert system are the knowledge base, the context, and the inference engine. Additional components include a user interface and an explanation facility. The basic expert system architecture is shown in Figure, 3.1. The following sections, discuss the basic components.

3.3.1 The Knowledge Base

The knowledge base is the core of all expert systems. It is in the knowledge-base where the domain-specific, problem-solving knowledge and heuristics are stored. Facts are typically represented as declarative knowledge whereas heuristics- take the form of rules. In engineering domains knowledge is continually changing and expanding making it necessary to choose a method that is: easily modified.

3.3.2 The Context

The context is the component of the expert system that contains the information about the problem :currently being solved. The context initially contains the information that defines the parameters of the problem and, the expert system reasons about the given problem, the context expands and contains the information generated by the expert system to solve it Upon completion of the problem solving process of the expert system, the context' :contains all the intermediate results of the problem solving process in addition to the solution.

For example, a context in an expert system to assess abridge initially contains information regarding the geometrical properties of structure. The context would expand as the problem solving process progresses to include information about loads, load factor selection,

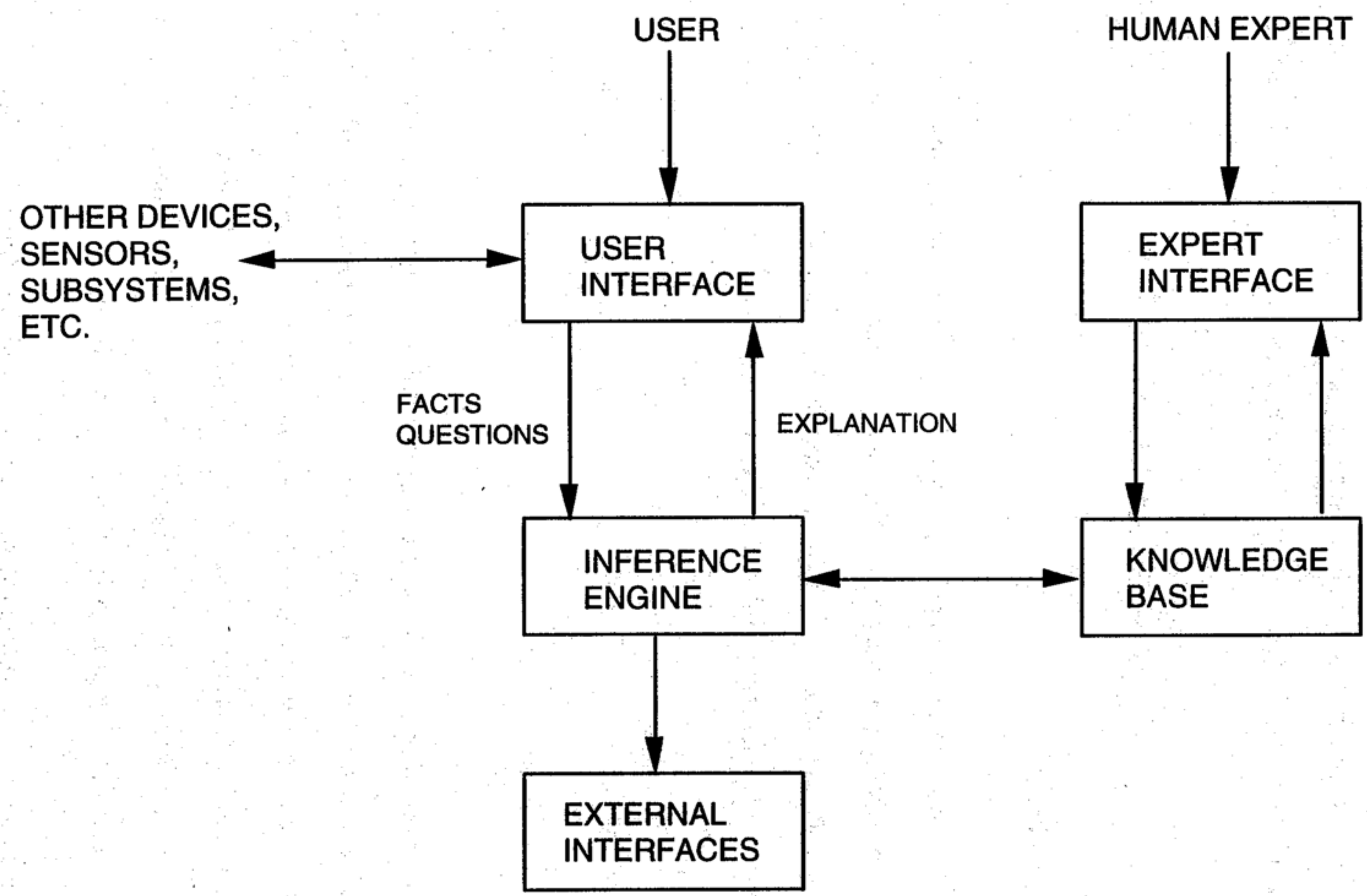


Figure 3.1 Expert system architecture

deterioration, etc. The context is a declarative form of the current state of the problem the expert system is solving.

3.3.3 The Inference Mechanism

The inference mechanism is that part- of the expert system that contains the control information. Also known as the rule interpreter in a rule-based system, it implements a search and pattern matching operation within the knowledge base to modify and expand the context information:

In a bridge rating system the inference engine will search for items regarding the interpretation of the rating factor. In a rule based expert system the reasoning strategy or search is a form of either of two fundamental reasoning strategies: forward chaining (fact driven) and backward chaining (goal directed' reasoning):

3.3.4 Backward and Forward Chaining

The object of a search procedure is to discover a path through a problem space from an initial configuration to a goal, state [27].

In the forward: chaining strategy a search for an answer is made -beginning with : some initial configuration(s) and working forward with an attempt to match that information with a rule. At each level of the search, the inference engine attempts to generate the following level by finding all the rules whose left sides, or IF parts, match a known fact or statement in the context. Once this occurs the rule is fired and the right side of the rule, or THEN, part is added to the context to produce new, configurations. This searching :and matching. process continues until a configuration that matches the goal state is reached:

In the backward chaining approach, the inference engine begins with the goal configuration(s). The next level is generated by searching for all rules whose right sides; or THEN parts, match the goal configuration(s). These are rules that, if they were applied would generate the goal configuration. If a match is found, the context is updated producing an intermediate configuration containing the right side, or the IF part of the :rule., The .chaining. process continues attempting to match the right side of the rule with the current status of :the: system. The process is complete when the configuration matches the initial state or no further inference can be made.

The choice of control strategy with either forward or backward chaining is determined by the design of the :system and the problem being solved. In general, it is more efficient to move from the smaller set of states to the larger set of states. It is also important to proceed in the direction that corresponds more closely with the way the user will think. Forward chaining makes more sense, if a new fact is likely to activate the problem solving process and if a question to which a response is desired is likely to :activate the: problem solving process, then backward chaining is more appropriate.

3.3.5 User Interface

The user interface is the facility portion of the expert- system. It allows the user and the expert system to interact in, a question answer format. The user interface asks questions or presents menu choices for entering the initial information. It also provides a means of communicating the answer or solution once it has been found.

3.4 EXPERT SYSTEM DEVELOPMENT

The major steps in development of an expert system are [Harmon and King, 1985]:

i) Selection of an expert system programming language, environment, or shell

ii) Selection of AI techniques for representation and inference mechanism

iii) Analysis, acquisition, and conceptualization of the knowledge to be included in the knowledge base

iv) Formalization and development of the knowledge base

v) Development of a prototype system using the knowledge base and AI tools

vi) Evaluation, review, and expansion of the expert system

vii) Refinement of the user interface

viii) Maintenance and updating of the system

This procedure was adhered to when developing the expert system REX presented in this study.

3.15 SELECTION OF AI TOOL

The selection of an expert system (ES) tool is. an. important step in the development of a knowledge based application. Shells can range. from very simple language interpreters to very complex development environments. Early expert systems and shells required large computers and commitments to large projects. Expensive research and development expert system shells are useful for fast prototype development; however they have limitations for delivery to the endusers who are; interested in shells which are portable, embeddable and system. Most development tools require large memories and a fair amount of processor horse power and therefore the systems developed on microprocessors today tend to be restricted in terms of the software, the size of the system and the capabilities which can be utilized in the system. Most microprocessor-based application, developments have used IBM PC-AT (or. compatible) computers.

3.5.1 Criteria ,for the Choice of the: Shell

Software development tools can be broadly divided into four categories (i) Large scale tools; (ii) Small scale tools; (iii) Specialized tools; and (iv) General purpose tools. Large scale tools can be fairly expensive, but offer a broad range of capabilities including comprehensive development environments for knowledge-based systems. They generally offer a range of forms of knowledge representation and several reasoning mechanisms. Like the large scale tools, small scale tools also provide a high level 'language' for knowledge-based application developments at a lesser cost with restricted capabilities in the types of knowledge representation, knowledge base size or reasoning. These tools are frequently designed to run on-microprocessor-based- systems. Specialized tools are designed to assist the user for particular types of applications and offer only a predetermined type of knowledge representation and reasoning capability. General purpose tools are used to construct a high-level tool.

The inherent characteristics; which can be- used to differentiate` one shell from the other can be broadly divided into functional, developmental, delivery and support features. The shell, functionality shall be matched with the application requirements; more: knowledge, engineering skill and training are required to use a more powerful developmental environment. Delivery of an expert system application in a given computing environment of the organization, would be an important step

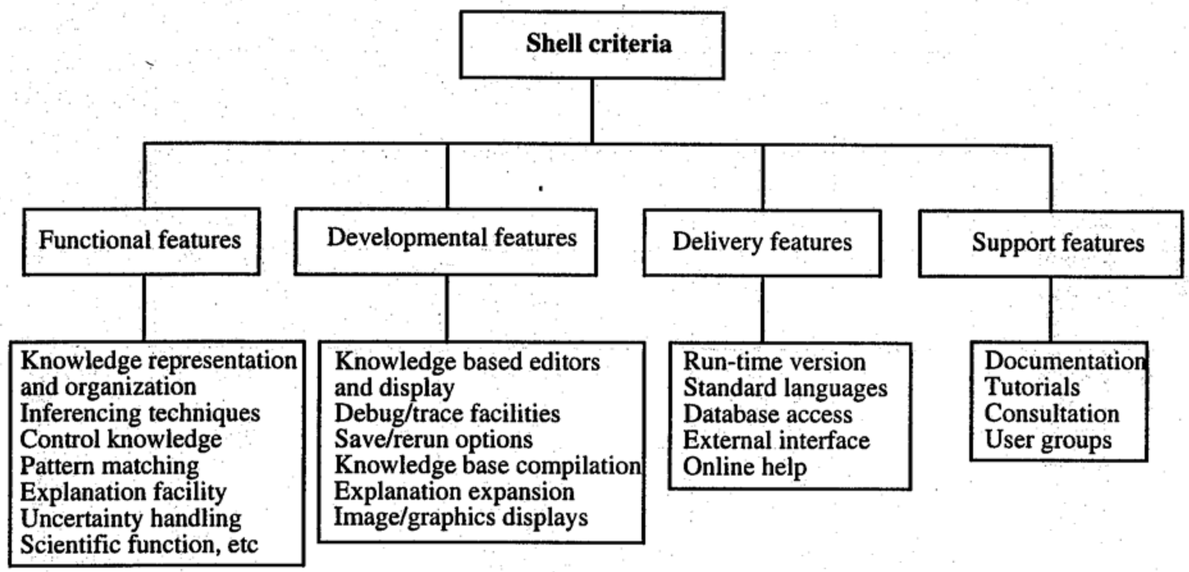


Figure 3.2 Shell features

Table 3.1 Comparison of shell features

Shells	Shell language	External routines	Database access	Data constraints	IF-THEN rules	Induction based rules	Certainty factors	Backward chaining	Forward chaining	KB compilation	Embeddable	Inference debug/trace
EXSYS -standard -professional	C	Y	Y	Y	Y	-	Y	Y	Y	Y	Y	Y
Level 5	PASCAL	-	Y	-	Y	-	Y	Y	-	Y	-	Y
Nexpert	C	Y	Y	-	Y	-	Y	Y	-	-	Y	Y
PC Easy	LISP	Y	Y	Y	Y	-	Y	Y	Y	-	-	Y
PC Plus	LISP	Y	Y	Y	Y	-	Y	Y	-	-	-	Y
VPExpert	C	Y	Y	Y	Y	Y	Y	Y	-	-	-	Y
KEE	LISP	Y	-	Y	-	-	-	Y	Y	-	-	Y

and other computer software, and already installed hardware. Figure 3.2 shows the above four features for the shells.

3:5:2 Identification of an Appropriate ES-Shell for Rating of Highway Bridges

The currently available expert systems are implemented in AI languages such as LISP and PROLOG and specialized languages like OPS5 as well as programming language C. The proposed study involves the development of a PC based expert system and hence only generic shells that run on PCs are evaluated. These can be grouped: into four broad categories; inductive tools, simple rule tools, hybrid tools, and languages. Inductive tools generate advice based on examples, of correct solutions provided by an expert or a database. Simple rule tools apply IF/THEN rules entered by the developer, to generate advice. Hybrid tools add more complex features such as frames and graphic rule traces, thereby enabling more sophisticated knowledge representation techniques. Languages such as LISP, PROLOGS etc. allow development to create customized inferencing techniques, interfaces, and data structures for problems which do not belong to one of the above paradigms: Generally, inductive tools are the easiest to use, hybrid tools provide the greatest power; languages are the most flexible and simple rule tools provide a good-balance-for many problems.:

Typical shells considered for evaluation include Exsys. Standard, Exsys Professional, Level 5,:Nexpert, PC Easy, PC Plus, VP Expert, etc. Table 3.1 shows the comparison of the shell functional features for the above shells. The execution speed of typical shells are shown in Table 3.2. The data are based on test-runs for 100 simple rules on identical IBM PS-2 Model-50 computers. Table 3.3 illustrates the largest possible sequential knowledge base of the shells. The implementation strategies of the different shells are given in, Table 3.4.

Table 3.2 Execution time

Shell	S 100
Exsys Standard	0.3
Exsys Professional	0.5
Level 5	NP
Nexpert	9.3
PC Easy	9.6
PC Plus	38.5
VP Expert	NP

Times are in seconds
NP - Not Possible

Discrepancies between fast shells such as Exsys Standard and Exsys Professional and slow shells such as PC Plus, can be partially explained by the implementation strategies shown in Table 3.4. Shell features and flexibility cause timing variations, because they require memory and more complex interpreters. Based on a critical review of the information from the current users, and published literature, Exsys Professional was chosen for the development of the proposed expert system for this study.

Table 3.3 Largest possible sequential knowledge base

Shell	No. of rules	Execution time	Rules per second
Exsys Standard	397	11.3	35.2
Exsys Professional	2000	26.4	18.9
Level 5	97	1.3	77.6
Nexpert	NR	NR	NR
PC Easy	211	22.9	9.2
PC Plus	225	45.5	4.9
VP Expert	17	2.1	7.9

NR-not run

Table 3.4 Implementation strategies

Shell	Implementation strategies
Exsys Standard	Compiler produces a binary file that is interpreted at run time
Exsys Professional	Compiler produces a binary file that is interpreted at run time.
Level 5	Compiler produces a binary file that is interpreted at run time.
Nexpert	Interpreter executes production rules in binary format produced by a built-in editor.
PC Easy	Shell is written in LISP and runs on top of a LISP interpreter.
PC Plus	Shell is written in LISP and runs on top of a LISP interpreter.
VP Expert	Interpreter executes ASCII production rules.

Of the shells listed in Table 3.1 M1, VP Expert, and EXSYS were investigated in detail. EXSYS was chosen for this application. The following two sections discuss the special features of EXSYS, which lead to its choice for use in this study.

3.5.3 Exsys Professional

Exsys Professional is a shell that offers a great level of sophistication to knowledge engineers in the development of an expert system, yet maintaining the ease of use. No special languages are needed and all input is English text, algebraic expression or menu selection. The developer of an expert system works within the Exsys Professional Rule editor which provides menus, prompts and help. It is not necessary to memorize: complex rule syntax. Exsys Professional also includes a rule compiler that allows development or editing of knowledge bases a word processor.

For more complex applications and increased control, a command language can be used to control the execution of the expert system. The. command language gives the developers control and flexibility in developing rule based systems. Rule sub-sets, looping and conditional tests are part of the command language, The Exsys Professional command language includes commands for:

i) Controlling command flow (WHILE, IF, GOTO...),

ii) Running rules or subsets of rules in either forward or backward chaining mode,

iii) Calling report specification files,

iv) Displaying results or intermediate results,

v) Instantiating facts or data,

vi) Screen control to ask questions;

vii) Call to dBase IV files, and

viii) Call to external programs:

There are great advantages to using a command language operating over a structured set of rules for complex applications. The command language alone increases the capabilities of Exsys Professional substantially and allows it to handle much more complex problems.

Exsys Professional expert systems can be run by an end user with essentially no training. The end user of the expert system can ask HOW conclusions were reached or WHY information is needed. The program will respond with a full explanation of the logic used to arrive at the conclusion, including backward chaining and external program calls for data. The developer ca customize screens and decide what options are available to the end user:

Exsys Professional is written in C far, high speed and efficient utilization of memory. For particularly large or complex problems, blackboarding can be utilized to divide a problem smaller expert systems that communicate through a common data (a "blackboard").

Expert systems developed with Exsys Professional are- directly compatible between IBM PC/XT/AT, VAX/VMS and UNIX computers. The Exsys application need only be r to the new environment and run with the appropriate runtime program.

3.6 KNOWLEDGE REPRESENTATION' IN EXSYS

EXSYS is a PC-based knowledge system software tool, implemented in the C programming language, capable of developing and using knowledge systems in excess of 2000 rules [Exsys,1988]. Knowledge systems built with EXSYS are designed using rules or frames. Backward or forward chaining can be utilized in EXSYS. For the system REX, the knowledge base was developed using rules. The rules are created and edited using, the rule editor; EDITXSP.EXE. A rule consists of five parts, an IF part, a THEN part, an optional ELSE part, an optional NOTE part, and an optional REFERENCE part.

To build a rule, conditions are added to the IF part of the rule. A condition is a statement of. fact (or potential fact) and in EXSYS it can be either, a text expression or an algebraic expression that can be tested for validity. All of the IF conditions in a rule must be true for the rule to be true and for the THEN conditions to be considered true and added to the context.

Text expressions are known as qualifiers. A typical qualifier in EXSYS appears as:

The LIVE LOAD CATEGORY is

1) Low volume roadways (ADTT < 1000), - reasonable enforcement and apparent control of overloads

2) Heavy volume roadways (ADTT > 1000), reasonable enforcement and apparent control of overloads

3) Low volume roadways (ADTT < 1000), significant sources of overloads without effective enforcement

4) Heavy volume roadways (ADTT > 1000); sources of overloads without effective enforcement.

The question would be posed to the user- in this ,fashion and associated with one or more. the options is a rule.

In EXSYS, in addition to asking the user for information, data can be obtained from a data base or external, programs.;

If more than one condition is present in the IF part of a rule, they may be combined using AND blocks or OR blocks or both AND and OR blocks. For example, the _¢: portion: of a rule may appear as:

IF:

	The VEHICLE LIVE LOAD is HS 15
OR	The VEHICLE LIVE LOAD is HS 20
AND	The [rating factor] < 1.0

Like the IF part, the THEN part is also a series of, conditions. Unlike the conditions in the IF part, the THEN conditions are not tests, but statements of fact. These statements are automatically considered true if the rule's IF portion is true and they are added to what the system knows. When the IF part is true and the THEN part is added to the context as knowledge the rule is said to be fired.

Another possible form for the condition to take is as a choice. Choices are all possible solutions to the problem among which the expert system will decide and have probabilities associated with them. They are usually used in the THEN/ELSE part of the rule. When used in the IF part, the choice functions as a test of the final value of the choice.

The ELSE part of the rule is the same as the THEN part, except that it is applied, if any condition of the IF portion is false. The NOTE and REFERENCE parts of the rule simply provide the user with information or the source of knowledge.

The EXSYS inference engine is activated when a consultation is initiated. This is done by invoking the EXSYSP.EXE runtime program. The expert system then searches for information it needs by using backward chaining or forward chaining techniques. A typical rule in EXSYS is structured as follows:

RULE NUMBER: 74 (RF2)

IF:

The rating factor is less than 1.0

THEN:

The bridge cannot withstand the capacity of the rating vehicle. The bridge' must be i) analyzed in more detail, ii) posted, or iii) retrofitted

ELSE:

The bridge is capable of withstanding the capacity of the rating vehicle

REFERENCE:

AASHTO: Guide Specifications for Strength Evaluation of Existing Steel and Concrete Bridges, 1989, p.3.

3.7 FEATURES OF EXSYS

The shell has the capability of linking an unlimited number of external programs to the shell. This allowed a modular approach when implementing all external tasks, by creating short, succinct` programs.

Any program that can be run on the computer can be accessed. This interfacing is achieved by calling external programs with the EXSYS command; RUN(filename). The RUN command can be invoked through rules or REPORT files. REPORT files are created' in the then portion of the rule and used to print reports, pass data to external programs and format the conclusion of the run. This was used throughout the development of REX and is illustrated in the following rule.

RULE NUMBER: 48 (rating2)

IF:

The MAIN STRUCTURE TYPE is VOIDED SLAB

THEN:

REPORT(VOID.RPT)
and RUN(VOIDIN /M)
and DISPLAY MESSAGES
and RUN(BRIDGES /M)
and RUN(DEFL /M)

NOTE: VOID.RPT picks up values pertaining to voided slab, creates VOID.DAT, and runs VOIDIN.EXE, which creates INPUT file for space
frame program, BRIDGES, DEFL scans- output of BRIDGES : for maximum moments.

This particular rule is true if the bridge is a voided slab type. The REPORT file, VOID.RPT, is generated by the system. This file is setup as follows:

FILE C:VOID.DAT
[NW] /V
[NL] /V
[FC] /V
[LXI /V
[T] /V

[VOIDS] /V
[A1] /V
CLOSE
BEEP

It contains data relating to the bridge that is necessary to run VOIDIN. This .data is output to the file, VOID.DAT, which is read by VOIDIN, using the FILE command. This creates: an effective method :of passing data to external programs.

Once the REPORT file is created the external program VOIDIN is run. A message screen is displayed. Then the programs BRIDGES and DEFL are run.

Data can be returned to EXSYS via a RETURN.DAT file. This file is in the following format:

[ML] value
[NID] value

where ML and MD are variable names:

One advantage of expert systems is that they can be run by an end user with little or no training. EXSYS contains four help facilities; hypertext, custom help files, a WHY[?] command, and a HOW command to aid the user in running the system.

The hypertext help system, allows a series of explanation screens to be created that: can' be accessed as needed by the user. The screens are -indexed by keyword. When they appear on the screen, hypertext words are- highlighted. Hypertext is created by- flagging the keywords in the knowledge base and creating and storing the individual screens for each hypertext word in a SCR file. The user can then invoke the hypertext screen using the F1 key.

Custom help files are used where it maybe necessary to explain in detail about a qualifier or variable. Unlike' hypertext, which is. associated with words, custom help screens respond to a request for information regarding a qualifier or a variable. Help files allow the qualifiers and variables to be kept short and still enable access to longer. explanations when necessary. A custom help file is created in a HLP file. The user can call the custom help file by entering [?].

The WHY command can be invoked at each question asked of the user and displays :the: logic of the rules associated with that question. No additional files or set up is necessary to enable the WHY command.

The HOW command is used to determine how the system arrived at its final value for a specific choice or fact. The system will respond by displaying all of the rules used to determine the value of that choice or statement.

CHAPTER 4

LOAD CAPACITY EVALUATION OF BRIDGES

4:1 INTRODUCTION

This chapter presents the basic concepts of the grillage analogy used in the bridge analysis, the stiffnesses of plane / space frame members, and the appropriate cross-sectional properties of different bridge structural elements idealized in the grillage analogy. The load and resistance .factor method for bridge load carrying capacity evaluation, the determination of load and: resistance factor method and the dead and live load configurations are discussed in detail.

4.2: BRIDGE ANALYSIS

4.2.1 Introduction

The grillage analogy is used for bridge analysis, which is an essential component in the development of the system, REX. It is an economical and simple method that can be fully automated using a microcomputer. The= published literature by Lightfoot (1964), Sowka and Mosley (1969), West (1973), Hambly (1975), Cope and Clark (1984), and Bakht and Jaeger(1986) show results from the grillage analogy as applied to bridge structures.

The grillage analogy has the following merits:

(a) It can be used even in cases where the bridge exhibits complex features such as heavy skew, edge stiffening, isolated and random locations of supporting piers, etc.

(b) Unlike a plane frame, this - analogy incorporates torsional rigidity of the bridge superstructure.

(c) The grillage idealization has no restriction on the number of transverse beams in the, analysis.

4.2.2. Grillage Analogy

The grillage analogy is essentially an assembly of one-dimensional beams, which is subjected to loads acting: in the direction perpendicular to the plane of the assembly. The deformation characteristics of a rectangular element of an isotropic- plate subjected to out-of-plane load. can be represented by an equivalent frame work-model with a distribution of stiffness that represents as accurately as possible the properties of the real structure. The rectangular model consists of an assembly of four side and two diagonal beams. This idealization is shown in Figure 4.1 and the- expressions for the properties of the various beams are as follows:

$$
\begin{aligned}
I_x &= \left(L_y - \frac{\nu L_x^2}{L_y}\right)\frac{t^3}{24(1-\nu^2)} \\
I_y &= \left(L_x - \frac{\nu L_y^2}{L_x}\right)\frac{t^3}{24(1-\nu^2)} \\
J_x &= \left(\frac{EL_y(1-3\nu)}{G}\right)\frac{t^3}{24(1-\nu^2)} \qquad \text{.....(4. 1)} \\
J_y &= \left(\frac{EL_x(1-3\nu)}{G}\right)\frac{t^3}{24(1-\nu^2)} \\
I_d &= \left(\frac{\nu(L_x^2+L_y^2)^{1.5}}{L_xL_y}\right)\frac{t^3}{24(1-\nu^2)}
\end{aligned}
$$

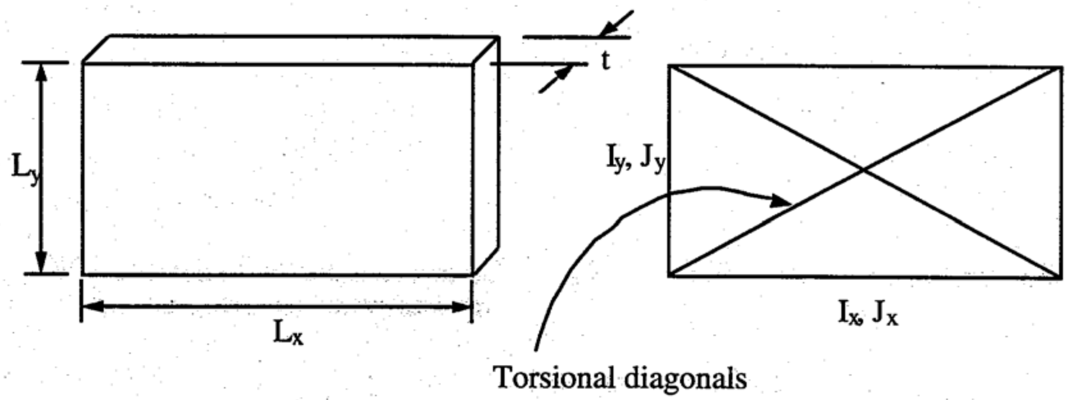


Figure 4.1 Grillage idealization of slab element

where I and J refer to the second moment of area and torsional inertia respectively, and v is the Poisson's ratio of the material of the plate. By making the Poisson's ratio zero, the diagonal beams can be eliminated, and the grillage reduced to an orthogonal assembly of beams. The expressions for various beam properties appropriate to the different types of bridge girders, corresponding to zero Poisson's ratio are given in later sections. The matrix displacement method is used in the analysis of the bridge structure idealized with longitudinal and transverse beams. The stiffness equations of typical planar and space frame elements used in. the analysis are presented below.

4.2.2.1 Stiffness of plane frame member

Figure 4.2a shows a typical plane frame element with two translational and one rotational - degrees of freedom at each node. The member stiffness - matrix for the- plane frame member accounting for axial, flexural and shear strains ` is shown in Egn..4.2.

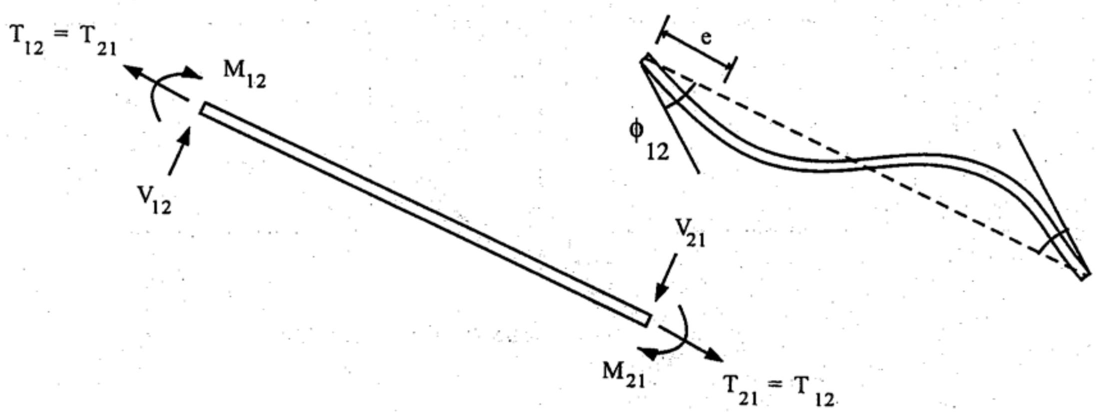


Figure 4.2a Typical plane frame element [Harrison, 1973]

$$\begin{bmatrix} T_{12} \\ M_{12} \\ M_{21} \end{bmatrix} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 \\ 0 & \frac{n+3}{n+12}\cdot\frac{4EI}{L} & \frac{n-6}{n+12}\cdot\frac{2EI}{L} \\ 0 & \frac{n-6}{n+12}\cdot\frac{2EI}{L} & \frac{n+3}{n+12}\cdot\frac{4EI}{L} \end{bmatrix} \cdot \begin{bmatrix} e \\ \phi_{12} \\ \phi_{21} \end{bmatrix} \qquad ..... (4.2)$$

$$\text{where} \quad n = \frac{\beta A G L^2}{EI}$$

4.2.2.2 Stiffness of space frame member

Figure 4.2b shows a typical space frame element with` six stress resultants at each end - three forces, two bending moments and a twisting moment. These resultants are not independent but are related to each other by six member equilibrium equations. The six independent stress resultants in a space frame member are related to the corresponding member deformations as shown in Eqn. 4.3.

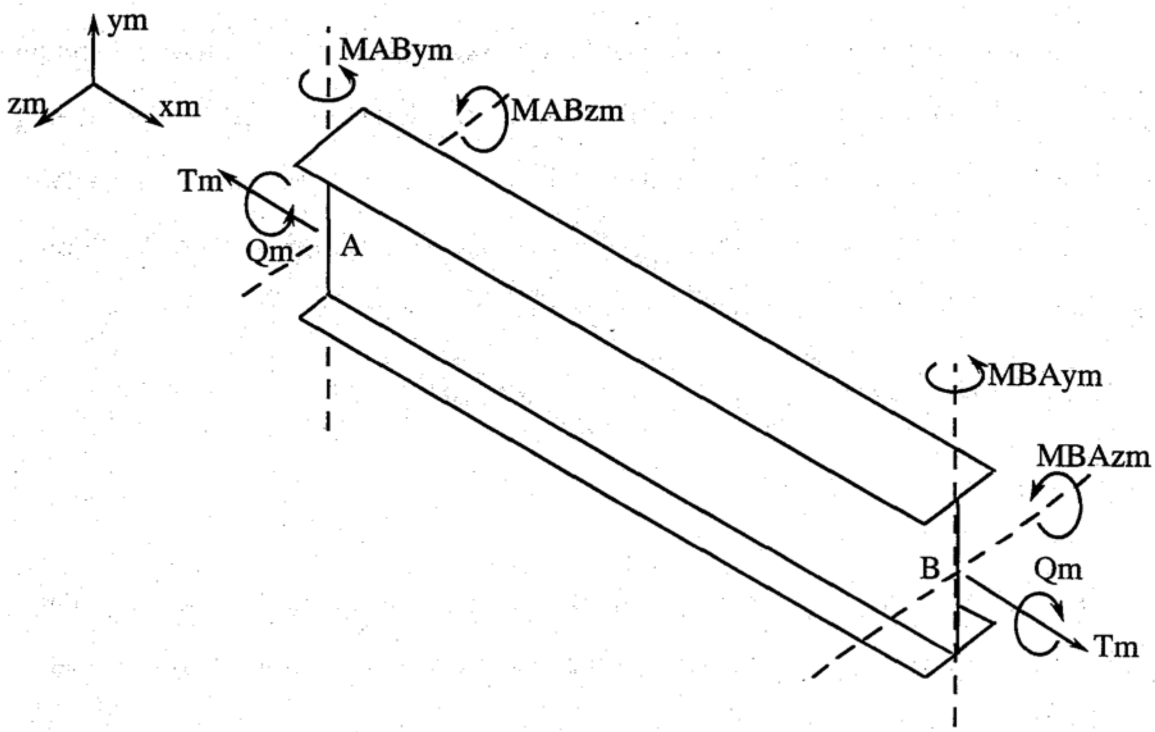


Figure 4.2b Typical space frame element [Harrison, 1973]

$$
\begin{bmatrix} T_m \\ MAB_{zm} \\ MBA_{zm} \\ MAB_{ym} \\ MBA_{ym} \\ Q_m \end{bmatrix} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{4EI_z}{L} & \frac{2EI_z}{L} & 0 & 0 & 0 \\ 0 & \frac{2EI_z}{L} & \frac{4EI_z}{L} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{4EI_z}{L} & \frac{2EI_z}{L} & 0 \\ 0 & 0 & 0 & \frac{2EI_z}{L} & \frac{4EI_z}{L} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{GI_x}{L} \end{bmatrix} \begin{bmatrix} e \\ \phi AB_z \\ \phi BA_z \\ \phi AB_y \\ \phi BA_y \\ \theta \end{bmatrix} \quad \text{...... (4. 3)}
$$

4.3 BRIDGE TYPES

Of the bridges listed in section 1.2, the scope of this study includes solid slabs, voided slabs, 1-girder (AASHTO types), T-beam, ;double-T, and segmental box bridge types. These are shallow superstructures in the sense that load distribution takes place mainly through bending and torsion in the longitudinal and transverse directions, with deflections due to shear being negligible. Shallow superstructures except segmental box bridges are well suited for analysis using the grillage analogy: method. The section properties and mesh design used in developing ;, the expert system are discussed in the following three sections:

4.3.1 Solid Slab

Solid slab bridges are used for spans up to 80 ft. (24.4 m). The idealized mesh for grillage analysis is shown in Figure 4.3a. The properties of the grillage members for solid slab elements are taken as follows:

$$I_x = \frac{L_y t^3}{24} \quad .....(4.5)$$

$$I_y = \frac{L_x t^3}{24} \quad .....(4.6)$$

$$J_x = \left(\frac{E}{G}\right)\frac{L_y t^3}{24} \quad .....(4.7)$$

$$J_y = \left(\frac{E}{G}\right)\frac{L_x t^3}{24} \quad .....(4.8)$$

where

E = modulus of elasticity

G = shear modulus

I_x = the moment of inertia in the longitudinal direction

I_y = the moment of inertia in the transverse direction

J_x = the torsional inertia in the longitudinal direction

J_y = the torsional inertia in the transverse direction.

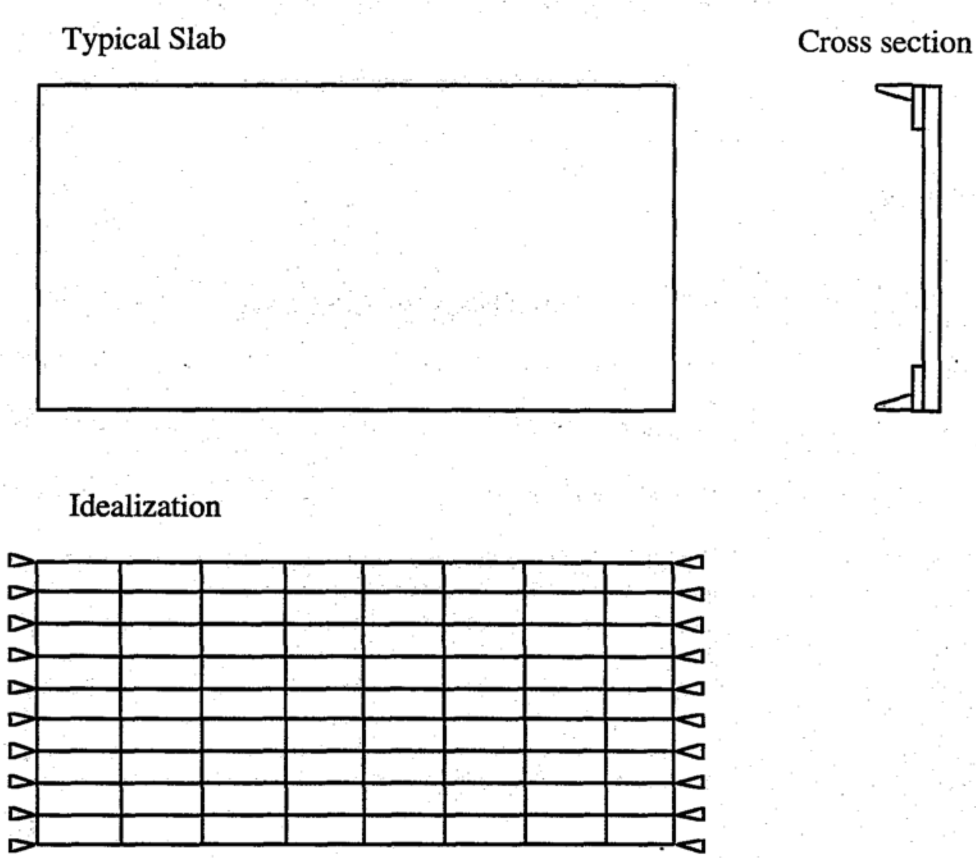


Figure 4.3a Solid slab - grillage idealization

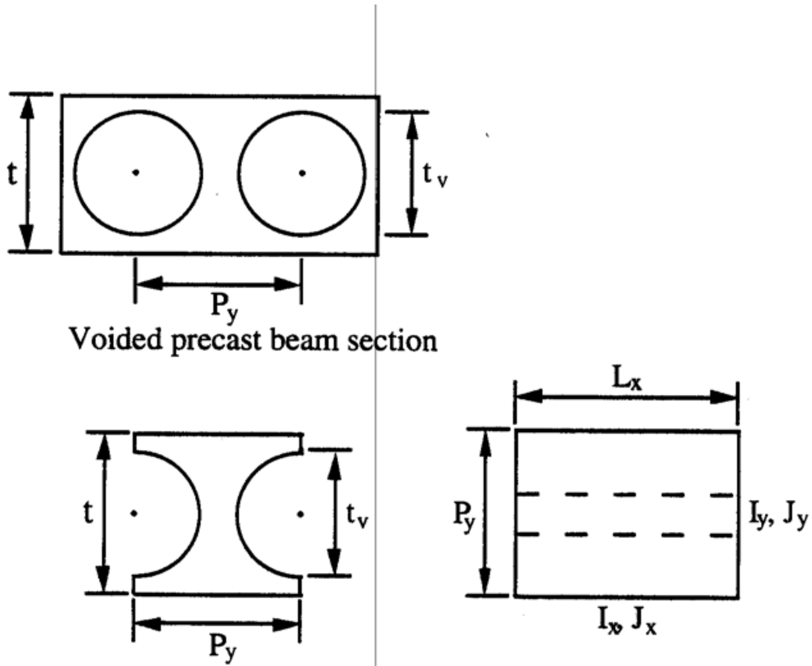


Figure 4.3b Grillage idealization of voided slab element

4.3.2 Voided Slab

Voided slab bridges are used for sans up to 50 ft. (15.2 m). Grillage idealization of voided slab bridges is similar to that of solid slab bridges, differing only in the properties of the grillage members and the necessary placement of the longitudinal grillage members coincidental with void centerlines. An idealized slab element is shown in Figure 4.3b. The properties of the grillage members for voided slab bridges are taken as follows:

$$I_x = \frac{P_y t^3}{12} + \frac{\pi t^4}{64} \qquad \text{.....(4. 9)}$$

$$I_y = \frac{L_y t^3}{12}\left[1 - \left(\frac{t_v}{t}\right)^4\right] \qquad \text{.....(4. 10)}$$

$$J_x = \frac{L_y t^3}{6}\left[1 - 0.85\left(\frac{t_v}{t}\right)^4\right] \qquad \text{.....(4. 11)}$$

$$J_y = \frac{L_x t^3}{6}\left[1 - 0.85\left(\frac{t_v}{t}\right)^4\right] \qquad \text{.....(4. 12)}$$

where

P_y = the center to center distance of the circular voids

t_v = the diameter of the circular voids.

4.3.3 AASHTO Girder and Slab

AASHTO girder bridges can be used for spans up to 100 ft. (34.8 m), depending on the type. To idealize a slab and girder bridge the longitudinal members of the grillage are positioned to coincide with the actual girders. These girders are given the properties of the girders: plus the associated portion of the slab. The transverse grillage-beams represent appropriate portions of the deck slab. An idealized element and typical assembly of beams are shown in Figures 4.4 and 4.5 respectively.

The properties of the grillage members for slab and girder elements are taken as follows:

$$I_x = \frac{L_y t^3}{12} \qquad \text{.....(4. 13)}$$

$$I_y = \frac{L_x t^3}{12} \qquad \text{.....(4. 14)}$$

$$J_x = J_g + \left(\frac{E}{G}\right)\frac{L_y t^3}{6} \qquad \text{.....(4. 15)}$$

$$J_y = \left(\frac{E}{G}\right)\frac{L_x t^3}{12} \qquad \text{.....(4. 16)}$$

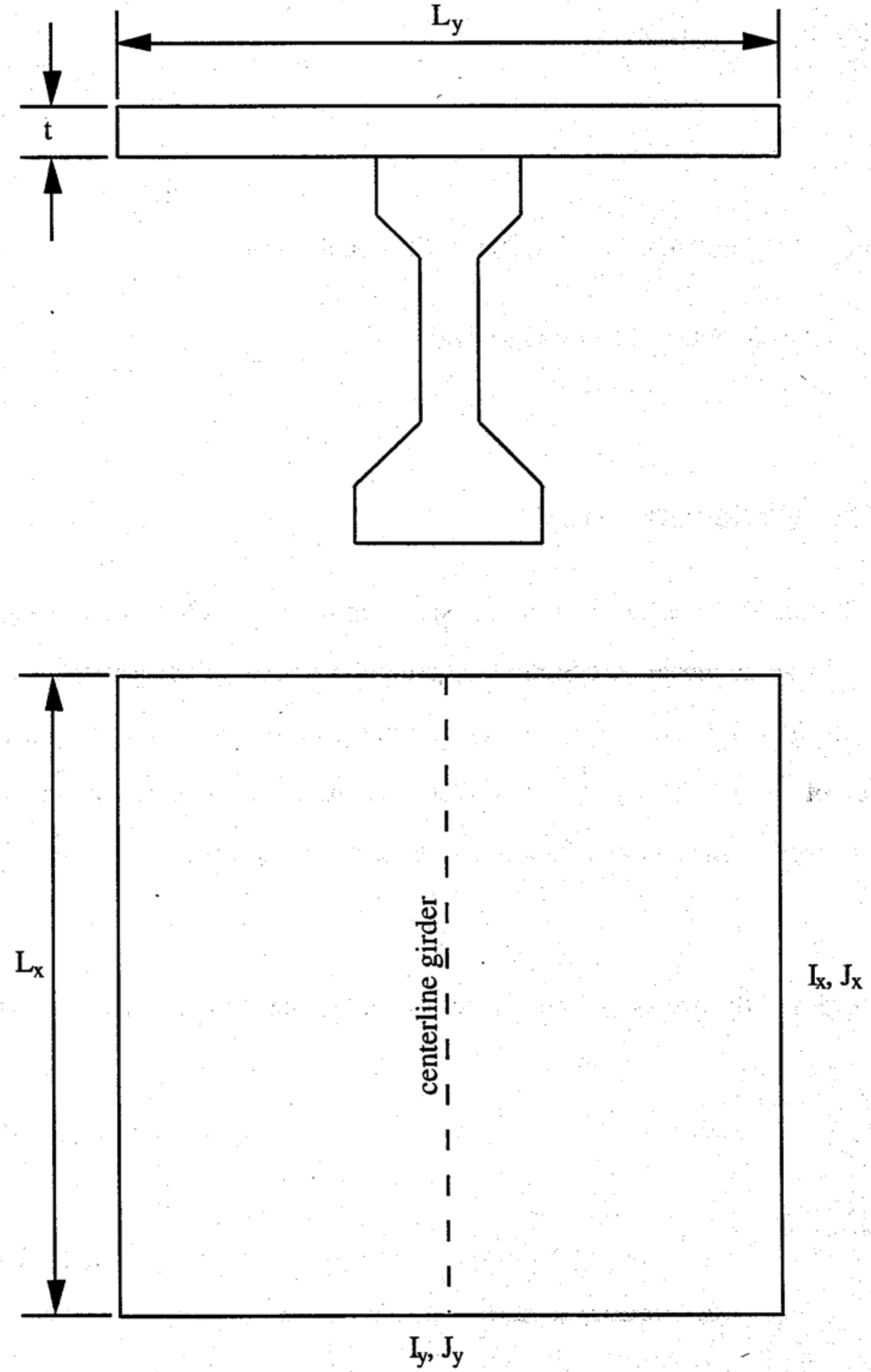


Figure 4.4 Grillage idealization of slab & girder element

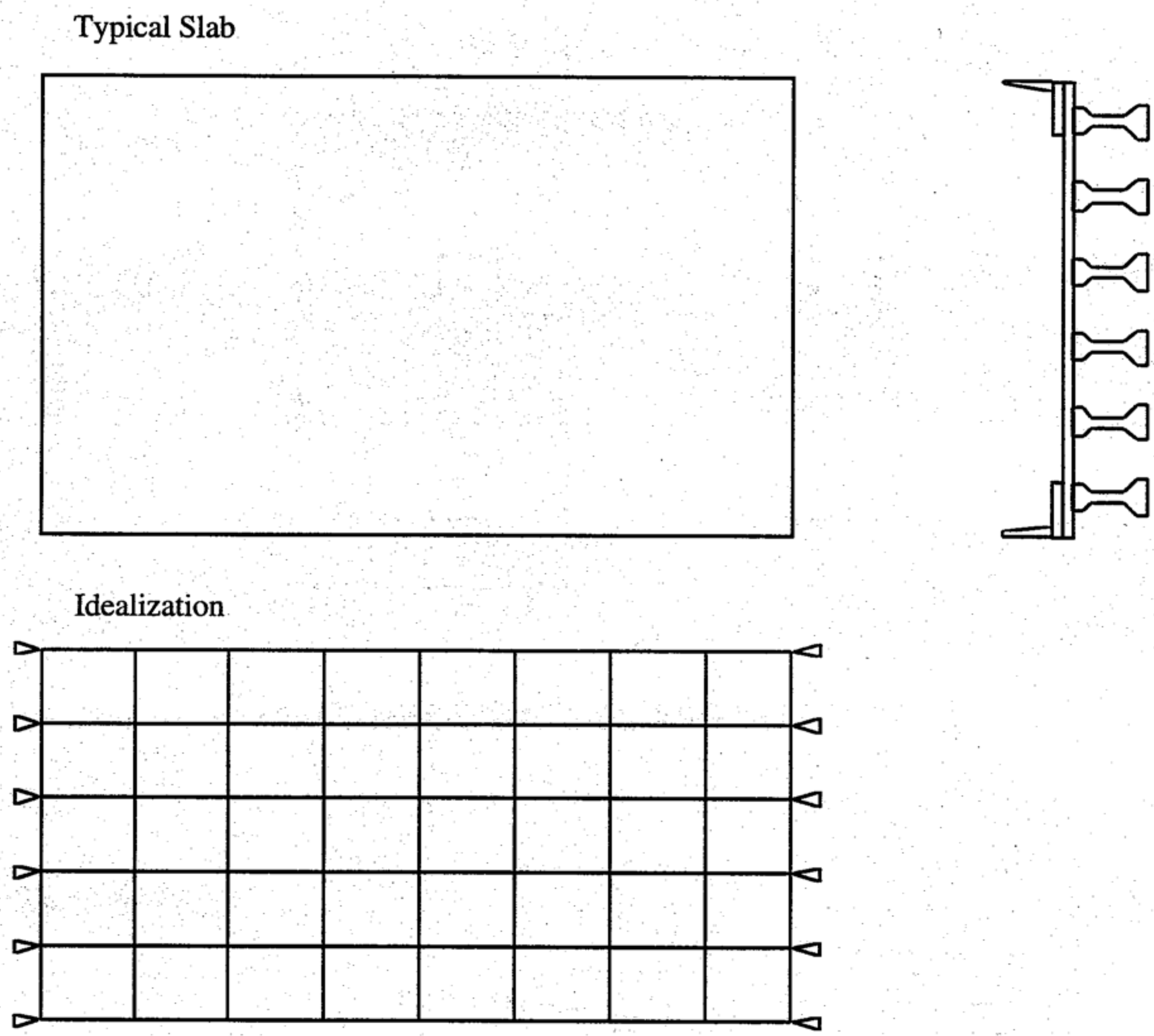


Figure 4.5 Slab and girder - grillage idealization

where

Jg - the girder torsional inertia.

For the analysis: of AASHTO girders the torsional inertias are calculated by dividing; the beam into a number of rectangles and, adding the torsional inertias of the individual rectangles as

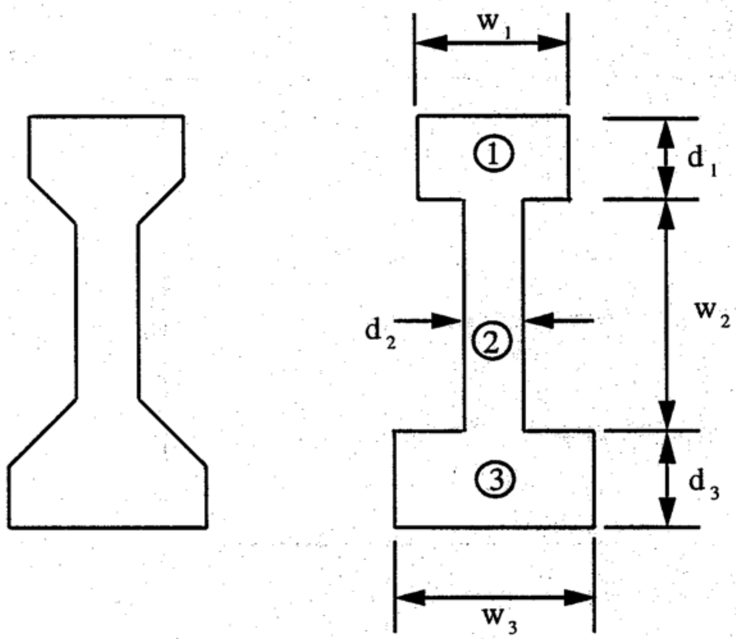


Figure 4.6 Idealization for calculating torsional inertia

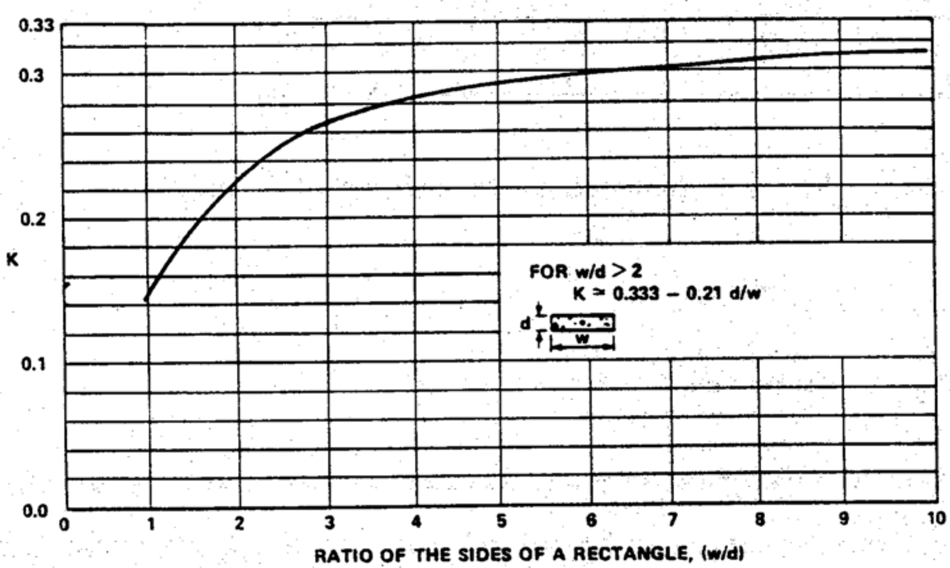


Figure 4.7 Values of the torsion coefficient [Bakht and Jaeger, 1985]

shown in Figure 4.6 and given by:

$$J_g = \sum_{n=1}^{3} K_n w_n d_n^3 \qquad .....(4.17)$$

where

w = the larger side of each rectangle

d = the smaller side of each rectangle

K = the torsional coefficient determined from Figure 4.7 [Bakht and Jaeger, 1985].

4.3.4 T-Bears and: Double-T Girders

T-Beams and Double-T girder bridges can be used for spans up to 65, ft. (19.8 m), depending on the type. To idealize a T-Beam bridge, the longitudinal members of the grillage are positioned to coincide with the center line of the T-Beams (center of the webs). These grillage members, are given the properties of the T-Beams. The transverse grillage beams represent appropriate portions of the top flange of the T-Beams. An idealized element and typical assembly of beams are shown in Figures 4.8 and 4.9 respectively.

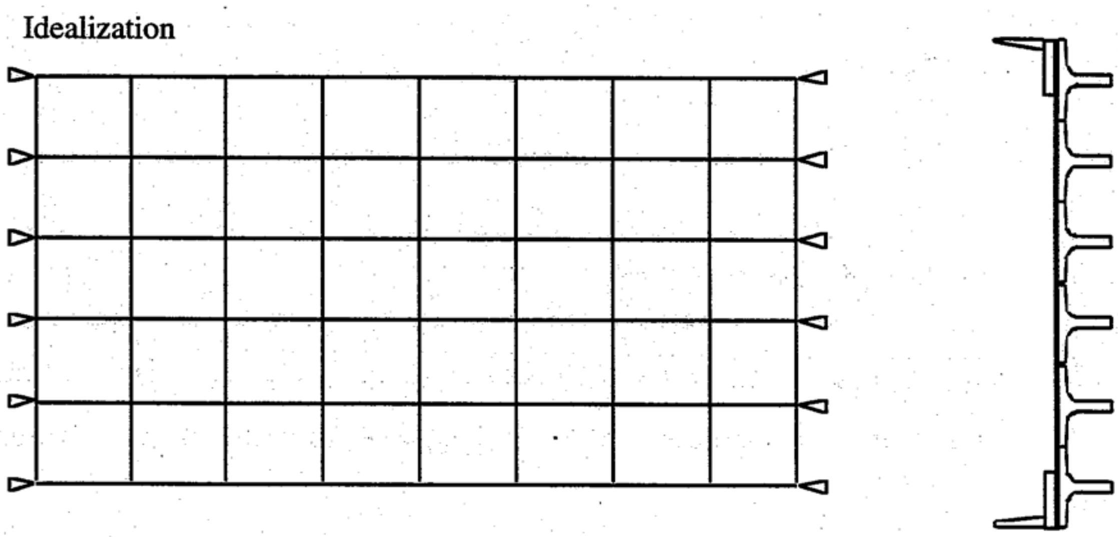


Figure 4.8 T-Beam - grillage idealization

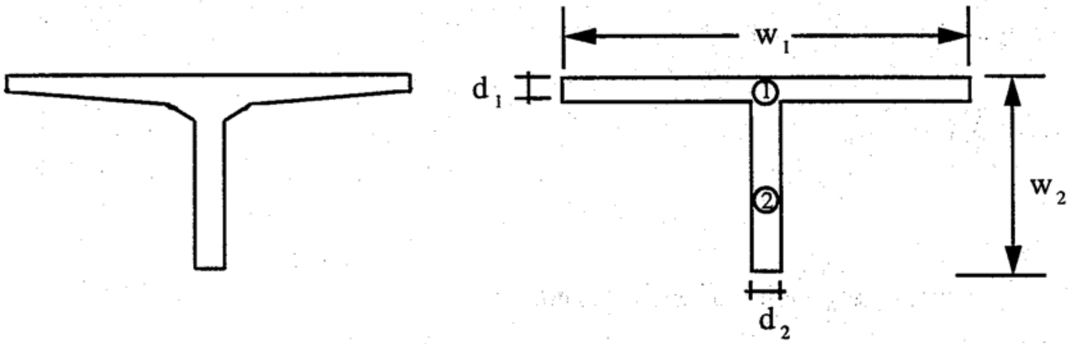


Figure 4.9 Idealization for calculating torsional inertia

The properties of the grillage members for T-Beam elements are similar to those of AASHTO girders, as illustrated in the previous section, and are taken as follows:

$$I_x = \frac{L_y t^3}{12} \qquad \text{.....(4. 18)}$$

$$I_y = \frac{L_x t^3}{12} \qquad \text{.....(4. 19)}$$

$$J_x = J_g + \left(\frac{E}{G}\right)\frac{L_y t^3}{6} \qquad \text{.....(4. 20)}$$

$$J_y = \left(\frac{E}{G}\right)\frac{L_x t^3}{12} \qquad \text{.....(4. 21)}$$

where

J_g = the girder torsional inertia.

The torsional inertias of the T-Beams are calculated by dividing the beam into a number of rectangles and adding the torsional inertias of the individual rectangles as shown in Figure 4.9 and given by:

$$J_g = \sum_{n=1}^{3} K_n w_n d_n^3 \qquad \text{.....(4. 22)}$$

where

w = the larger side of each rectangle

d = the smaller side of each rectangle

K = the torsional coefficient determined from Figure' 4.7 [Bakht and Jaeger, 1985]:

The Double-T beam can be idealized as an equivalent T-beam without compromising the accuracy of the analysis results. There are two approaches to idealize a Double-T cross-section into T-Beam cross-section; first, the Double-T can be cut between the two Ts (flange) to result in two T=Beam cross-sections; second; a single T can be built-up keeping the same area, moment' of inertia and depth of centroid as that of the Double-T resulting in one- T-Beam per Double-T girder. Figure 4.10 shows the idealization of a Double-T girder into a T-Beam.

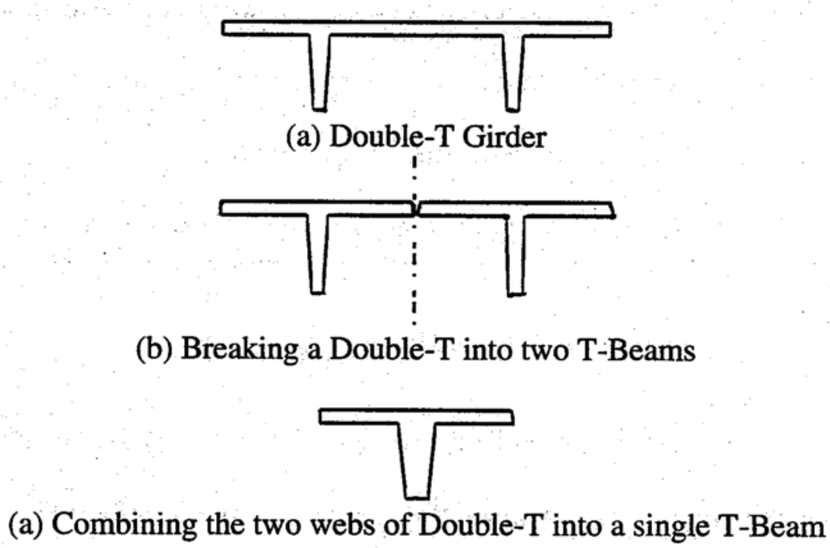


Figure 4.10 Idealization of Double-T girder into T-Beam

4.3.5 Segmental Box Girders

Conventional methods of bridge construction have a serious limitation- in case of large spans. The concept of segmental construction was developed to solve the problem of limited span length. Segmental box bridges can have spans to about 800 ft. (250 m) or even 1000 ft (300 m). With cable-stayed structures the span range can be extended to 1300 ft (400 m) and perhaps longer with the materials available: today. Table 4.1 summarizes the range of application of various forms of

Table 4.1 Range of application of bridge type by span length

Span	Bridge Types
0 - 150 ft	I-type pretensioned girder
100 - 300 ft	Cast-in-place post-tensioned box girder
100 - 300 ft	Precast balanced cantilever segmental, constant depth
250 - 600 ft	Precast balanced cantilever segmental, variable depth
200 - 1000 ft	Cast-in-place cantilever segmental
800 - 1500 ft	Cable-stay with balanced cantilever segmental

The segmental box bridge is idealized for analysis as a two-dimensional plane frame model. The plane frame elements are positioned to coincide with the actual centroid of the box sections and are given the actual properties of the segmental cross-section. The matrix displacement method for plane frame analysis allows the segmental bridge modeling either as a multi-span or continuous structure. A typical segmental box cross-section and idealized beam model are shown in Figure 4.11.

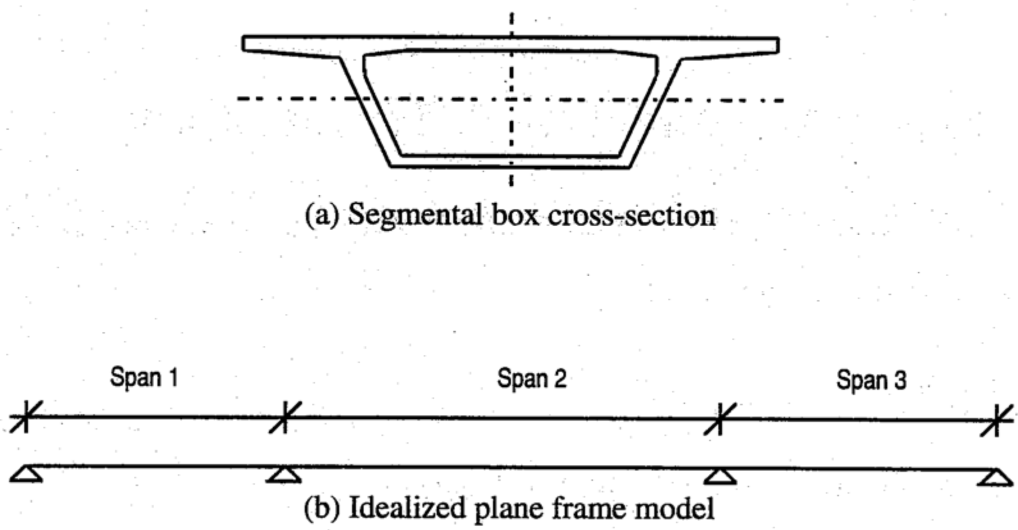


Figure 4.11 Segmental box bridge idealization for plane frame analysis

Segmental box bridges are among the. structures that are sensitive to their long-term deformations. After a long duration of time, deflections in excess of the calculated values and severe cracking have been observed on various segmental bridges. This behavior is due to the long-term (time dependent) load effects such as creep, shrinkage, and relaxation of prestressed steel. A linear model (elastic deformations and creep deformations vary linearly with stresses) for prediction of creep and shrinkage coefficients has been. developed. These coefficients are used to predict the time-dependent deformations in segmental box bridges. Stresses resulting from the time-dependent strains in a segmental box bridge are often comparable with the live and dead load stresses. Therefore, segmental box bridges, apart from load rating, need to be checked for serviceability stresses resulting from the time-dependent strains, which include stresses due to multistage construction. Segmental box bridges are post-tensioned after all the segments are assembled in place. The continuity of the prestressing strands gives rise to secondary moments that affect the: behavior of the bridge. A detailed discussion of basic theory is presented in

Chapter 5 and the method adopted in computation of time-dependent deformations and the effects of continuity of prestressing strands on segmental box bridges.

4.4 BRIDGE LOAD CARRYING CAPACITY EVALUATION

The evaluation conducted within REX conforms to the =load- and resistance factor method discussed in Section 2.3.2.5, Eqn. 2.11:

$$RF = \frac{\phi R_n - \gamma_D D}{\gamma_L L(1+I)} \qquad .....(\mathbf{2.11}).$$

A flowchart for the evaluation process is shown in Figure 4.12.

Essentially, the evaluation compares the factored live load effects and the factored resistance.

4.5 LOADS

By definition,, the grillage analogy accommodates loads, perpendicular, to the grid. Live and dead loads are considered in order to determine the, values of D and L in Eqn. 2.11.

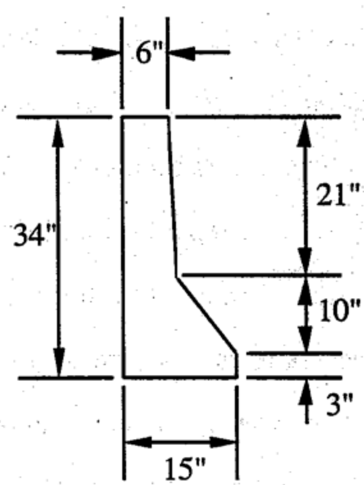


Figure 4.13 Standard parapet

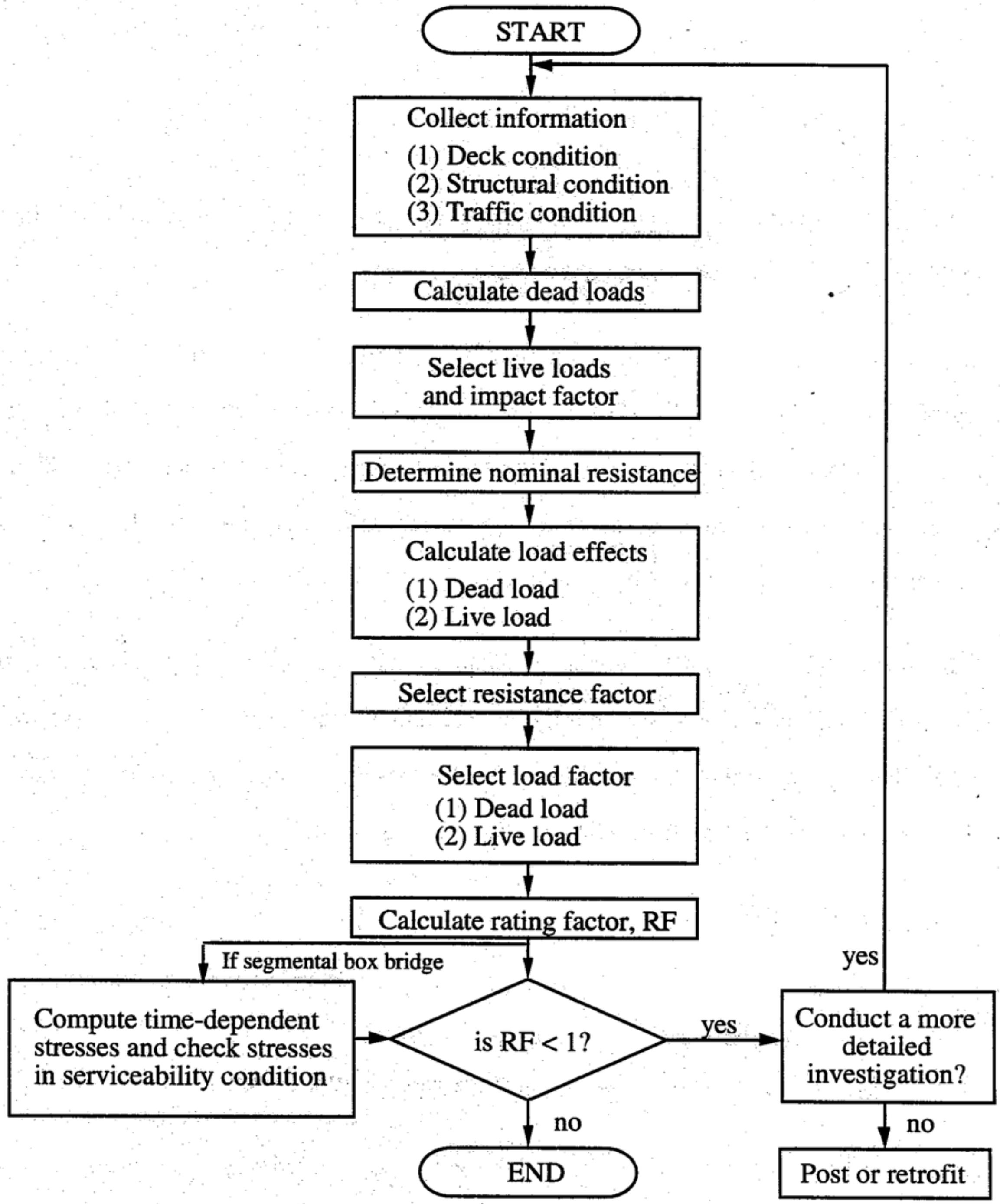


Figure 4.12 Flow chart for evaluation process

4.5.1 Dead Loads

The dead: load consists of the physical weight of the structure. This includes the bridge deck, girders, edge beams or sidewalks,: parapet, and overlay.

In the system REX, the structure weight is computed within one of the programs, SLAB GEN, VOID GEN, TB GEN, GIRD GEN, or REX-2 (these are discussed in more detail in Chapter 6). The load is computed for each longitudinal grillage girder (or plane frame element for: segmental box bridge) based on the bridge geometry defined by the user. Currently only concrete structures are considered in the system.

Edge beams (sidewalks) and parapets can also be included in the weight of the structure. The edge beam dimensions can be defined by the user and a standard parapet used as shown in Figure 4.13. The edge-stiffening that is provided by the presence of edge beams and/or parapets is taken into account by adjusting Eqs. 4.5 through 4.16. In general:

$$EI_{TOTAL} = EI_b + El \qquad .....(4.23)$$

where

EI_b = the stiffness provided by the edge beam and/or parapet.

Overlays can also be added to the dead load of the structure. The user has the options of using asphalt (1441b/ft^3), concrete(1501b/ft^3), other, or none:

4.5.2 Live Loads

The live load configurations available to the user consists of traditional AASHTO H and HS type loads, current AASHTO loads, and Florida live load configurations as shown in Figures 4.14, 4.15, 4.16a, 4.16b, respectively.

The user may place one or more :trucks¯ on a bridge by defining. the: axis of the> center of the rear wheel. The user may also create a custom live load by defining each load and wheel individually.

4.6 LOAD AND RESISTANCE FACTORS

Of the variables in the, rating equation, the load and resistance factors are the most elusive. As discussed in Section 2.3.2.5, the factors can be determined by quantifying the effects of traffic, analysis choice, deck smoothness, inspection, maintenance, and redundancy.

The load factors are used to account for uncertainties in load effects due to the method of analysis as well as load magnitudes. The dead load factor includes normal variations in material dimensions and densities. The live load factor accounts. for uncertainties in expected maximum vehicle loading effect, impact, and' distribution of loads during a time period between inspections. The resistance factor accounts for uncertainties in, strength prediction theories, material properties, and deterioration over time periods between inspection. Furthermore, the load and resistance factors are adjusted to produce an overall safety margin which leads to an adequate level of safety considering all uncertainties described above. An impact allowance is added to the static loads used for the rating [AASHTO, 1989].

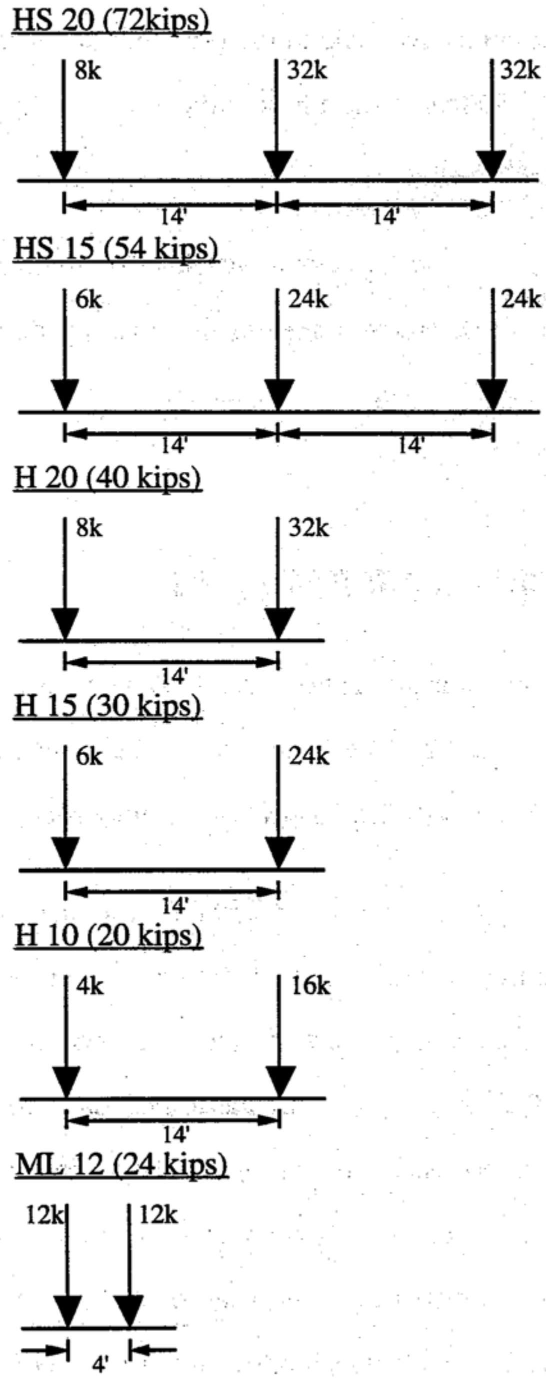


Figure 4.14 AASHTO live load configurations (traditional)

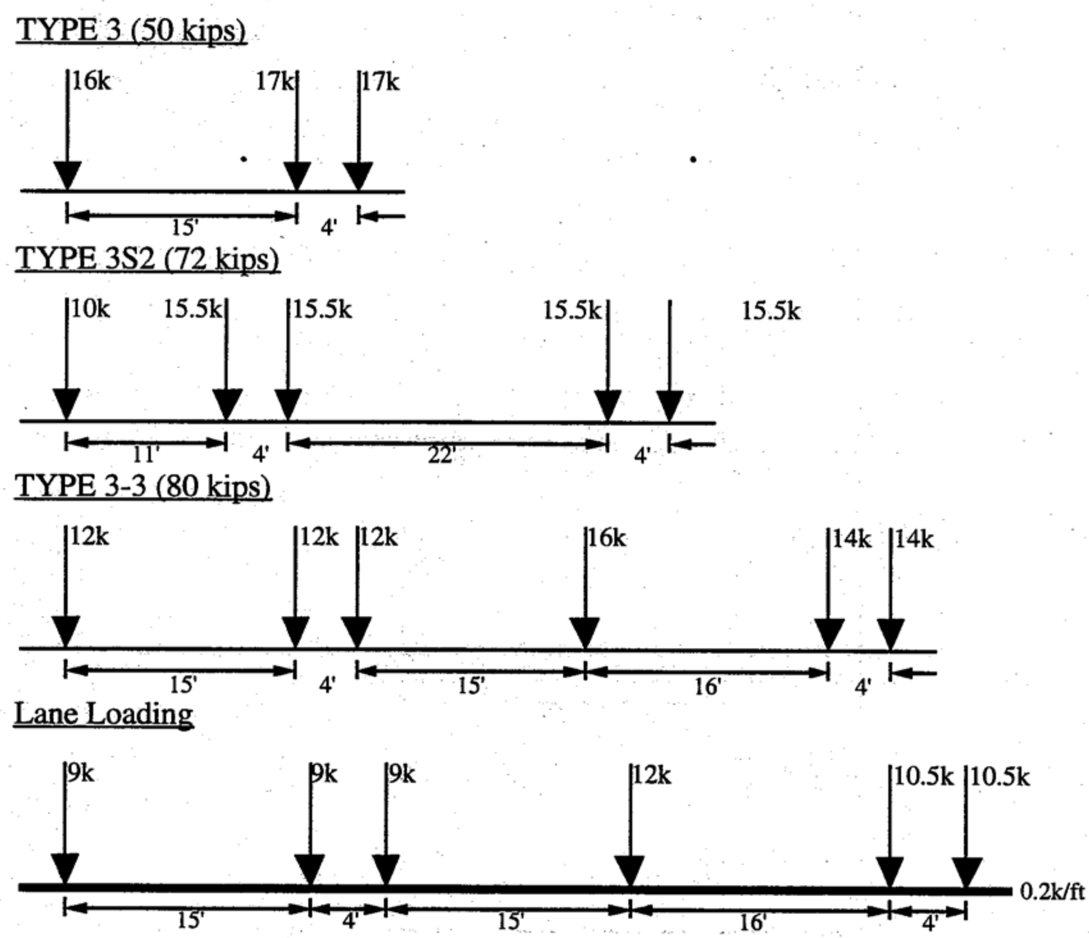


Figure 4.15 AASHTO live load configurations [AASHTO, 1989]

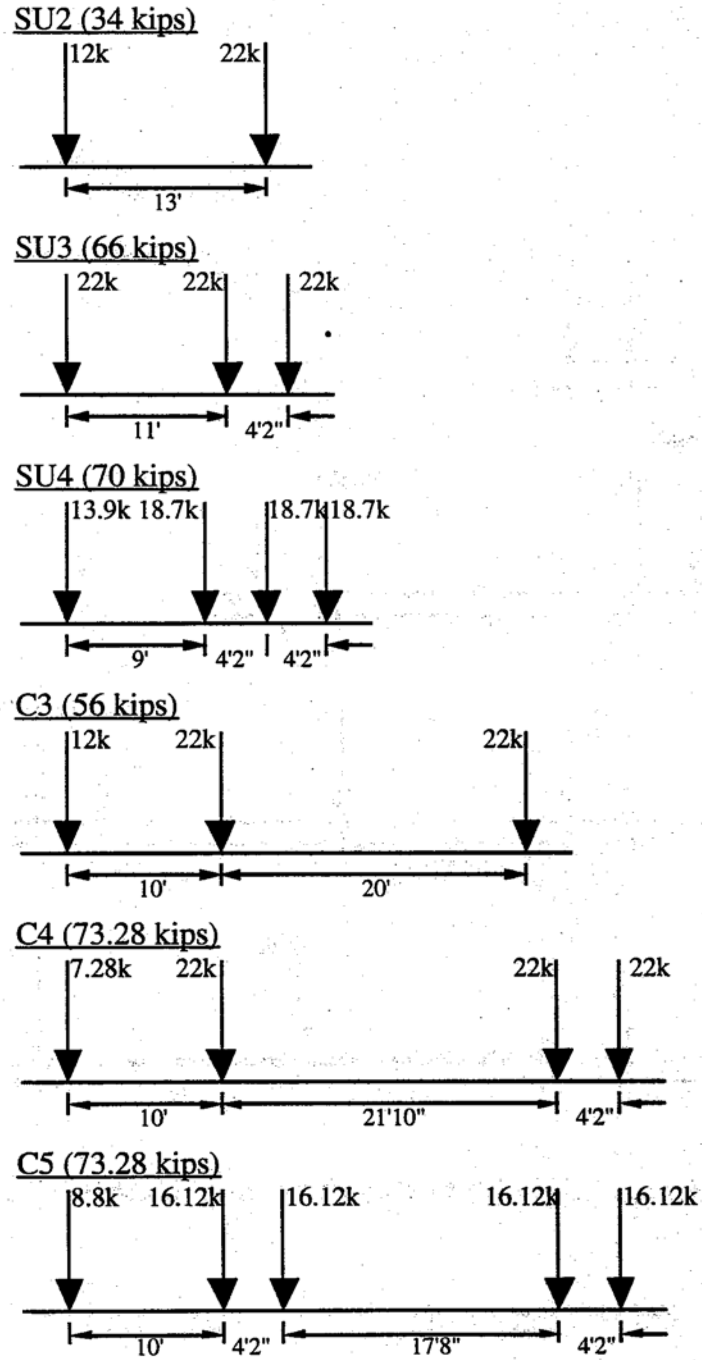


Figure 4.16a Florida live load configurations (cont'd)

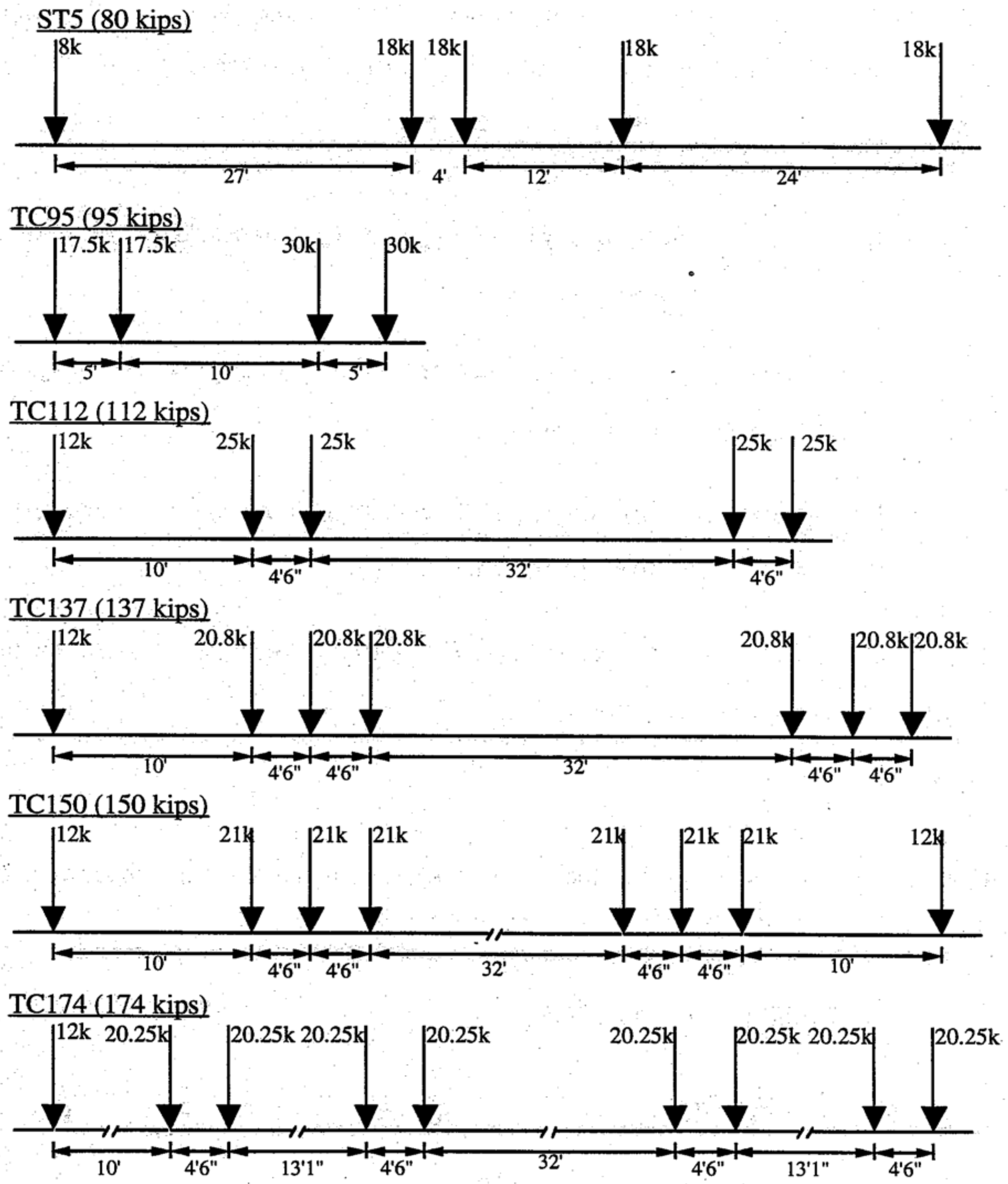


Figure 4.16b Florida live load configurations

The user can choose from different load categories allowing the system to select the appropriate load factors or enter values. The different categories are based on TRB weigh in motion studies and are posed to the user in the following format [TRB, 1987]:

The LIVE LOAD CATEGORY: is

1) Low volume roadways (ADTT < 1000), reasonable enforcement and apparent control of overloads

2) Heavy volume roadways (ADTT > 1000), reasonable enforcement and apparent control of overloads

3) Low volume roadways (ADTT < 1000), significant sources of overloads without effective enforcement

4) Heavy volume roadways (ADTT > 1000), sources of overloads without effective enforcement

5) other

The values selected for the live load factor, are 1.4, 1.6, ,1.8, and 1.95 for categories 1, 2, 3, and 4, respectively:

The DEAD LOAD CATEGORY is

1) Structural section

2) Factory fabricated components

3) A/C overlay

4) other

The values selected: for the dead load, factor, γ_D, are 1.20, 1.05, and 1.40 for categories l, 2, and 3, respectively.

The CONDITION OF WEARING SURFACE is

1) Good condition

2) Fair- condition

3) Poor condition

4) ** Use impact factor as function of bridge length **

5) other

The values selected for the impact factor, I, are 0.1, 0.2, 0.3, and 50/(125+L) conditions 1, 2, 3, and 4, respectively.

The values corresponding to the options available for the load categories correspond to reliability modeling studies which calibrate code specified factors. The values are calibrated by performing the following steps [TRB, 1987]:

i) Assemble a representative sample of components for each category. This means different spans, geometry, number of lanes, traffic, etc. These should be selected from both existing :bridges and hypothetical or generic designs.

ii) Compute safety indices for each example.

iii) Select a representative value of (3's as a target. If past judgment and experience indicate that structures are overly conservative, the target R may be reduced. Similarly, if there have- been failures due to load exceeding resistance or other indications that the safety margin is insufficient, target (3's should be raised:

iv) Choose by iteration, load and resistance factors, so that the target (3 is obtained for the sample with the least amount of scatter:

v) Perform sensitivity studies on the data base, i.e., vary parameters for which data are insufficient and subjective estimates had to be made.

The values that the system selects for the live load and dead load factors will depend on the target (3 of 2.5. Also current provisions base the impact factor on deck 'smoothness' and not as a function of length as present AASHTO provisions dictate. The capacity reduction factor is discussed in the Chapter 6.

CHAPTER 5

CONSTRUCTION AND SERVICE LOAD STRESSES IN SEGMENTAL BOX BRIDGES

5.1. INTRODUCTION

The computation of stage-by-stage stresses and deformations in segmental concrete box bridges is an essential step in checking serviceability criteria. Concrete and prestressing tendons exhibit nonlinear, time-dependent behavior which needs to be accounted for in the analysis. The checks for serviceability are more complex, because they involve determination of stress and strain distributions in a cross section at: various loading stages. The analysis should account for the time-dependent effects of creep and shrinkage of concrete This chapter describes the basic concepts underlying the computational procedures, used to determine the time dependent effects and the secondary moments in continuous segmental box bridges:

5.2. TIME-DEPENDENT STRAINS [Ghali, 1986]

5.2.1. Creep of concrete: stress- strain relation

A typical stress-strain curve for concrete, shown in Figure 5.1, assumes that the stress in concrete is proportional to strain in service conditions. The value of E,(tO) depends upon magnitude of the stress. A stress increment $\Delta\sigma_c$ (to) introduced at time to and sustained without change in magnitude to time t produces instantaneous strain plus creep of total value given by (Figure 5.2)

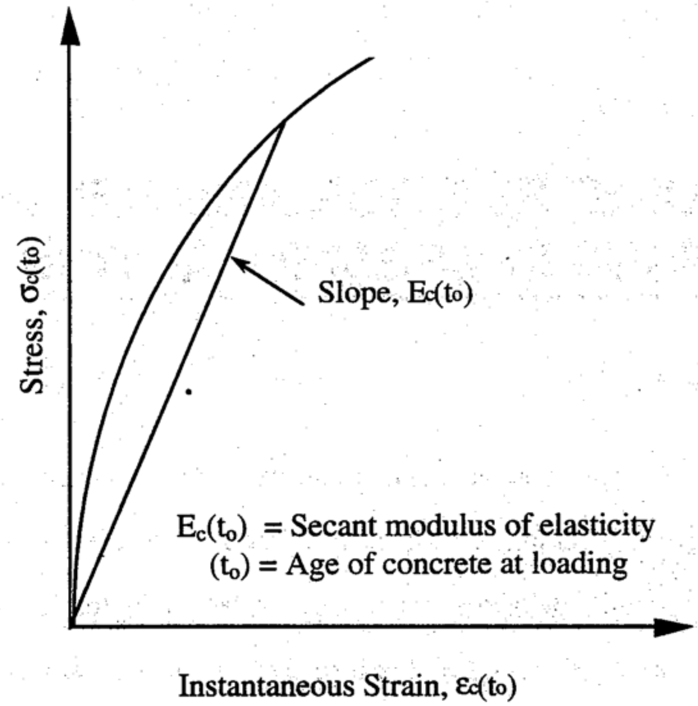


Figure 5.1 Stress-strain curve for concrete [Ghali, Favre, 1986]

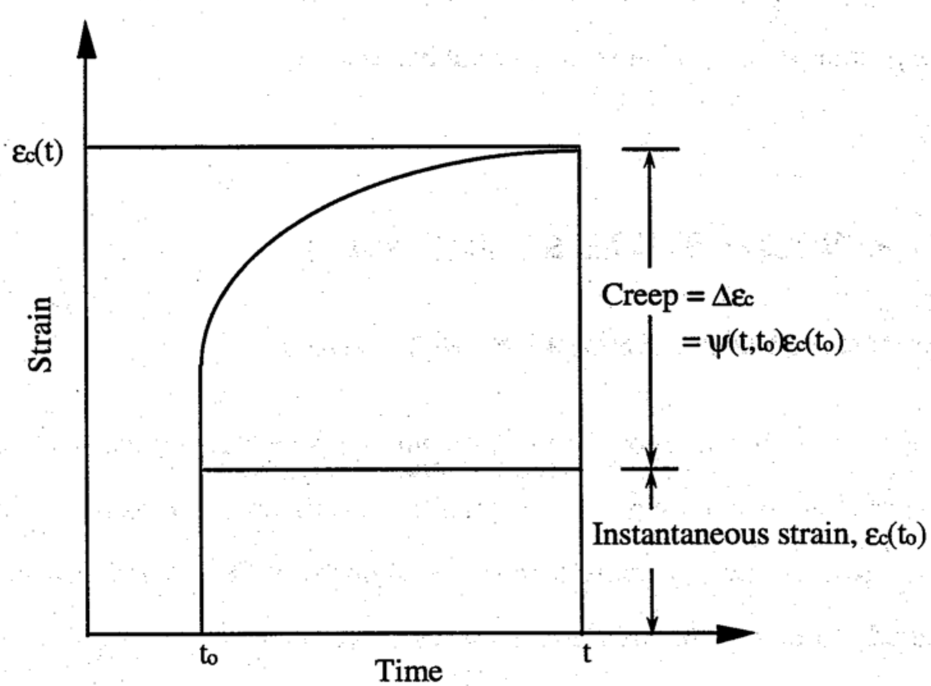


Figure 5.2 Creep of concrete under the effect of sustained stress [Ghali, Favre, 1986]

$$\Delta\varepsilon_c(t) = \frac{\Delta\sigma_c(t_0)}{E_c(t_0)}[1+\phi\ (t, t_0)] \qquad .....(5.1)$$

where

$E_c(t_0)$ = secant modulus of elasticity of concrete at t_0

$\phi\ (t,t_o)$ = creep coefficient (equal to the ratio of creep during the period t_0 to t to the instantaneous strain at t_0)

The value of ϕ depends, in addition to t and t_0, on the humidity of atmosphere and cross section dimensions. Creep effects are cumulative and strain superposition is assumed to be valid(Figure 5.3). A stress increment $\Delta\sigma_c(t,t_0)$ introduced gradually on the concrete from zero at t_0 to full value at time t produces instantaneous strain and creep of total magnitude at time t given by

$$\Delta\varepsilon_c\ (t,t_0) = \frac{\Delta\sigma_c(t,t_0)}{E_c(t_0)}[1+\chi\phi(t,t_0)] \qquad .....(5.2)$$

where

χ = aging coefficient (a function of t and t_0)

The value of χ can be taken to be 0.8 for many practical calculations. Eqn. 5.2 may be rewritten as

$$\Delta\varepsilon_c(t,t_0) = \frac{\Delta\sigma_c(t,t_0)}{\bar{E}_c(t,t_0)} \qquad .....(5.3)$$

where

$$\bar{E}_c(t,t_0) = \frac{E_c(t_0)}{1+\chi\phi(t,t_0)} \qquad .....(5.4)$$

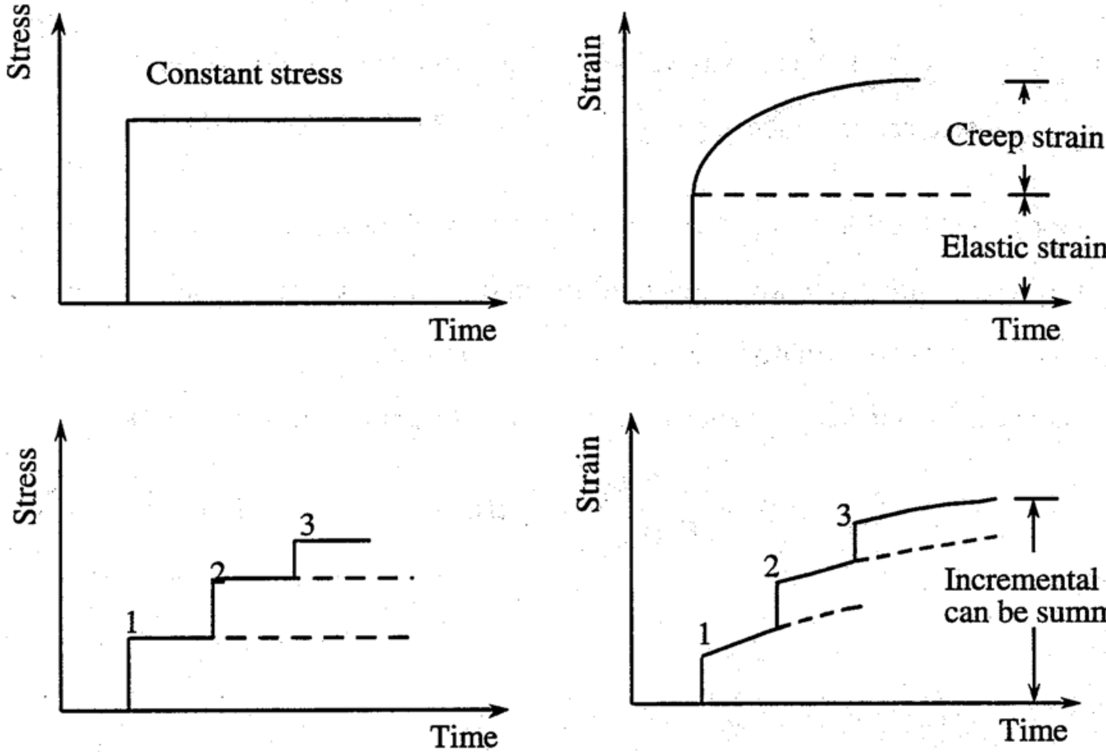


Figure 5.3 Superposition of creep effects [Herbert, 1990]

5.2.2 Relaxation of prestressed steel

The magnitude of the intrinsic relaxation in the tendon increases rapidly as the initial stress approaches the specified tensile strength, f_{pu}. For the same initial stress, the relaxation of a prestressed tendon in a concrete member is smaller than the intrinsic relaxation. The reduced relaxation value which must be used in the design is given by

$$\Delta\bar{\sigma}_{pr} = \chi_r \, \Delta\,\sigma_{pr} \qquad .....(5.5)$$

in which χ_r is the reduction factor as shown below.

$$\chi_r = e^{(-6.7+5.3\lambda)\Omega} \qquad .....(5.6)$$

where

λ = ratio of the initial stress in the tendon σ_{po} to its specified tensile strength f_{pu}

$$\Omega = -\frac{\Delta\sigma_{ps} - \Delta\sigma_{pr}}{\sigma_{po}} \qquad .....(5.7)$$

where

$\Delta\sigma_{ps}$ = the change in stress in prestressed steel in a given period of time due to the combined effect of creep, shrinkage and relaxation.

$\Delta\sigma_{pr}$ = intrinsic relaxation which is dependent upon the quality of steel and on the initial stress magnitude.

5.2.3 Instantaneous stress and strain

Figure 5.4a shows a typical cross - section with prestressed / non- prestressed steel subjected at any instant to changes in the normal axial force ΔN and bending moment ΔM. The forces ΔN and ΔM represent statical equivalent of the internal forces on the section at the instant considered due to the dead load plus the effect of initial prestressing (including the statically indeterminate effects, if any).

Plane sections remain plane and hence the changes in strain and stress will be linear and at any fiber with coordinate y, their values are

$$\Delta\varepsilon = \Delta\varepsilon_0 + \Delta\psi y \qquad .....(5.8)$$

$$\Delta\sigma = \Delta\sigma_0 + \Delta\gamma y \qquad .....(5.9)$$

where the subscript o refers to the reference point and $\Delta\psi$ and $\Delta\gamma$ are changes in slopes of strain and stress diagrams: $\Delta\psi$ represents also a change in curvature.

Stress and strain changes at any concrete fiber or at a steel layer are related as

$$\Delta\sigma = E\,\Delta\varepsilon \qquad .....(5.10)$$

where

E = modulus of elasticity.

Each of the symbols, σ, ε and E in the above equations may have subscripts *c*, *ns* or *ps* to refer to concrete, non-prestressed or prestressed steel, respectively. When concrete is considered, E_c represents the modulus of elasticity of concrete at the instant considered.

The stress resultants ΔN and ΔM may be expressed as

$$\Delta N = \int \Delta\sigma \; dA \qquad .....(5.11)$$

$$\Delta M = \int \Delta\sigma \; y \; dA \qquad .....(5.12)$$

Substitution of Eqn. (5.9) into Eqs. (5.11) and (5.12) gives:

$$\Delta N = A(\Delta\sigma_0) + B(\Delta\gamma) \qquad .....(5.13\ a)$$

$$\Delta M = B(\Delta\sigma_0) + I(\Delta\gamma) \qquad .....(5.13\ b)$$

where *A*, *B* and *I* are the area and its first and second moments about an axis through the reference point O of a transformed section composed of the area of concrete plus the areas of the two steels each multiplied by its modulus of elasticity and divided by E_c.

Substituting $\Delta\sigma_0 = E_c\,(\Delta\varepsilon_0)$ and $\Delta\gamma = E_c\,(\Delta\psi)$ and solving Eqs. (5.13 a) and (5.13 b), the instantaneous changes in axial strain and curvature are obtained as

$$\Delta\varepsilon_0 = \frac{1}{E_c(AI - B^2)}[I\,(\Delta N) - B\,(\Delta M)] \qquad .....(5.14\ a)$$

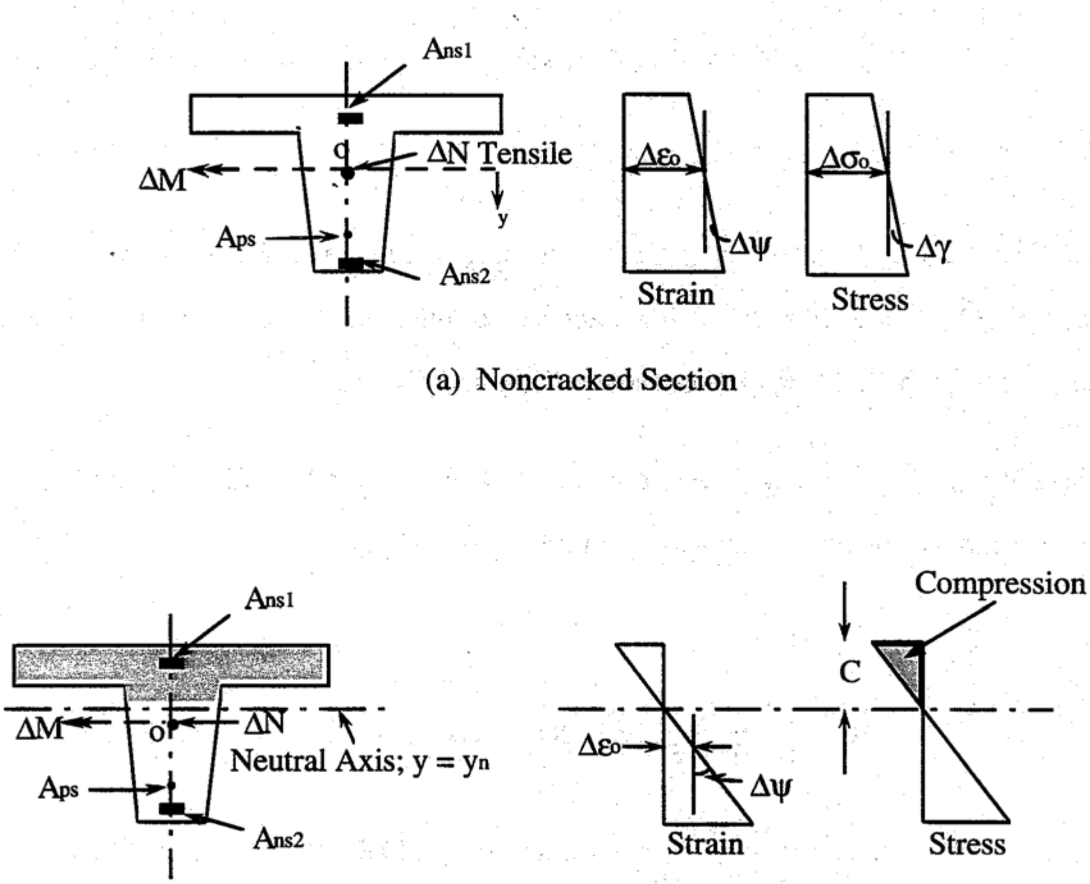
$$\Delta\psi_0 = \frac{1}{E_c(AI - B^2)}[-B\,(\Delta N) + A\,(\Delta M)] \qquad .....(5.14\ b)$$

When the reference point O is chosen at the centroid of the transformed section, B= 0 and Eqs. (5.14 a) and (5.14 b) take the following forms:

$$\Delta\varepsilon_0 = \frac{\Delta N}{E_c A} \qquad .....(5.15\ a)$$

$$\Delta\psi_0 = \frac{\Delta M}{E_c I} \qquad .....(5.15\ b)$$

The centroid of the transformed section changes its position, since E_c changes with time. The instantaneous changes in strain and stress in any reinforced concrete uncracked or fully cracked section (Fig. 5.4 a and 5.4 b respectively) are given by Eqs. (5.14 a) and (5.14 b).



(a) Noncracked Section

(b) Fully-Cracked Section

Figure 5.4 Noncracked and fully - cracked sections [Ghali, 1986]

5.2.4. Compression zone in a fully cracked section

Under the service load conditions, it is expected that the segmental box bridges will experience stresses smaller than the maximum tensile strength of concrete. However, in precast concrete structural elements, situation may arise where the section could crack during the service life of the structure.

Figure 5.4b shows the strain and stress distributions in a cross-section reinforced with many layers of steel due to forces ON and OM which produce cracking at the bottom fiber. It is assumed that the stress in the concrete is zero prior to the instant t when ON and OM are applied. Concrete in tension is ignored and the plane cross section is assumed to remain plane. Thus, Eqs (5.8). and:(5.10) apply with E equal to zero for the concrete below the compressed zone c:

The stress in the concrete / steel at any fiber is given by

$$\sigma = E\,(1-\frac{y}{y_n})\,\varepsilon_0 \qquad .....(5.16)$$

Substitution of Eqn. (5.16) into Eqs. (5.11) and (5.12) gives:

$$\int_{y_t}^{y_n}(y_n - y)\,dA + \Sigma[\frac{E_s}{E_c}A_s(y_n - y_s)] = 0 \qquad .....(5.17)$$

(when $\Delta N = 0$)

$$\frac{\int_{y_t}^{y_n} y(y_n - y)dA + \Sigma[\frac{E_s}{E_c} A_s\, y_s(y_n - y_s)]}{\int_{y_t}^{y_n}(y_n - y)dA + \Sigma[\frac{E_s}{E_c} A_s\,(y_n - y_s)]} - \frac{\Delta M}{\Delta N} = 0 \qquad .....(5.18)$$

(when $\Delta N \neq 0$)

where

y_t = y coordinate at the extreme compression fiber (the top of the section); the summation is for all steel layers.

y_n= y coordinate at the neutral axis;

y_s= y coordinate measured downwards from the reference point;

A_s= area of steel in one layer of reinforcement;

dA=an elemental area of concrete in compression;

E_s and E_c=moduli of elasticity of steel and concrete;

Eqn. (5.17) indicates that when $\Delta N = 0$, the neutral axis is at the centroid of the transformed section. When $\Delta N \neq 0$, Eqn. (5.18) shows that y_n depends upon the eccentricity ($\Delta M/\Delta N$) and not on the separate magnitudes of ΔM and ΔN. Eqs. (5.17) and (5.18) apply only when the stress at top fiber is compressive and when the stress changes sign within the section depth as shown in Fig. 5.4 b.

5.2.5 Decompression forces

Partially prestressed sections are often designed to have no cracking under sustained dead load, but cracking is allowed due to live load. The changes in strain and stress due to additional loading introduced at any specified instance producing internal forces {ΔN, ΔM} can be determined, which are of magnitudes sufficient to produce cracking. The pair of forces {ΔN, ΔM} could be partitioned into a decompression part to be applied on a noncracked section and a remaining part on the fully cracked section.

The decompression forces are the values of the normal force at O and the bending moment which reduce the stress in concrete to zero; from Eqs. (5.13 a) and (5.13 b)

$$\Delta N_{decompression} = A(-\sigma_0) + B(-\gamma) \qquad .....(5.19\ a)$$

$$\Delta M_{decompression} = B(-\sigma_0) + I(-\gamma) \qquad .....(5.19\ b)$$

where

A, B and I are the properties of the transformed noncracked section at time t.

The decompression forces are applied on a noncracked section and the corresponding changes in axial strain and curvature are [$-\sigma_o/E_c(t)$] and [$-y/E_c(t)$].

The forces to be applied on: a fully cracked section are:

$$\Delta N_{\text{fully cracked}} = \Delta N - \Delta N_{\text{decompression}} \qquad .....(520\ a)$$

$$\Delta M_{\text{fully cracked}} - \Delta M - \Delta M_{\text{decompression}} \qquad .....(520\ b)$$

Eqs. (5.14 a) , (5.14 b) and (5.10) may be used to calculate the changes in strain and stress distribution in the cracking stage using A, B and I corresponding to fully cracked section. The width of cracks in reinforced concrete members -depends mainly upon the increment of steel stress which occurs at the cracking stage,-and not on. the steel stress after cracking.

5:2:6 Time-dependent changes in strain and stress

The normal strain ϵ_o (t_o) and curvature Ψ (t_o) define the strain distribution at time to for a cross section reinforced with prestressed and nonprestressed steels. It is desirable to find the changes in strain, and: stress due to creep and shrinkage .of: concrete and relaxation of prestressing steel: The reduced relaxation of, prestressed steel, $\Delta\sigma_{pr}$, the creep coefficient ϕ, the aging coefficient χ, and the normal strain resulting from shrinkage of concrete ε_{cs}, depend upon t_o and t and material properties. The normal strain ε_{cs}, represents the shrinkage which occurs when the shortening of a member is not restrained by the reinforcement or by end forces. The strain change at any concrete fiber due to creep and shrinkage can be artificially restrained by application of a stress given by

$$\Delta\sigma_{\text{resrraint}} = -\bar{E}_c\ [\phi\ \epsilon_c\ (t_o) + \epsilon_{cs}\ ] \qquad .....(5;21)$$

where

$\bar{E}_c =$ age adjusted elasticity modulus.

The restraining stress has the following resultants:

$$\Delta N_{creep} = -\bar{E}_c\,\phi[A_c\,\varepsilon_o(t_0) + B_c\psi(t_0)] \qquad .....(5.22\text{ a})$$

$$\Delta M_{creep} = -\bar{E}_c\,\phi[B_c\,\varepsilon_o(t_0) + I_c\psi(t_0)] \qquad .....(5.22\text{ b})$$

$$\Delta N_{shrinkage} = -\bar{E}_c\,\varepsilon_{cs}A_c \qquad .....(5.23\text{ a})$$

$$\Delta M_{shrinkage} = -\bar{E}_c\,\varepsilon_{cs}B_c \qquad .....(5.23\text{ b})$$

where A_c, B_c, and I_c are the properties of the concrete section without the reinforcements. The area of post-tensioned ducts (not grouted before the instant t_o) may be excluded from A_c, B_c and I_c in Eqn. (5.22).

The strain due to relaxation of prestressed steel can be artificially prevented by the forces given by:

$$\Delta N_{relaxation} = \Sigma\,(A_{ps}\,\Delta\,\bar{\sigma}_{pr}) \qquad .....(5.24\text{ a})$$

$$\Delta M_{relaxation} = \Sigma\,(A_{ps}\,y_{ps}\,\Delta\,\bar{\sigma}_{pr}) \qquad .....(5.24\text{ b})$$

where the summation takes into account the prestressed steel layers. All strains can be prevented by the restraining forces:

$$\Delta N = \Delta N_{creep} + \Delta N_{shrinkage} + \Delta N_{relaxation} \qquad .....(5.25\text{ a})$$

$$\Delta M = \Delta M_{creep} + \Delta M_{shrinkage} + \Delta M_{relaxation} \qquad .....(5.25\text{ b})$$

The artificial restraint can now be eliminated by the application of { $-\Delta N$, $-\Delta M$ } on an age-adjusted transformed section composed of the area of concrete plus the areas of the reinforcements, each multiplied by its modulus of elasticity and divided by the age adjusted modulus of elasticity of concrete. The resulting strain is the change due to creep, shrinkage and relaxation during the period t_0 to t and may be determined by Eqs. (5.14 a) and (5.14 b).

$$\Delta\varepsilon_0(t,t_0) = \frac{1}{\bar{E}_c(\bar{A}\bar{I}-\bar{B}^2)}[\bar{I}(-\Delta N)-\bar{B}(-\Delta M)] \qquad .....(5.26\ a)$$

$$\Delta\psi_0(t,t_0) = \frac{1}{\bar{E}_c(\bar{A}\bar{I}-\bar{B}^2)}[-\bar{B}(-\Delta N)+\bar{A}(-\Delta M)] \qquad .....(5.26\ b)$$

where $\bar{A}, \bar{B}, \bar{I}$ are properties of the age-adjusted transformed section. The change in strain $\Delta\varepsilon(t,t_0)$ at any concrete fiber or any layer of reinforcement can be calculated by Eqn. (5.8). The corresponding changes in stress in concrete, prestressed and nonprestressed steel are given by:

$$\Delta\sigma_c\ (t,t_0) = \Delta\sigma_{restraint} + \bar{E}_c\ \Delta\ \varepsilon_c\ (t,t_0) \qquad .....(5.27)$$

$$\Delta\sigma_{ps}(t,t_0) = \Delta\bar{\sigma}_{pr} + E_{ps}\ \Delta\ \varepsilon_{ps}\ (t,t_0) \qquad .....(5.28)$$

$$\Delta\sigma_{ns}(t,t_0) = E_{ns}\ \Delta\ \varepsilon_{ns}\ (t,t_0) \qquad .....(5.29)$$

For a statically indeterminate structure, the time dependent effects change the reaction and produce the statically indeterminate(secondary) increments of internal forces at all sections. These increments must be determined and added to (-ΔN) and (-ΔM), and the sum used to calculate the time dependent changes by Eqs. (5.26 a) and (5.26 b).

5.2.7 Tension stiffening

The effect of tension stiffening when cracking occurs is determined by interpolation between lower and upper limits of strain calculated using the properties of a noncracked section and a fully cracked section in which concrete is ignored in tension. Mean values $\{\Delta\varepsilon_0, \Delta\psi_0\}$ are obtained using the interpolation equations given by

$$\Delta\varepsilon_{0\ mean} = (1-\zeta)\,\Delta\,\varepsilon_{0\ noncracked} + \zeta\,\Delta\,\varepsilon_{0\ fully\ cracked} \qquad .....(5.30\ a)$$

$$\Delta\psi_{0\ mean} = (1-\zeta)\,\Delta\,\psi_{0\ noncracked} + \zeta\,\Delta\,\psi_{0\ fully\ cracked} \qquad .....(5.30\ b)$$

The interpolation coefficient ζ is given by

$$\zeta = 1 - \beta_1\beta_2\left(\frac{f_{ct}}{\Delta\sigma_{max}}\right)^2 \qquad .....(5.31)$$

where

$\Delta\sigma_{max}$ = the change in stress at the extreme tension fiber due to $\{\Delta N, \Delta M\}_{fully\ cracked}$ applied on a noncracked section

f_{ct} = the concrete strength in tension

β_1 = 1.0 for high bond or

= 0.5 for plain reinforcing bars

β_2 = 1.0 for first loading

= 0.5 for the case when the load is applied in a sustained manner

The mean value of the crack width at the level of a steel layer is expressed as

$$\omega = \zeta\, s\, \Delta\varepsilon_{s\ fully\ cracked} \qquad .....(5.32)$$

where

$\Delta\varepsilon_{s\ \text{fully cracked}}$ = strain increment at the level of a reinforcement layer calculated for a fully cracked section.

s = spacing between the cracks.

5.2.8 Equilibrium checks

The analysis is based on requirements of equilibrium and compatibility of strain in concrete and all layers of reinforcements. The calculation for the time dependent stress increments can be checked by verifying that the stress changes in the concrete and the reinforcements are self equilibrating when the analysis is carried out for a cross section of a statically determinate structure.

5.2.9 Multistage prestressing and loading

Bridge structures are often prestressed in a number of stages during construction. The prestressing is generally carried out in stages to suit the development of forces due to the structure self weight as the construction progresses. For each set of forces introduced simultaneously (e.g., prestressing plus dead load), the instantaneous increments of stress and strain at t_0 are determined with the properties of transformed noncracked section (or fully cracked if cracking occurs at this stage). These increments of stress and strain are added to the values existing before this load stage. Figure 5.5. shows the flow chart for the analysis of stress and strain in a concrete section prestressed/loaded in multiple stages.

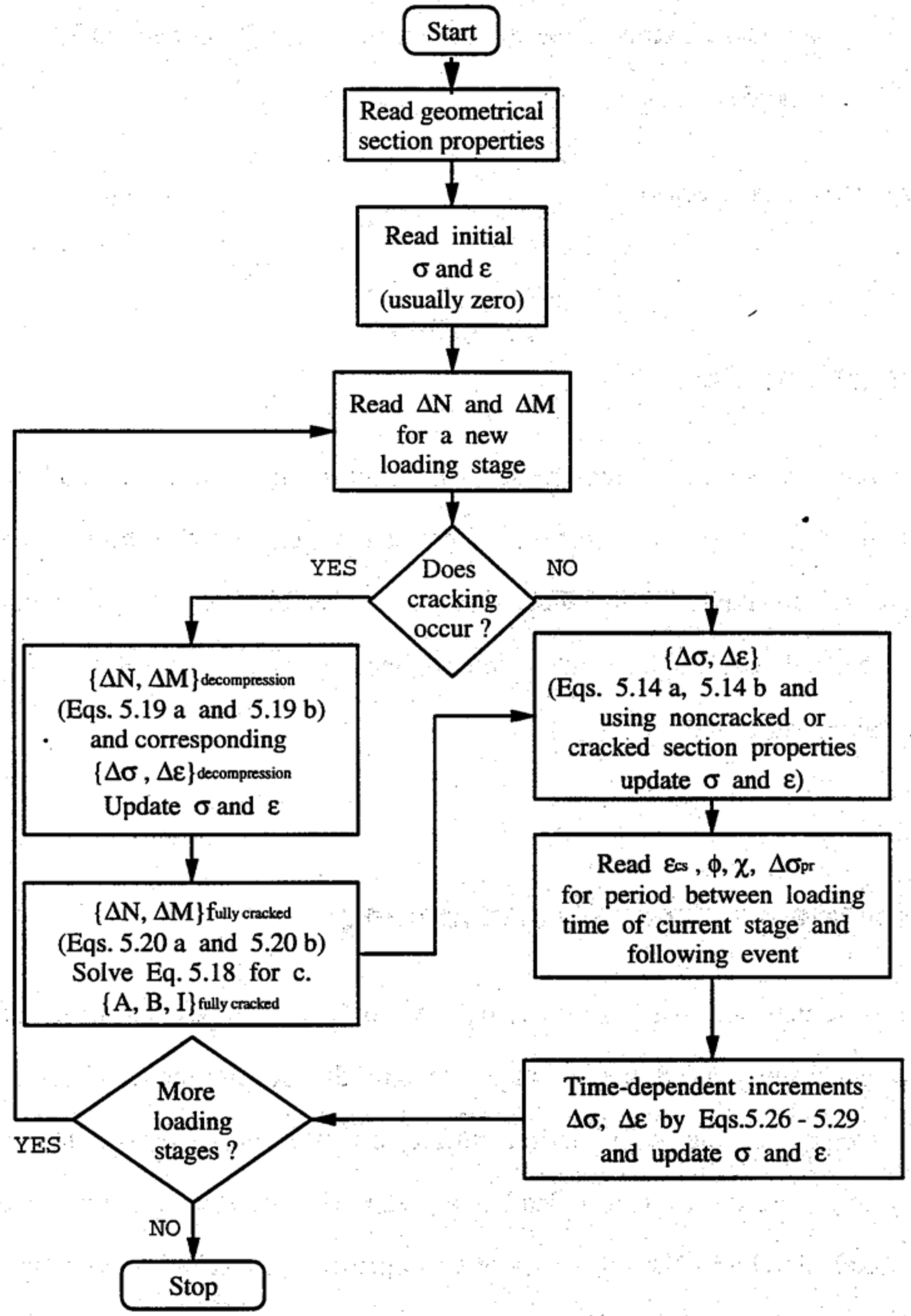


Figure 5.5 Flowchart for analysis of stress and strain in a concrete section prestressed and/or loaded in a multiple of stages [Ghali, 1986]

5.2.10 Creep and shrinkage properties [Ghali, 1986]

A large number of variables affects the magnitude of creep and shrinkage. The coefficient for creep at time t for age at loading t_0 is given by

$$\varphi(t,t_0)=\frac{(t-t_0)^{0.6}}{10+(t-t_0)^{0.6}}\,\varphi_u \qquad .....(5.33)$$

where

$$\varphi_u=\varphi(t_\infty\,,t_0)$$

φ_u equals ultimate creep after a very long time for age at loading t_0. The value φ_u is given by

$$\varphi_u=2.35\,\gamma_c \qquad .....(5.34)$$

where

γ_c = correction factor, the product of several multipliers depending upon ambient relative humidity, average thickness of the member or its volume to surface ratio and on the temperature.

The free shrinkage for moist cured concrete which occurs between t_0 = 7 days and any time t, is expressed as

$$\varepsilon_{cs}(t,t_0)=\frac{t-t_0}{35+(t-t_0)}(\varepsilon_{cs})_u \qquad \text{with } t_0=7 \qquad .....(5.35)$$

For steam cured concrete, the shrinkage between t_0 = 1 to 3 days and any time t is given by

$$\varepsilon_{cs}(t,t_0=1\text{ to }3)=\frac{t-(1\text{ to }3)}{55+(t-1\text{ to }3)}(\varepsilon_{cs})_u \qquad .....(5.36)$$

where

$(\varepsilon_{cs})_u$ = the ultimate free shrinkage corresponding to t_∞ (say at 10,000 days)

The ultimate free shrinkage is given by

$(\epsilon_{cs})_u = -780 \times 10^{-6}\, \gamma_{cs}$ ….. 5.37

where

γ_{cs} = a correction factor, the product of a number of multipliers which depends upon the same, factors mentioned above for y_c.

The correction factor γ_{cs} = 1.0 when the period of initial .moist curing is 7 days, the relative: humidity of the ambient air 40%, the average thickness is 6 in. or the volume to surface ratio is 1.5 in.

5.3 SERVICE LIFE STRESSES

5.3.1 Effect of continuity

Bridges with continuous spans are more economical and efficient resulting from smaller design moments and deflections, and higher rigidity against lateral loads. It allows redistribution: of stresses under overload conditions and ensures a higher margin of safety against collapse. Continuous beams are generally shallower than simple span beams and need lesser amounts of materials. However, the cost effectiveness of continuity in prestressed concrete members depends on span length, design criteria, construction conditions, etc.

In the design and analysis of continuous prestressed beams, the following assumptions are generally made:

(1) Both steel and concrete act as elastic materials within the range of stresses permitted in the design and plane sections remain plane.

(2) The principle of superposition of loads, forces, moments, and stresses is valid.

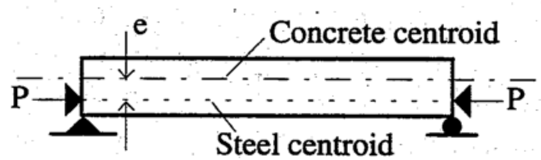
(3) The effect of friction- on the prestressing force-is- negligible. and the prestressing, force: is assumed constant throughout the length of the member. 5-18

(4) The eccentricity of the prestressing force is small in comparison to the span and, hence, the horizontal component of the prestressing force is assumed equal to the prestressing force at any section of the member.

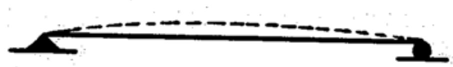
(5) Axial deformation of the member is assumed to take place without any restraint.

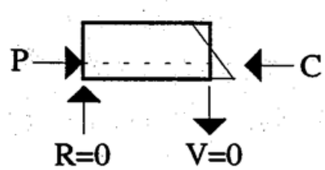
5:3.1:1 Effects of prestressing

When am eccentric prestressing force is applied to a statically determinate beam, bending moment is induced, equal to the product of the force times the distance between the steel centroid and the concrete centroid (Figure 5.6). This moment is referred to as primary moment. The beam will deflect when prestressed, usually cambering upward, but no external reactions are produced. If the effect of member self-weight is excluded from consideration, the compressive stress resultant C :coincides with the centroid of the prestressing steel.



(a) Beam profile


(b) Deflection due to prestressing



(c) Free-body diagram of portion of beam

Figure 5.6 Forces and deflections for statically determinate beam [Nilson]

For a statically indeterminate beam, the action. is more complex. The primary moment causes a tendency for the beam to deflect as before, but is restrained by the redundant system of supports. Reactions are produced at those supports, giving rise to *secondary moments in* the beam. In this case, the total moment produced at any section by prestressing is the sum of the primary and secondary moments:

The effect of prestressing a statically indeterminate beam may be understood with reference to Figures 5.7 and 5.8. The beam of Figure 5.7(a) is subjected to a prestressing force P with a constant eccentricity e. The primary bending moment *Pe* would cause the central part of the continuous beam to rise off its support, as in Figure 53(b) if it were free to do so. It is restrained against this. displacement by the redundant support system, however. To provide this restraint, a downward force R is developed at the center support, as shown in Figure 53(c). This force is equilibrated by the reactions R/2 at each end of the continuous span. The actual deflected shape of the continuous beam, subjected to the prestressing force P, and constrained to zero deflection at all supports, is represented in Figure 5.7(d).

The support forces due to prestressing can be found using the classical method of superposition. Appropriate redundant reactions are selected such that their removal will result in a statically stable and determinate primary structure. The redundants are replaced by unknown forces, and the values of these forces adjusted so that zero deflection is obtained at the corresponding support locations.

The total moment due to prestressing the indeterminate beam is equal to the sum of the primary and secondary moments (Figure 5.8(c)). The magnitude of the secondary moments in any given case depends on the particular tendon profile selected. For special cases, the secondary moments may be zero (concordant tendons) but this is not usually so. They are. often comparable to the primary moments, and in many cases may be larger, even though they are called secondary: The support reactions that result from prestressing a statically indeterminate beam produce shear forces, as well as bending moments, and these should be considered in the analysis:

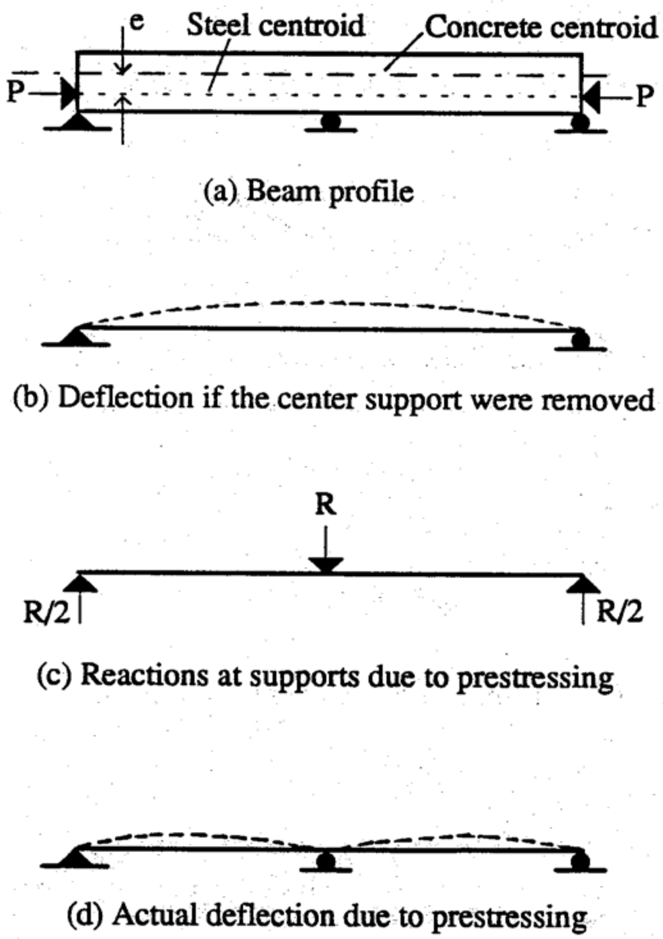


Figure 5.7 Forces and deflections for statically indeterminate beam [Nilson]

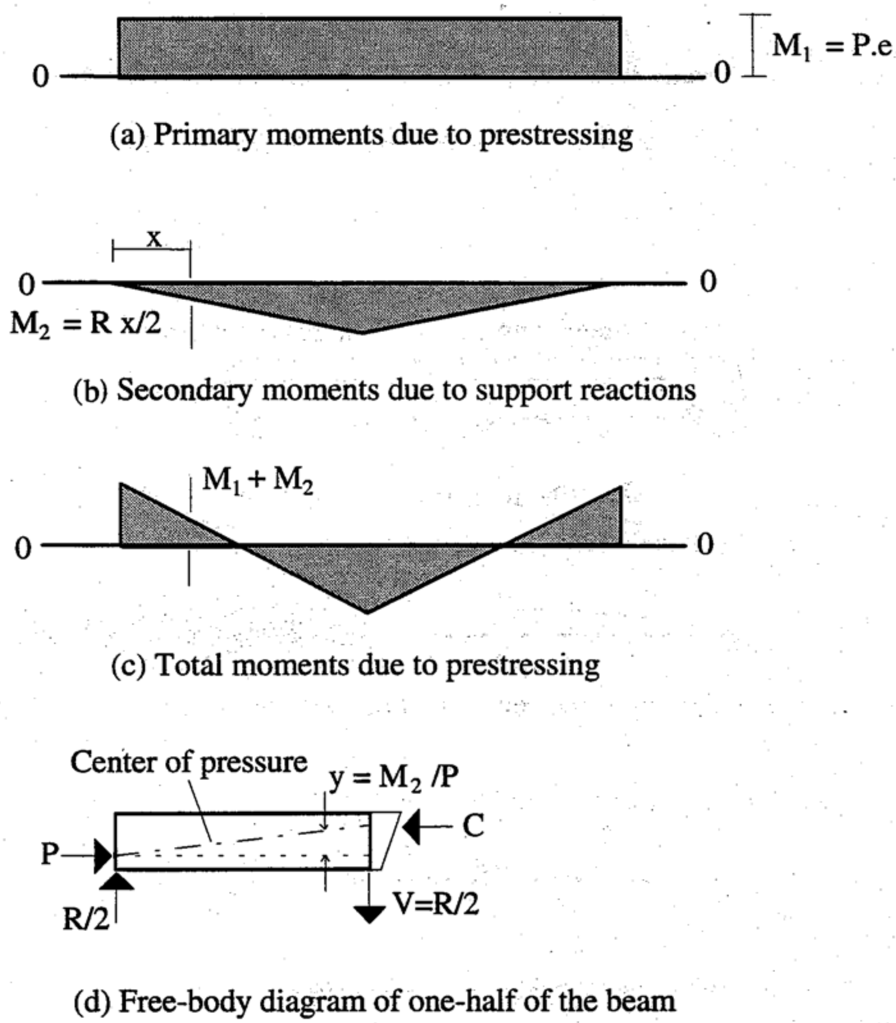


Figure 5.8 Moments and thrust line for a statically indeterminate beam [Nilson]

At the full service load stage, when all prestress losses are assumed to have already occurred, extreme fiber stresses in concrete are: found based on the moment due to dead load, secondary moment resulting from continuity; of prestress, time-dependent effects, and the moment-due to live load:

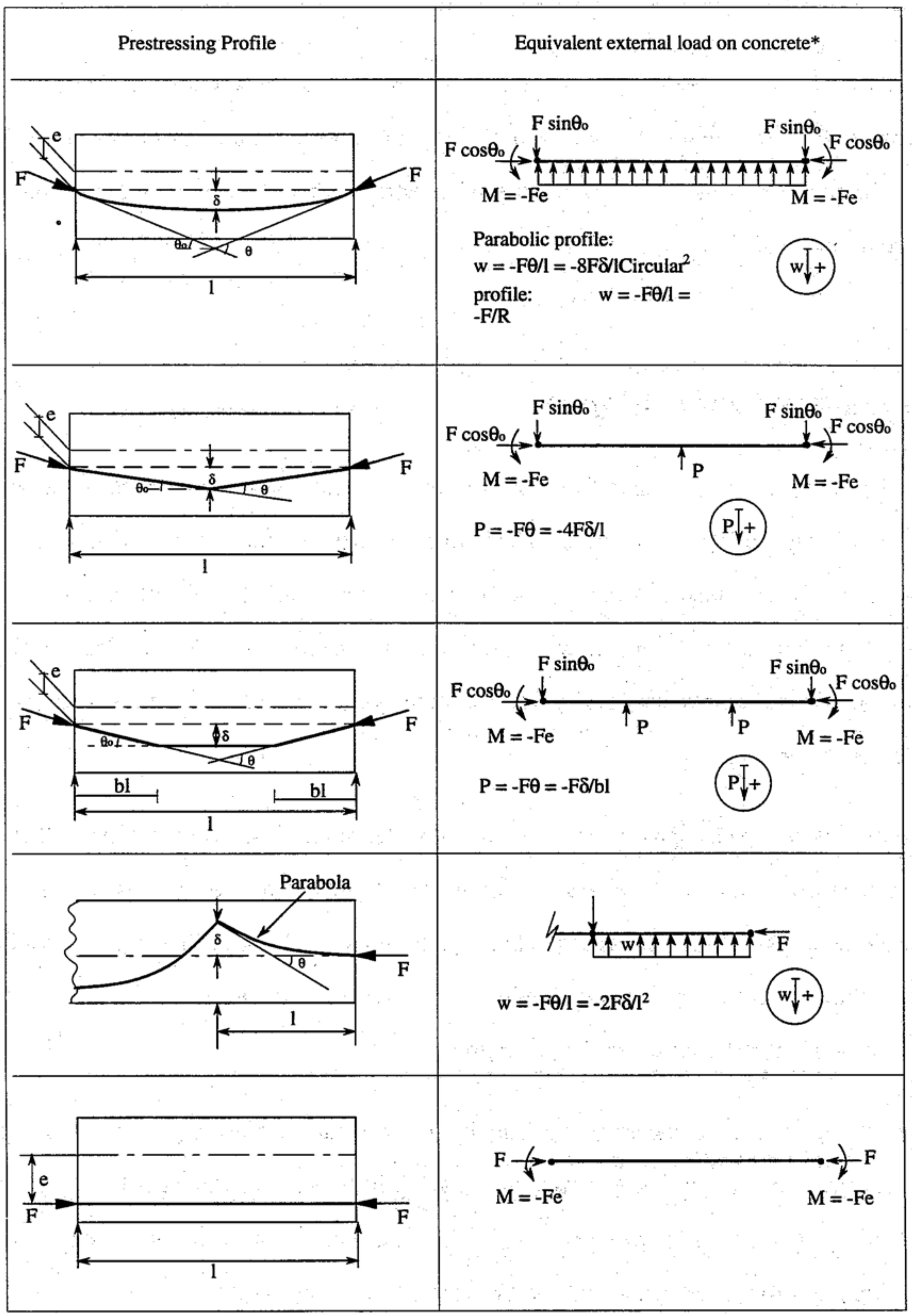
5.3.1.2 Equivalent load analysis

The total moments resulting from prestressing a continuous member may be found directly, without considering the separate contributions of primary and secondary moments, by the method of equivalent loads. Although the method of superposition: of deflections is quite convenienthere there re only one or two redundant reactions, for more highly indeterminate members, the method of equivalent: loads permits a more systematic solution, and is better suited for use with computer programs.

The equivalent load approach is based on consideration of the vertical forces that are applied to a member wherever there is a change in the alignment' of the prestressing tendons. These forces produce moments, just as any other system of external loads. The stresses resulting from these moments must be combined with the uniform axial compression P/A, due to prestressing to obtain the total stresses at any section.

The concept of equivalent loads is particularly advantageous for continuous beams. The vertical forces . that correspond to the particular tendon profile are determined from Figure 5.9. The structure is then analyzed for the effects of these equivalent loads by using matrix displacement method for plane frame analysis as described in section 4.2.

For the indeterminate structure, the moments found from such an analysis are the total moments due to prestressing, and include the secondary moments due to support reactions as well as the primary moments due to tendon eccentricity.



* Assuming shallow members for δ in function of θ

Figure 5.9 Equivalent load formulas for typical tendon profiles in beams [Naaman, 1982]

5.4 CONCRETE STRESSES IN THE SEGMENTAL BOX SECTION

The principle of superposition is valid for a continuous beam that is stressed after the complete structural system has been constructed. A segmental box bridge is a typical example illustrating a stage-by-stage construction process, as shown in Figure 5.10.

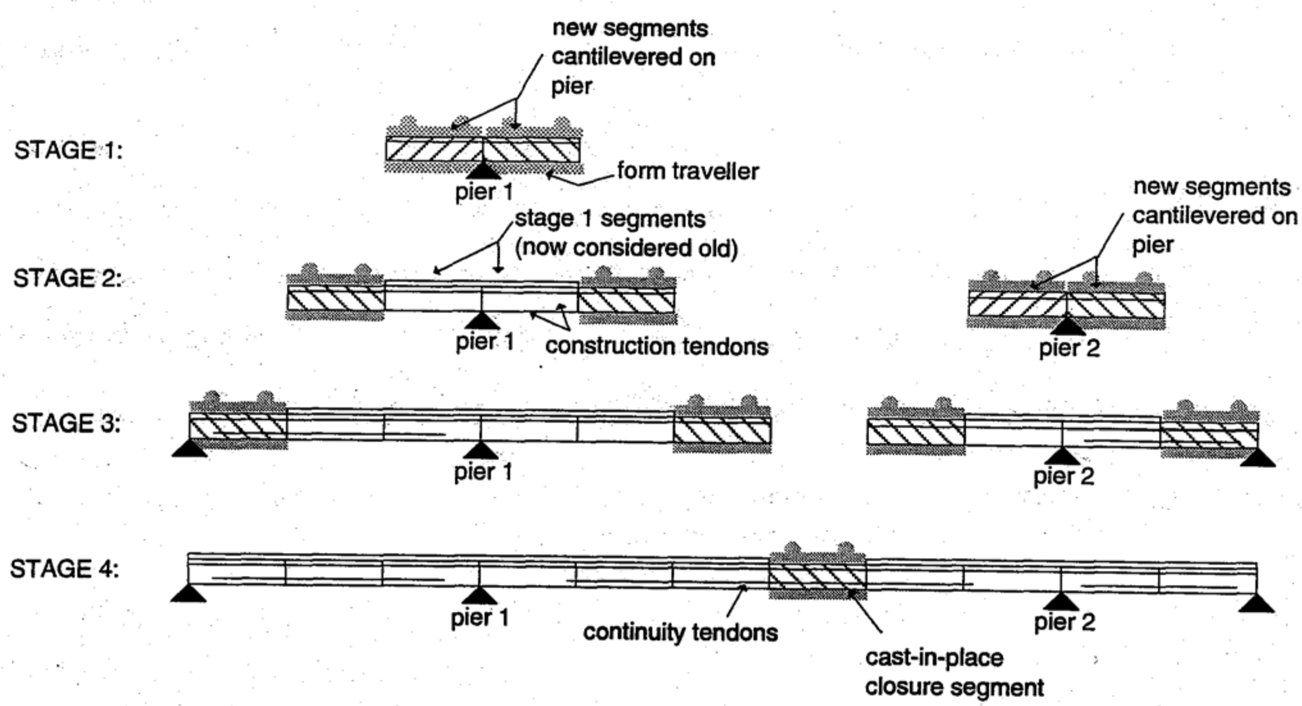


Figure 5.10 Stage-by-stage cantilever construction of segmental box bridges

The variation in the concrete time dependent strains during the lifetime of the structure must be considered. The detailed methods of analysis must take into account the initial strains to which the structure is subjected, as well as the time dependent changes in strain due to shrinkage, creep, and relaxation, as discussed in sections 5.2 and 5.3.

In the case of members cast in segments, subjected to stresses while still in the form of determinate structural elements, and later rendered continuous and indeterminate by cast-in-place closure joints and additional prestressing, the instantaneous strains in the structure can still be considered to be in proportion to the distribution of moments in the structure at the time: the structure was rendered continuous. However, the-time-dependent changes in strain which tend to take place at each section cannot be taken as proportional to the distribution of moments in the structure at the time continuity was established, due to variations in free strain changes that would take place at various locations along the structure. The variation of strains along the length of the structure results in redistribution of moments, which can be calculated using the method described in section 5.2.

The stresses in a segmental box bridge are computed in two phases, that involve computation of time-dependent effects including construction stages, dead load, and continuity effects, and live load stress computation as described in section 5.2 and 5.3. The total stresses are then obtained by algebraic summation of these stresses, as illustrated in Equation 5.1.

Final Stresses = **Time dependent stresses (including construction, dead load and continuity effects)** + **Live load stresses** ....(5.1)

CHAPTER 6

RATING EXPERT SYSTEM (REX) DESIGN

6:1 METHODOLOGY

A modular design approach was taken for the development of the REX system [Arockiasamy, et al]. This method made the appropriation of tasks more lucid and would facilitate further enhancements. The development of: REX system has been carried out in two phases.-During the first phase, the system REX-1 was developed to include solid slab, voided slab, AASHTO girder and slab, and T-beam bridges. 'The segmental box bridge rating and time dependent stresses were included in the system REX-2 during the second phase development. Figure 6.1 (a) and (b) depict detailed flowcharts of the, expert systems REX-1 and REX=2, which show the interaction between various modules and the knowledge: base:

The REX system execution is carried out in four main stages. In the first stage, the system puts forth a series of queries to the user for determination of load and resistance factors. The system interacts with the 'user, in the second stage, through several scrollable lists and onscreen data forms, and- gathers' information required to idealize the bridge in an appropriate manner: and creates: input necessary for analysis. The structural analysis is performed in the following stage. Solid slab, voided slab, AASHTO girder and slab, and T-beam bridges are analyzed using space frame idealization and the segmental box bridge with plane frame modeling. In the last stage of the system execution, structure rating is performed. Outputs from several programs executed earlier are compiled and the

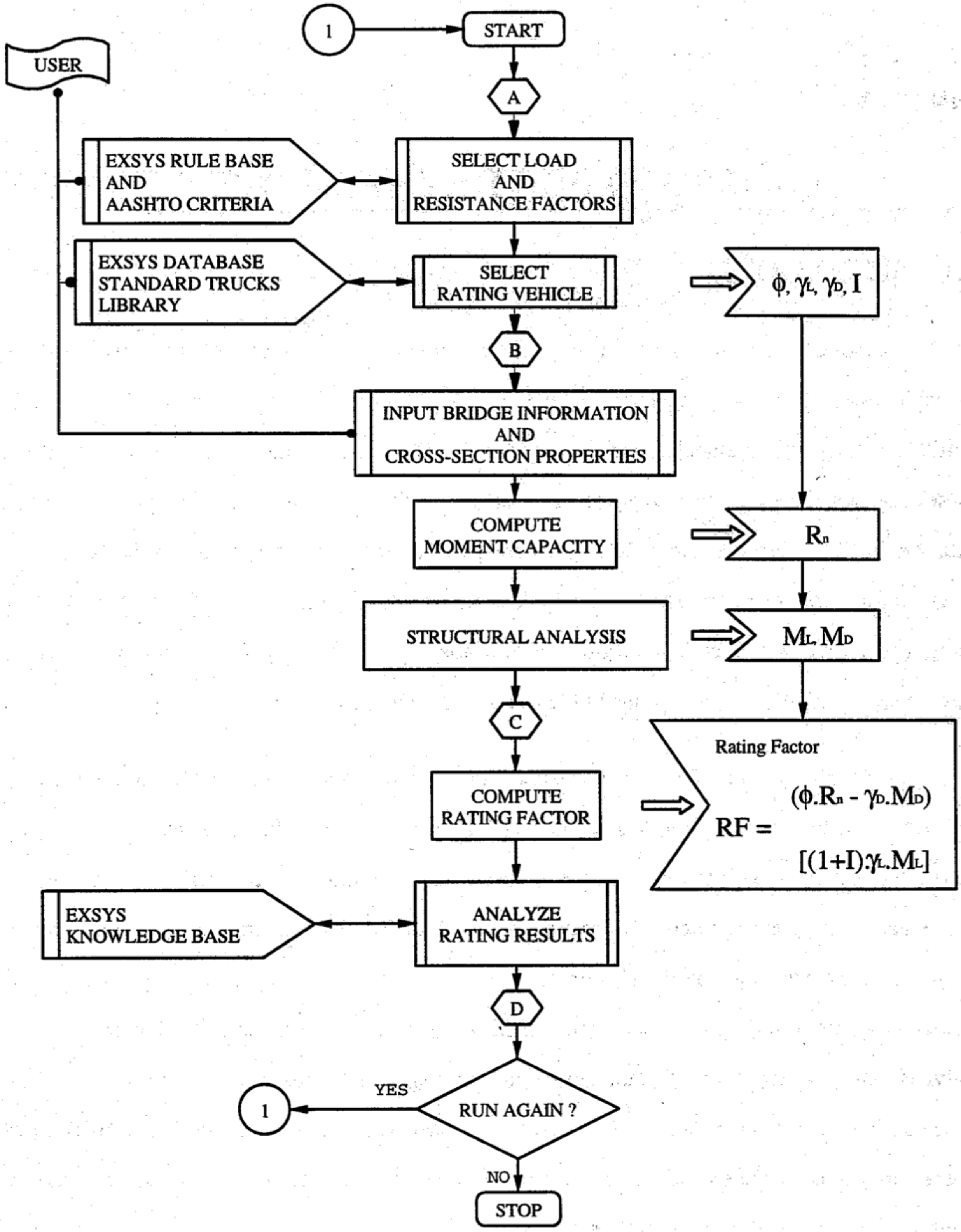


Figure 6.1(a) Flowchart for the expert system REX -1

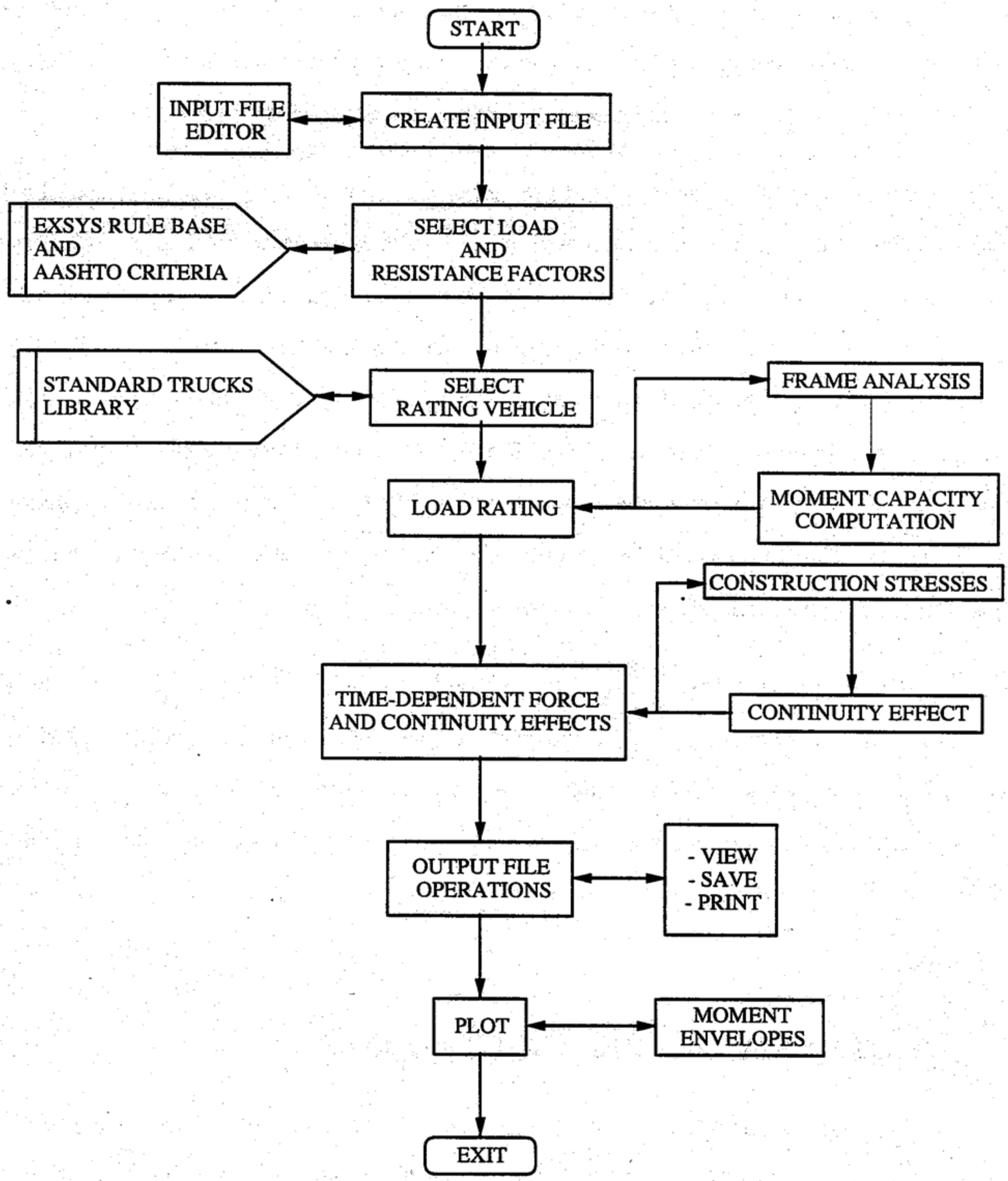


Figure 6.1(b) Flowchart for the expert system REX -2

6.2 KNOWLEDGE BASE

The goal of the knowledge base is to select load and resistance factors and interpret the results of the rating equation. The knowledge incorporated into the shell was obtained from AASHTO and TRB codes and reports and is referenced accordingly in each rule.

The knowledge base interprets the user input and computes the reliability-based load.: factors. These factors are intended to represent conditions existing based on field data obtained from a variety of locations using weigh-in-motion and other data gathering methods (Figure 6.2). The dead load factor accounts for normal variation of material densities and dimensions. The live load factor accounts for the likelihood of extreme loads side-by-side and following in the same lane and the possibility of overload vehicles. These factors also include the effect of frequent presence of overweight trucks on many highways. The resistance factor or capacity reduction factor considers both the uncertainties in estimating member properties and also any bias or conservativeness deliberately-introduced into these estimates (Figure 6.3).

The inference mechanism utilized was. forward chaining. In EXSYS, rules are simply tested in' the order in which they occur. If information is needed, questions will be asked, instead of other rules being invoked. In this system, rule order was crucial to ensure that the question answer session was set up in a format that was congruent with the way one might think about a bridge.

6.3 BRIDGE ANALYSIS AND RATING MODULE

The analysis and rating modules are developed for different bridge types. The user specified input would be different for each bridge type. This section illustrates the input data format with detailed flowcharts. However, the procedure fourating factor determination for all.

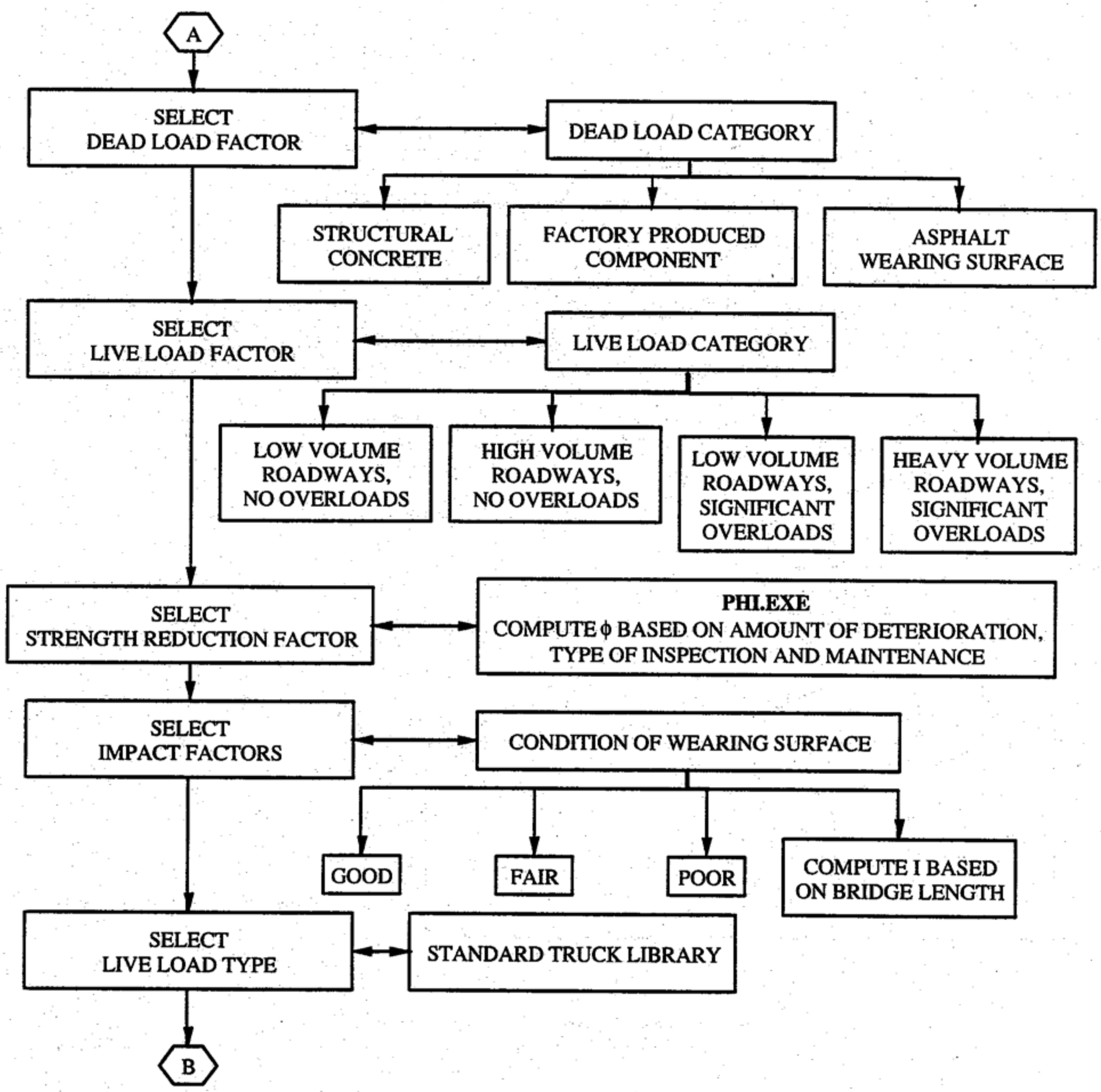


Figure 6.2 Flowchart for computation of load and resistance factors

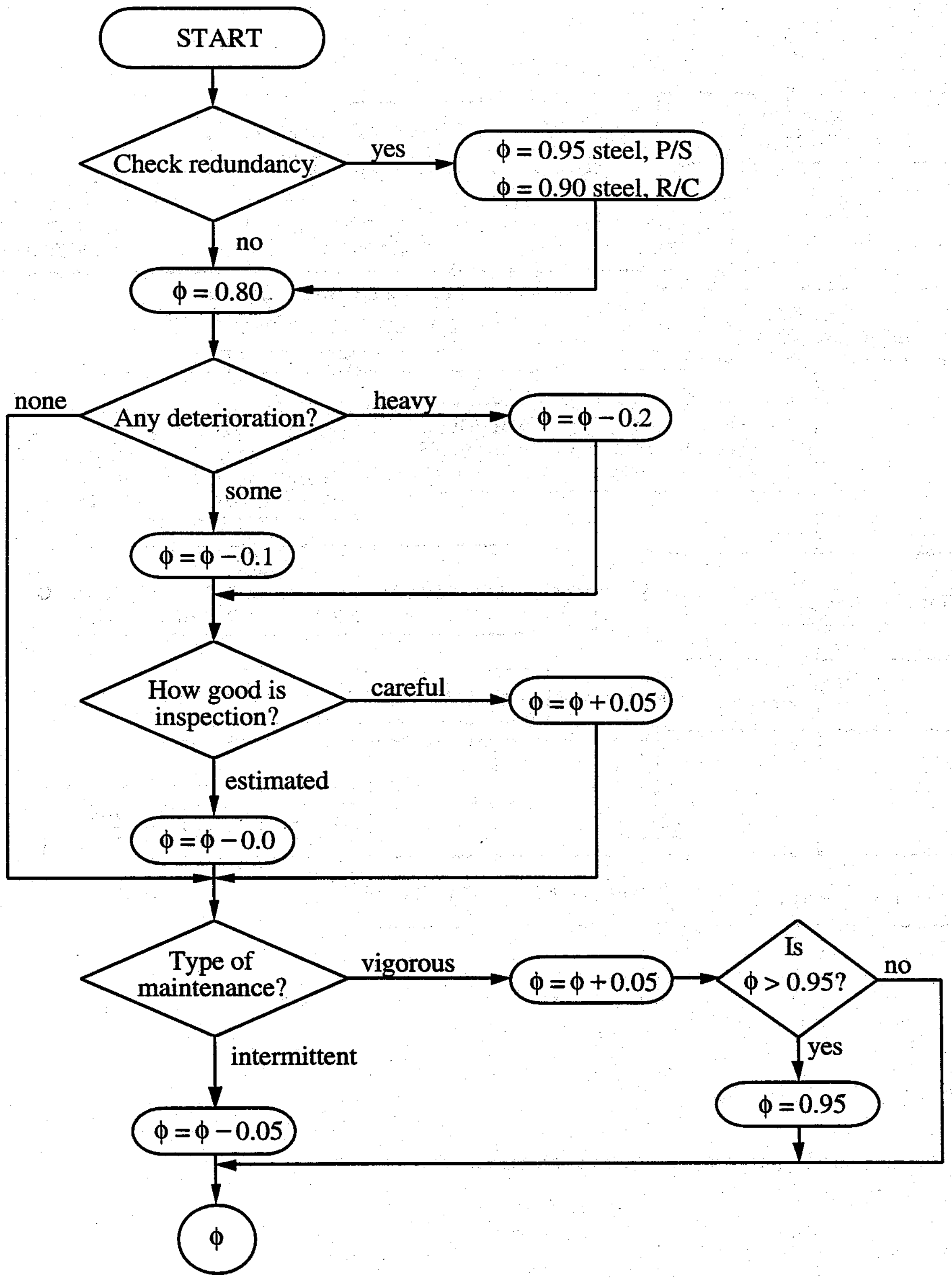


Figure 6.3 Flow chart to select resistance factor [AASHTO, 1989]

bridge types is the same as discussed in section 6.5. The user interface is provided in the form of several scrollable lists and on-screen data forms:

6.3.1 SOLID SLAB BRIDGE [Sawka,1992]

The flowchart illustrating the detailed rating procedure for solid slab bridge is shown in Figure 6.4. The input required by various programs that interface with the user are explained below:

SCR_SLAB.EXE:

Poisson's ratio of concrete, v

Density of concrete (16/ft3), γ

Concrete strength of slab, f' (psi)

SCREEN4.EXE

YEAR. BUILT

AGE

RIGHT EDGE BEAM DEPTH (in)

RIGHT EDGE BEAM WIDTH- (ft)

LEFT EDGE BEAM DEPTH (in)

LEFT EDGE BEAM WIDTH (ft)

RIGHT PARAPET (YES - 1; NO - 0)

LEFT PARAPET (YES - 1; NO - 0)

BRIDGE LENGTH (ft)

BRIDGE WIDTH (ft)

SLAB THICKNESS (in)

OVERLAY UNIT WEIGHT (Asphalt=144;-Concrete=150; lb/ft)

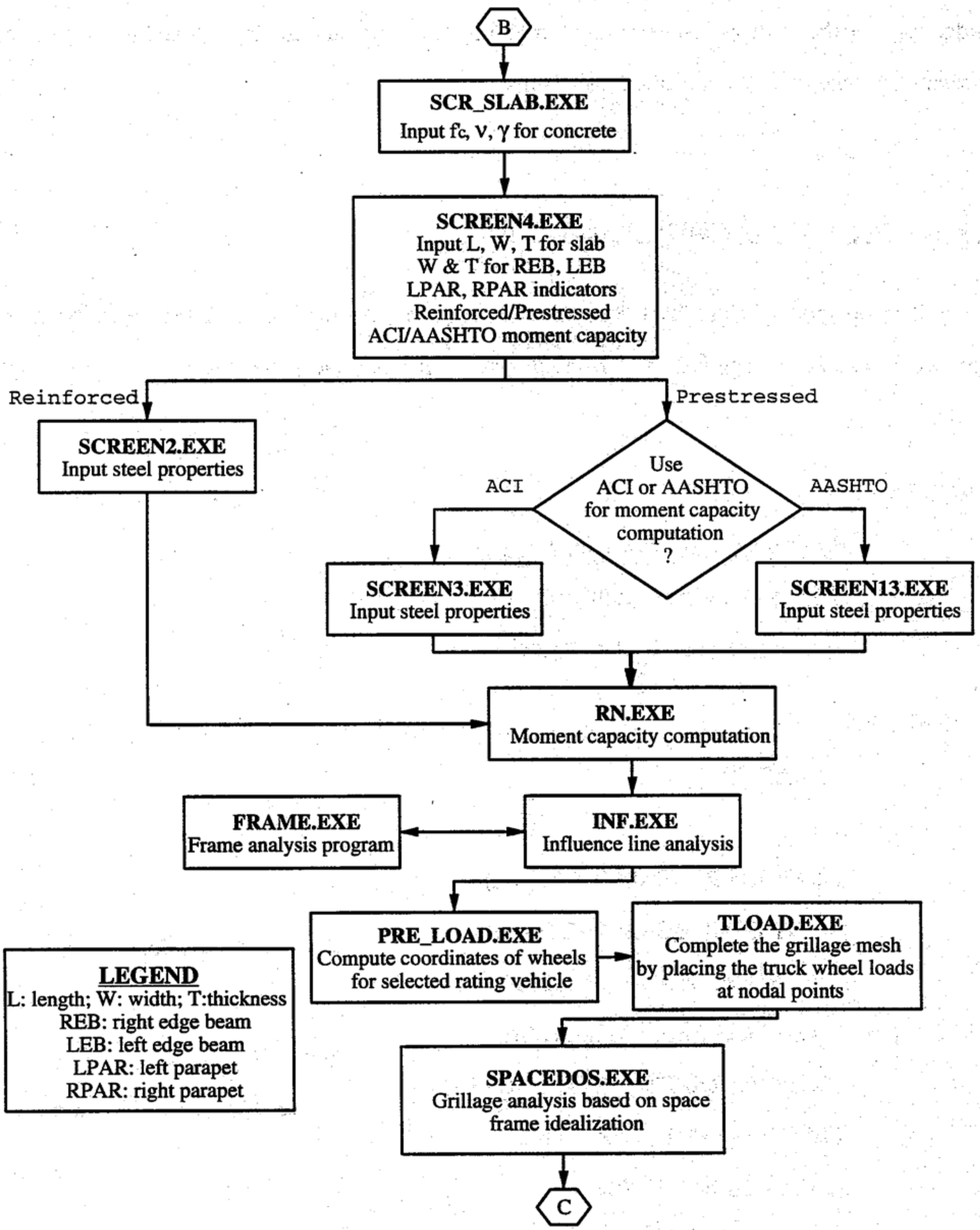


Figure 6.4 Flowchart for rating of solid slab

ENTER THICKNESS OF OVERLAY (in)

STEEL (Prestressed - 1; Reinforced, -0)

METHOD FOR RN: (ACI - 1; AASHTO - 2)

SCREEN2.EXE

If nominal resistance is known enter value (kip-ft)

Specified yield strength of steel, f_y (psi),

Area of tension steel, A_S (in Z)

Depth of tension steel, d (in)

Area of compression steel, A'_S (in)

Depth of compression-steel, d' (in)

SCREEN3.EXE

If the nominal resistance is known enter value (kip-ft)

NonPrestressed Steel

Specified yield strength of steel, f_y (psi)

Area of tension steel, A_S (in ^{Z})

Depth of tension steel, d (in)

Area of compression steel, A_s' (in^2)

Depth of compression steel, d_s' (in)

Prestressed Steel

Stress in prestressed tendons, f_{ps} (psi)

Effective prestress, f_{pe} (psi)

Specified tensile strength of prestressing steel, PU (psi)

Specified yield strength of prestressing tendons, Py (psi)

Area of prestressing tendons, A_{ps} (in^2),

Depth of prestressing tendons, d_P (in)

If tendons are bonded, enter l

SCREEN13.EXE

If the nominal resistance is known enter value (kip-ft)

Specified tensile strength of prestressing steel, f_{pu} (psi)

Area of prestressing tendons, A_{pu} (in ^{Z})

Depth of prestressing tendons, d_p. (in)

6.3.2 VOIDED SLAB BRIDGE

The flowchart illustrating the detailed rating procedure for voided slab bridge is shown in Figure 6.5. The input required by various programs that interface with the user are explained below:

SCREENLEXE:

Poisson's ratio of concrete, v

Density of concrete (lb/ft^3), γ

Concrete strength of slab, f'_c (psi)

SCREEN5.EXE:

YEAR BUILT AGE

BRIDGE LENGTH (ft)

BRIDGE WIDTH (ft)

NUMBER OF ELEMENTS SPACING OF VOIDS (in)

OVERLAY UNIT WEIGHT (Asphalt=144;Concrete=150; lb/cu ft)

ENTER THICKNESS OF OVERLAY (in)

STEEL (Prestressed»1; Reinforced»0)

METHOD FOR Rn: ACI» 1; AASHTO»2

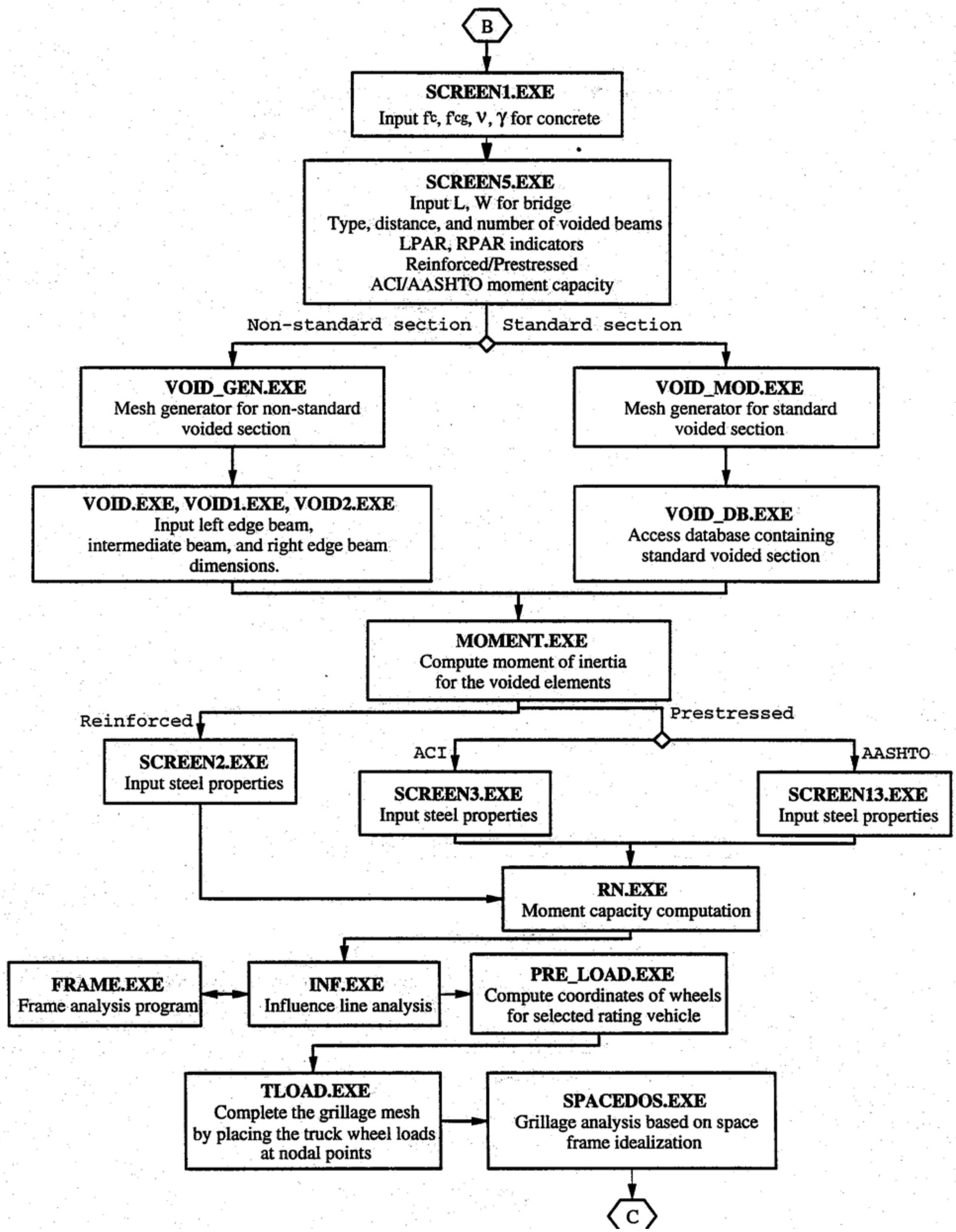
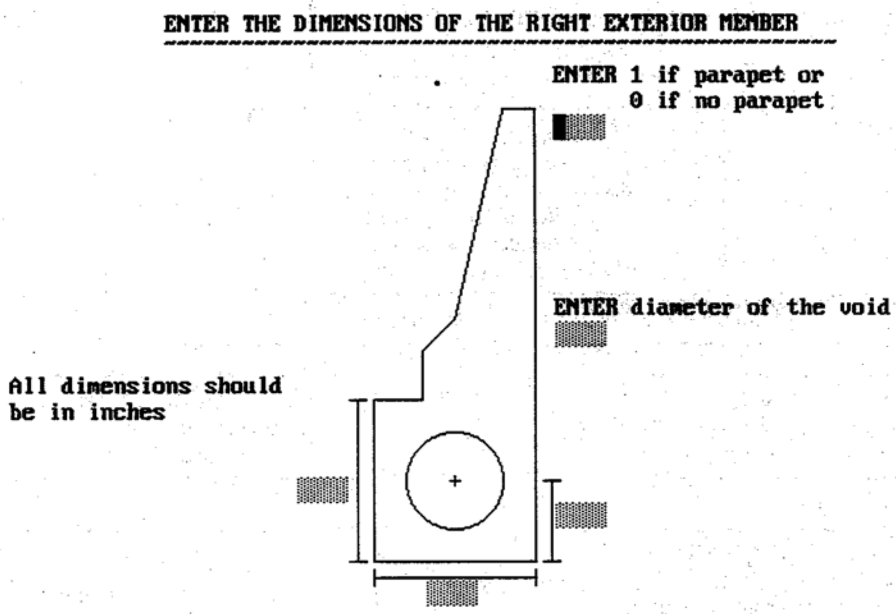
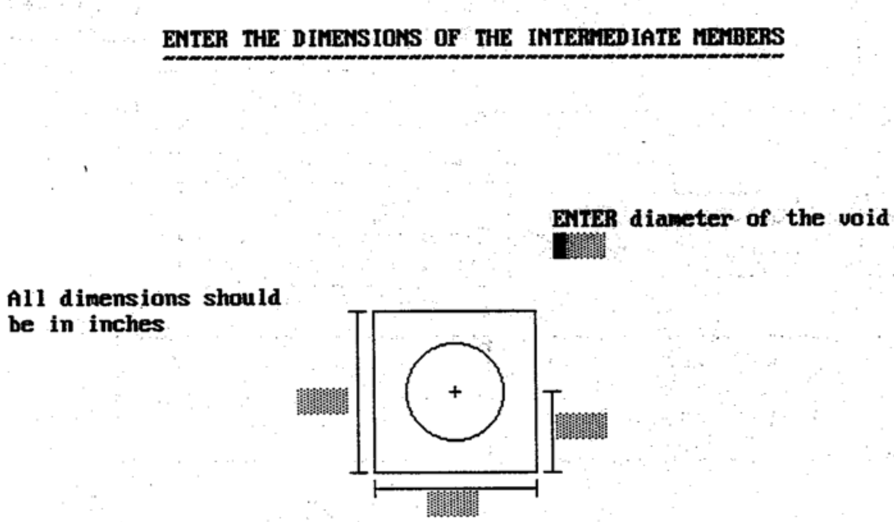


Figure 6.5 Flowchart for rating-of voided slab bridge

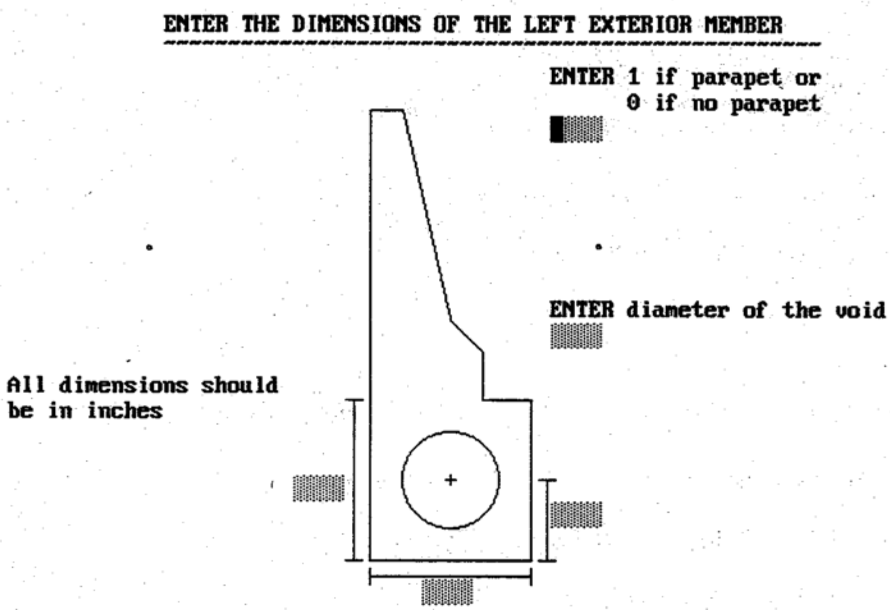
VOID.EXE:



VOID1.EXE:

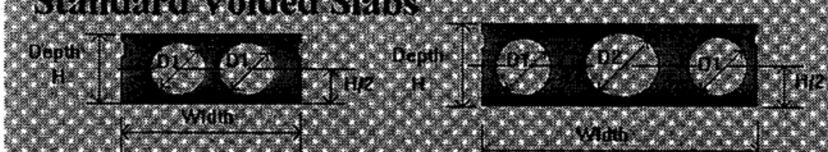


VOID2.EXE:



VOID_MOD.EXE

Standard Voided Slabs



Section Properties

Voided Element Type	Width ft.	Depth in.	No. of Voids	Void Dia. in. D1	Void Dia. in. D2	Weight lb/ft	Net Area $in.^2$	Ix $in.^4$	S $in.^3$
1	3	15	2	8	-	457	439	9,725	1296
2	3	18	2	10	-	511	491	16,514	1836
3	3	21	2	12	-	562	538	25,747	2452
4	4	15	3	8	8	593	569	12,897	1720
5	4	18	3	10	10	654	628	21,855	2428
6	4	21	3	12	10	733	703	34,517	3287

Enter the voided element used in the slab in the above line

SCREEN2.EXE

If nominal resistance is known enter value (kip-ft)

Specified yield strength of steel, f_y (psi)

Area of tension steel, A_s (in)

Depth of tension steel, d (in)

Area of compression steel, A'_s (in^2)

Depth of compression steel, d' (in)

SCREEN3.EXE

If the nominal resistance is known enter value (kip-ft)

NonPrestressed Steel

Specified yield strength of steel, fy (psi)

Area of tension steel; A_S (in Z)

Depth of tension steel, d (in)

Area of compression steel, $A_{s'}$ (id)

Depth of compression steel, d_s' (in Z)

Prestressed Steel

Stress in prestressed tendons, f_{ps} (psi)

Effective prestress, f_{pe} (psi)

Specified tensile strength of prestressing steel; f_{pu} (psi)

Specified yield strength of prestressing .tendons, f_{py} (psi)

Area of prestressing tendons, A_{ps} (in^Z)

Depth of prestressing tendons, d_p (in)

If tendons, are bonded, enter 1

SCREEN13.EXE

If the nominal resistance is known enter value (kip-ft)

Specified tensile strength of prestressing steel, f_{pu} (psi)

Area of prestressing tendons, A_{ps} (in^2)

Depth of prestressing tendons, d_P (in)

6.3.3 AASHTO GIRDER ANDSLAB' BRIDGE

The flowchart illustrating the detailed rating procedure for AASHTO girder and slab bridge is shown in Figure 6.6. The input required by various programs that interface with the user are explained below:

SCREEN1.EXE:

Poisson's ratio of concrete, v

Density of concrete (lb/ft^3) y

Concrete strength of slab, f'_c (psi)

Concrete strength of girder, f'_{cg} (psi)

SCREEN6.EXE:

YEAR BUILT AGE

BRIDGE LENGTH (ft)

BRIDGE WIDTH (ft)

AASHTO GIRDER TYPE' (,l through 6)

ENTER SPACING OF INTERIOR GIRDERS (ft)

NUMBER OF GIRDERS

OVERLAY UNIT WEIGHT (Asphalt=144;Concrete=150; lb/cu ft)

ENTER THICKNESS OF OVERLAY (in)

STEEL (Prestressed» l; Reinforced»0)

METHOD FOR Rn: ACI» 1; AASHTO» 2

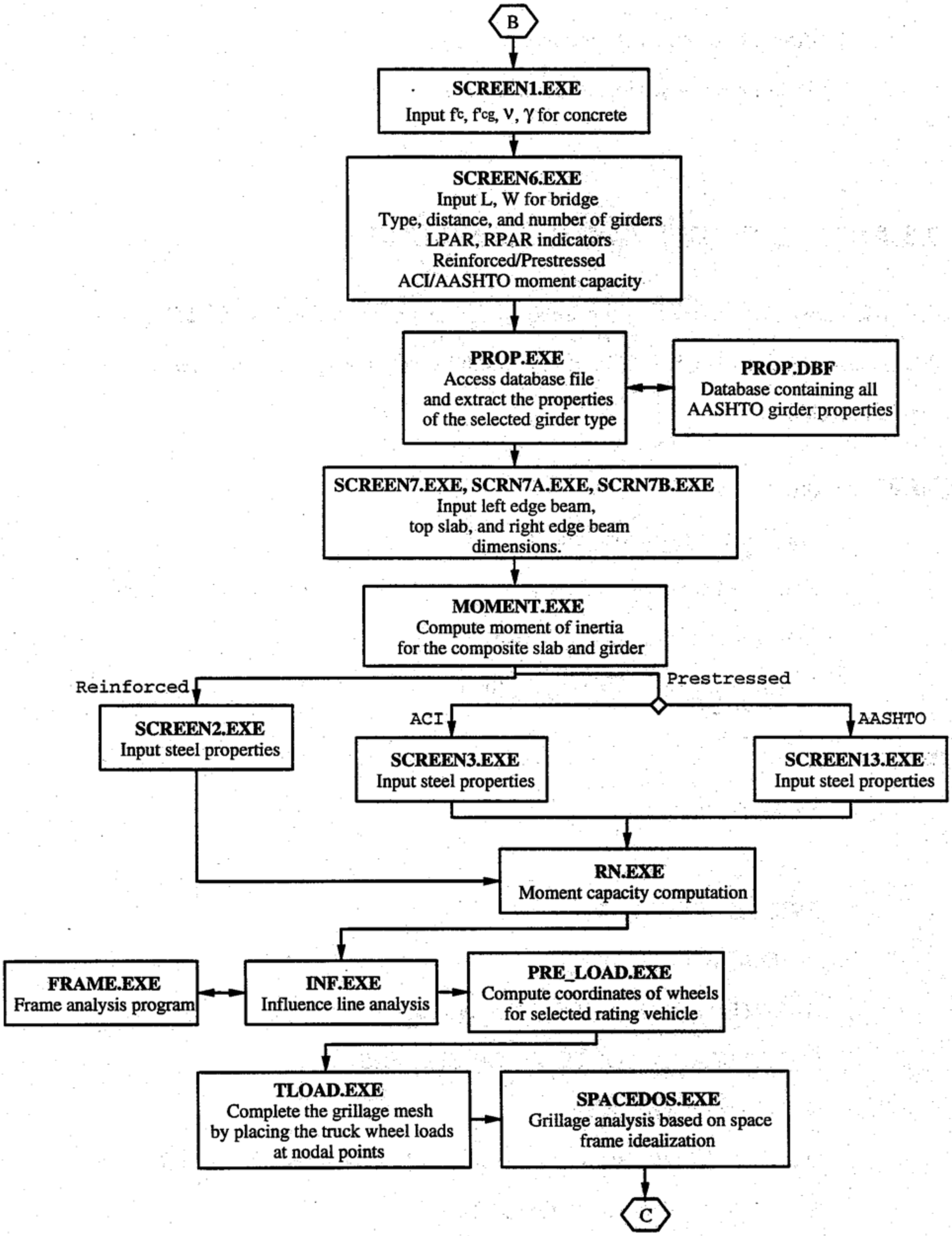


Figure 6.6 Flowchart for rating of AASHTO girder and slab

SCREEN7.EXE:

ENTER THE DIMENSIONS OF THE RIGHT EXTERIOR MEMBER
SLAB WIDTH RT OF CTRLINE, ft

SLAB WIDTH LT OF CTRLINE, ft

SLAB THICKNESS, in

WIDTH OF EDGE BEAM; ft

THICKNESS OF EDGE BEAM, in

PARAPET? (YES= 1;NO=0)

SCRN7A.EXE:

SLAB WIDTH RT OF CTRLINE, ft

SLAB WIDTH LT OF CTRLINE, ft

SLAB THICKNESS, in

SCRN7B EXE:

ENTER THE DIMENSIONS OF THE LEFT EXTERIOR MEMBER
SLAB WIDTH RT OF CTRLINE, ft

SLAB WIDTH LT OF CTRLINE, ft

SLAB THICKNESS, in

WIDTH OF EDGE BEAM, ft

THICKNESS OF EDGE BEAM, in

PARAPET? (YES=1;NO=0)

SCREEN2.EXE

If nominal resistance is known enter value (kip-ft)

Specified yield strength of steel, f (psi)

Area of tension steel, A_s (in 2)

Depth of tension steel, d (in)

Area of compression steel, A'_s (in 2)

Depth of compression steel, d' (in)

SCREEN3.EXE

If the nominal resistance is known enter value (kip-ft)
NonPrestressed Steel

Specified yield strength of steel, f_y (psi)

Area of tension steel, A_s (in ^{2})

Depth of tension steel, d (in)

Area of compression steel, A_s’ (in 2)

Depth of compression steel, d_s’ (in 2)

Prestressed Steel

Stress in prestressed tendons, f_{ps} (psi)

Effective prestress, f_{pe} (psi)

Specified tensile strength of prestressing steel, f_{pu} (psi)

Specified yield strength of prestressing tendons, f_{py} (psi)
Area of prestressing tendons, A_{ps} (in ^{2})

Depth of prestressing tendons, d_p (in)

If tendons are bonded, enter 1

SCREEN13.EXE

If the nominal resistance is known enter value (kip-ft)
Specified tensile strength of prestressing steel, f_{pu} (psi)

Area of prestressing tendons, A_{ps} (in)

Depth of prestressing tendons, d_p (in)

6.3.4 T-BEAM BRIDGE

The flowchart illustrating the detailed rating, procedure for T-beam bridge is' shown in Figure 6.7. The input required by various programs: that interface with the user are explained below:

SCREEN1.EXE:

Poisson's ratio of concrete v

Density of concrete (lb/ft^3), γ

Concrete strength of slab, f'_c (psi)

Concrete strength of girder, f'_{cg} (psi)

SCREENII.EXE:

YEAR BUILT AGE

BRIDGE LENGTH (ft)

BRIDGE WIDTH (ft)

ENTER SPACING OF INTERIOR BEAMS (ft)

NUMBER OF BEAMS

OVERLAY UNIT. WEIGHT (Asphalt= 144 Concrete=150; lb/cu ft)

ENTER THICKNESS OF. OVERLAY (in) .

STEEL (Prestressedi»1; Reinforced» 0)

METHOD FOR Rn:-ACI» 1; AASHTO» 2

SCREEN10.EXE:

DIMENSIONS OF THE RIGHT EXTERIOR MEMBER

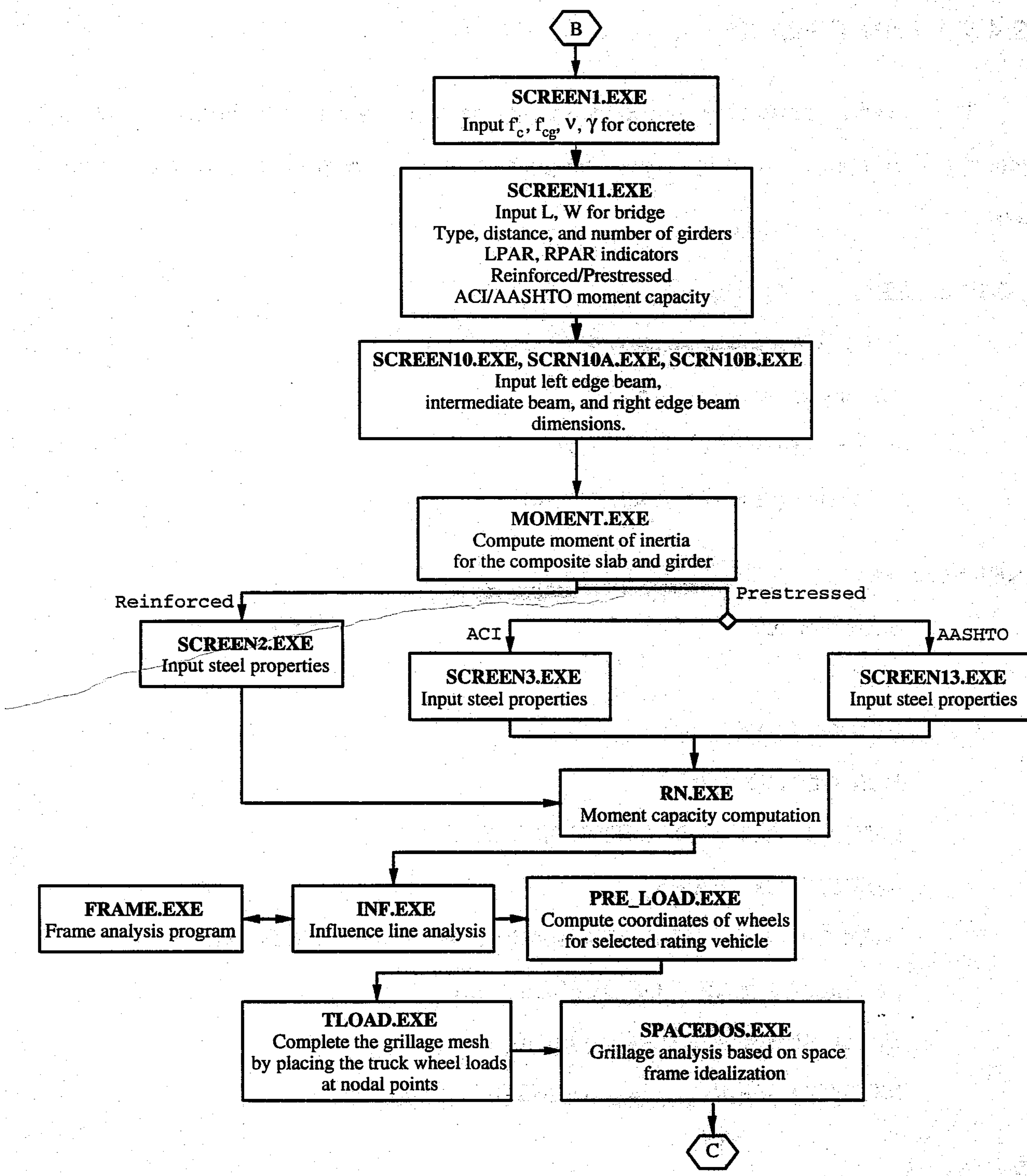


Figure 6.7 Flowchart for rating of T-beam bridge

SCRNIOA EXE:

DIMENSIONS OF INTERMEDIATE MEMBER

SCRN10B.EXE:

DIMENSIONS OF. THE, LEFT EXTERIOR MEMBER

SCREEN2.EXE:

If nominal resistance, is known enter value (kip-ft)

Specified yield strength of steel, f (psi)

Area of tension steel, A_s (in.)

Depth of tension steel, d (in)

Area of compression steel, A'_s (id)

Depth of compression steel, d' (in)

SCREEN3.EXE:

If the nominal resistance is known enter value (kip-ft)

NonPrestressed Steel

Specified yield strength of steel, fy (psi)

Area of tension steel, A_s (in 2)

Depth of tension steel, d (in)

Area of compression steel, A_s’ (in 2)

Depth of compression steel, d_s’ (in)

Prestressed Steel

Stress in prestressed tendons, f_{ps} (psi)

Effective prestress, f_{pe} (psi)

Specified tensile strength of prestressing steel, f_{pu} (psi)

Specified yield strength of prestressing tendons, f_{py} (psi)

Area of prestressing tendons, A_{pu} (in 2)

Depth of prestressing tendons, d_p (in)

If tendons are bonded, enter 1

SCREEN11EXE:

If the nominal resistance is known enter value (kip-ft)

Specified tensile: strength of prestress ng steel, f_{pu} (psi)

Area of prestressing tendons, A_{ps} (in 2)

Depth of prestressing tendons, dp (in)

6.3.5 SEGMENTAL BOX BRIDGE

The flowchart illustrating the detailed rating procedure for segmental box bridge is shown in Figure 6.8. The input required by various programs that interface with the user are explained; below:

SCREEN-4.EXE:

Number of spans on the bridge

Number of lanes

Number of cross-section types

Compressive strength of concrete, f, (psi)

Density of concrete, y (lb/ft3)

Poisson's ratio, v

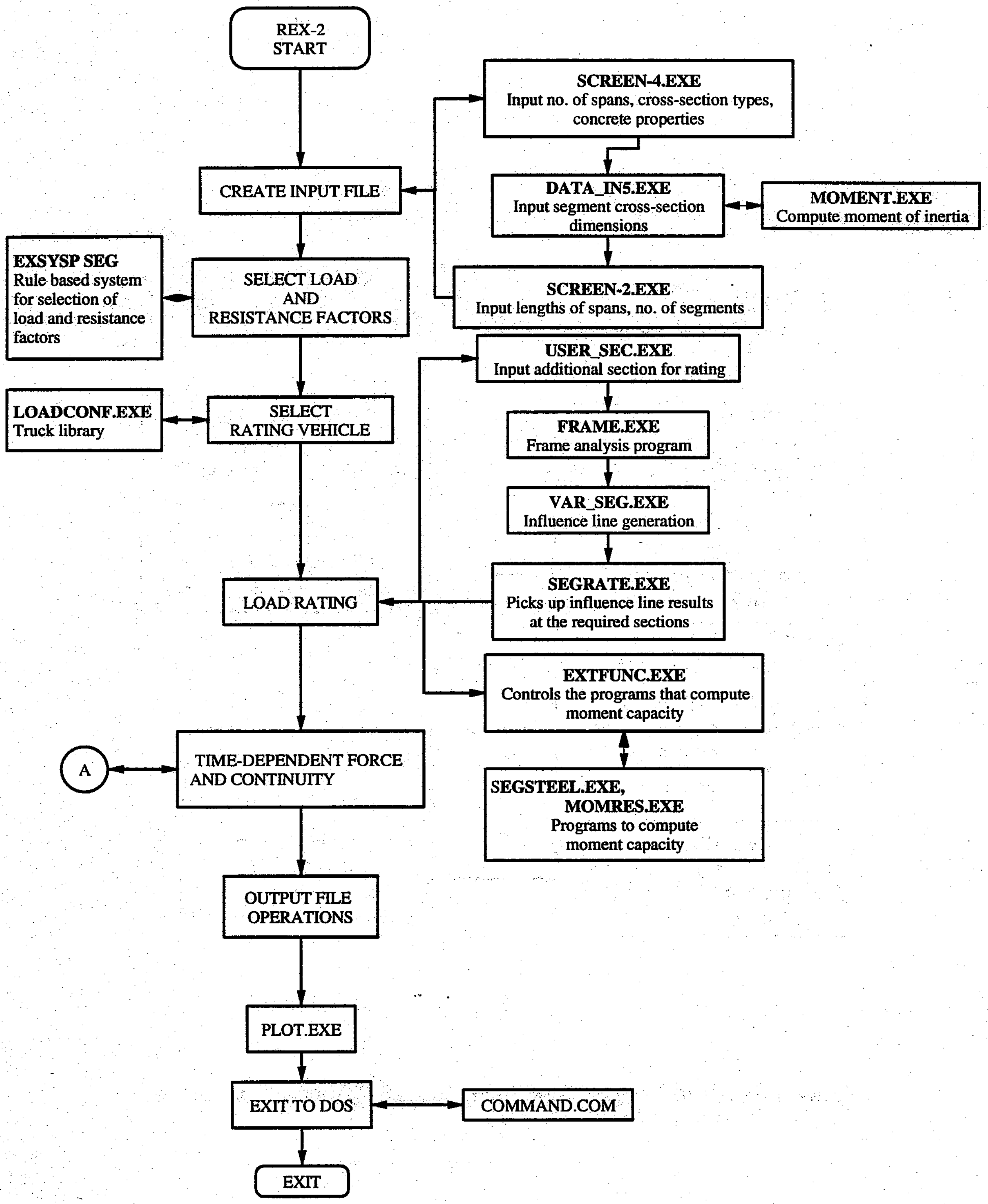


Figure 6.8 Flowchart for rating of segmental box bridge

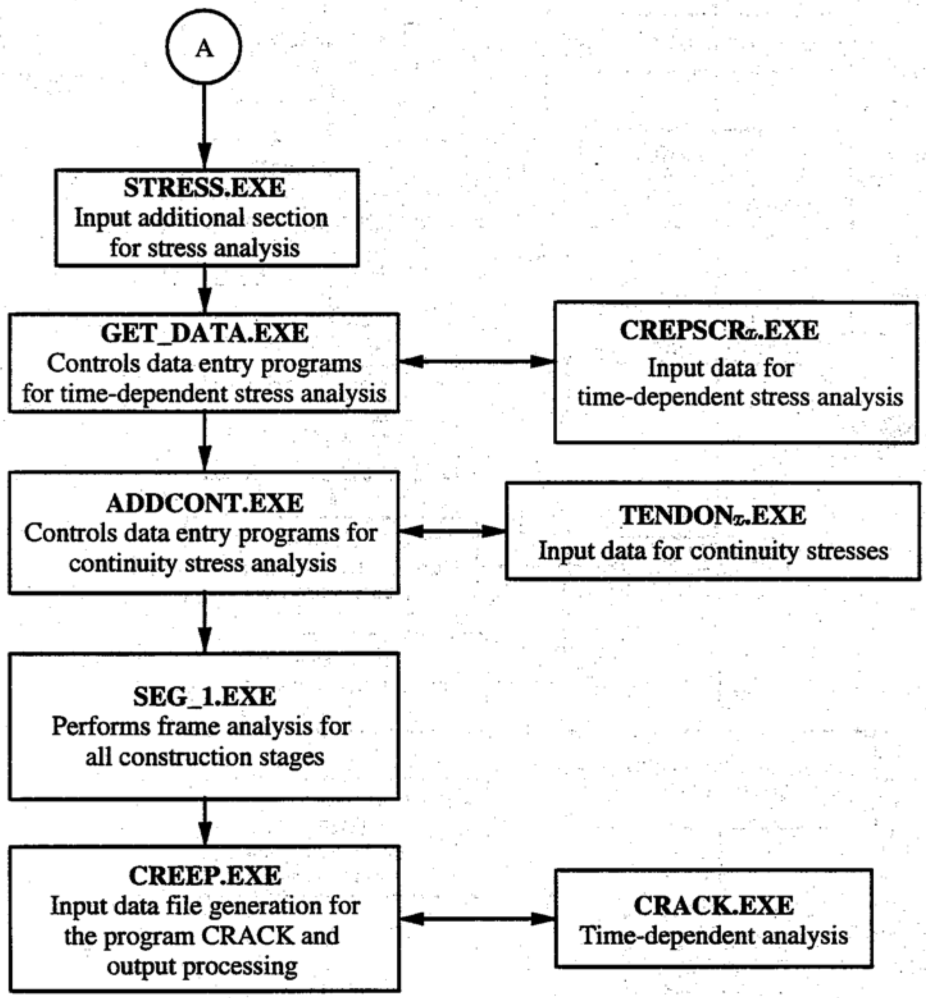
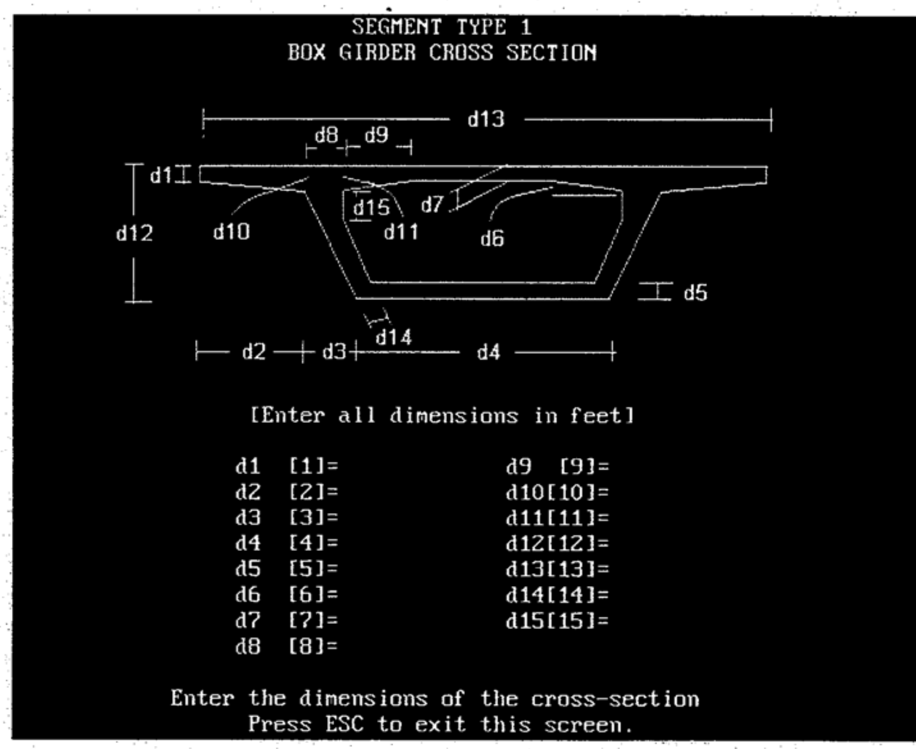


Figure 6.8 (con'td.) Flowchart for rating of segmental box bridge

DATA_IN.EXE:



SCREEN-2.EXE:

Length of span (feet)

No. of segments in this span (excluding support segments)

USER_SEC.EXE:

Location of user defined section for rating (node number)

SEGSTEEL.EXE:

If the nominal resistance is known, enter value (kip-ft)

Specified tensile strength of prestressing steel, f_{pu} (psi)

Specified yield strength of prestressing tendons, f_{py} (psi)

Modulus of elasticity of prestressing steel, E_{ps} (psi)

Number of layers of prestressing steel at this section

LAYERSTL.EXE:

Area of prestressing steel in this layer (in,)

Depth of prestressing steel layer from the compression flange (ft)
Effective prestress in the prestress steel layer (psi)

CREP2IN.EXE

Total number of stages required for construction

Enter the age of the bridge (Years)

CREPSCR2.EXE:

Enter the segment erection sequence Stage

Erection day

Erected segment numbers

CREPSCR3.EXE:

Prestressing steel details for cantilever construction

Segment number

Area of prestressing steel (in)

Depth from the top flange surface (ft)

Effective prestress in steel (psi)

CREPSCR4.EXE:

Initial concrete compressive strength: (psi)

Ultimate creep coefficient of concrete

Aging coefficient of concrete Shrinkage of concrete

Temsile strength of concrete (psi)

Concrete curing method (moist cured / steam cured)

TENDONLEXE:

Number of continuity tendons in each span

TENDON2.EXE:

Location of tendon (starting and ending segment numbers)

Longitudinal tendon profile (straight / parabola / harped)

TENDONIEXE:

Straight tendon profile:

Depth of tendon from the top flange surface, at left end, right end (ft)

Area of prestressing steel (in ^{2})

Effective prestress (psi)

TENDON4.EXE:

Parabolic tendon profile:

Depth of tendon: from the top flange surface, at left end, center, right end (ft)
Area of prestressing steel (in ^{2})

Effective prestress (psi)

TENDON5.EXE:

Harped tendon profile:

Number of hold-down points

Location of hold down points (segment numbers)

Depth of tendon from the top flange surface, at left end, center, right end (ft)

Area of prestressing steel (in ^{2})

Effective prestress (psi)

STRESS.EXE:

Location of user defined section for stress computation

6.4 MOMENT OF RESISTANCE COMPUTATION MODULE

The module RN computes the nominal moment M_n for reinforced / partially prestressed: / prestressed concrete members. The detailed flowcharts for computing the nominal moments, Figures 6.9 and 6.11 follow ACI specifications. The nominal resistance moment :computation for segmental box bridges with prestressing tendons positioned at multi-layers with varying depths from the compression flange has been made based on strain compatibility (Figure 6.10). The system is capable of handling the bridge types mentioned earlier with any combination of edge beams and parapets as shown in Figures 6.12 and 6.13.

6.5 OUTPUT MODULE

6.5.1 REX-1

In the system REX-l, the program SCAN scans the file OUTPUT for the maximum deflection and the maximum live and dead load moments. This program reads the files containing the load and resistance factors and moment of resistance and determines the rating factor (Figure 6.14a).

The program RESULTS creates a comprehensive file containing the bridge :geometry, the concrete and steel properties, the live load configuration, the rating factor for the bridge, the deflections, and a plot of the bridge:

The user is given an option to view the moment and deflection plots on the screen through the program PLOT.EXE.

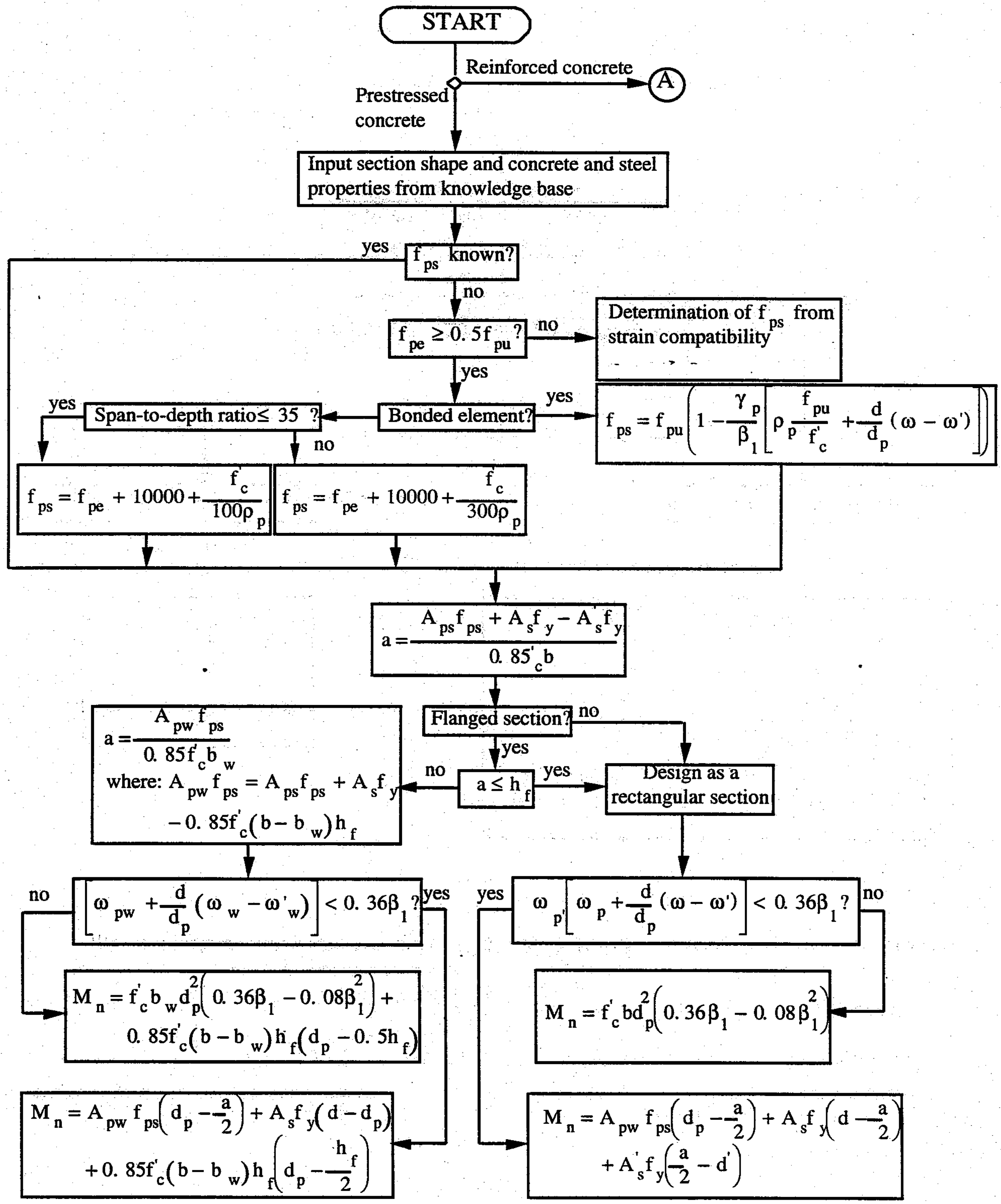


Figure 6.9 Flow chart for computation of nominal moment for system REX-1 [Nawy, 1990]

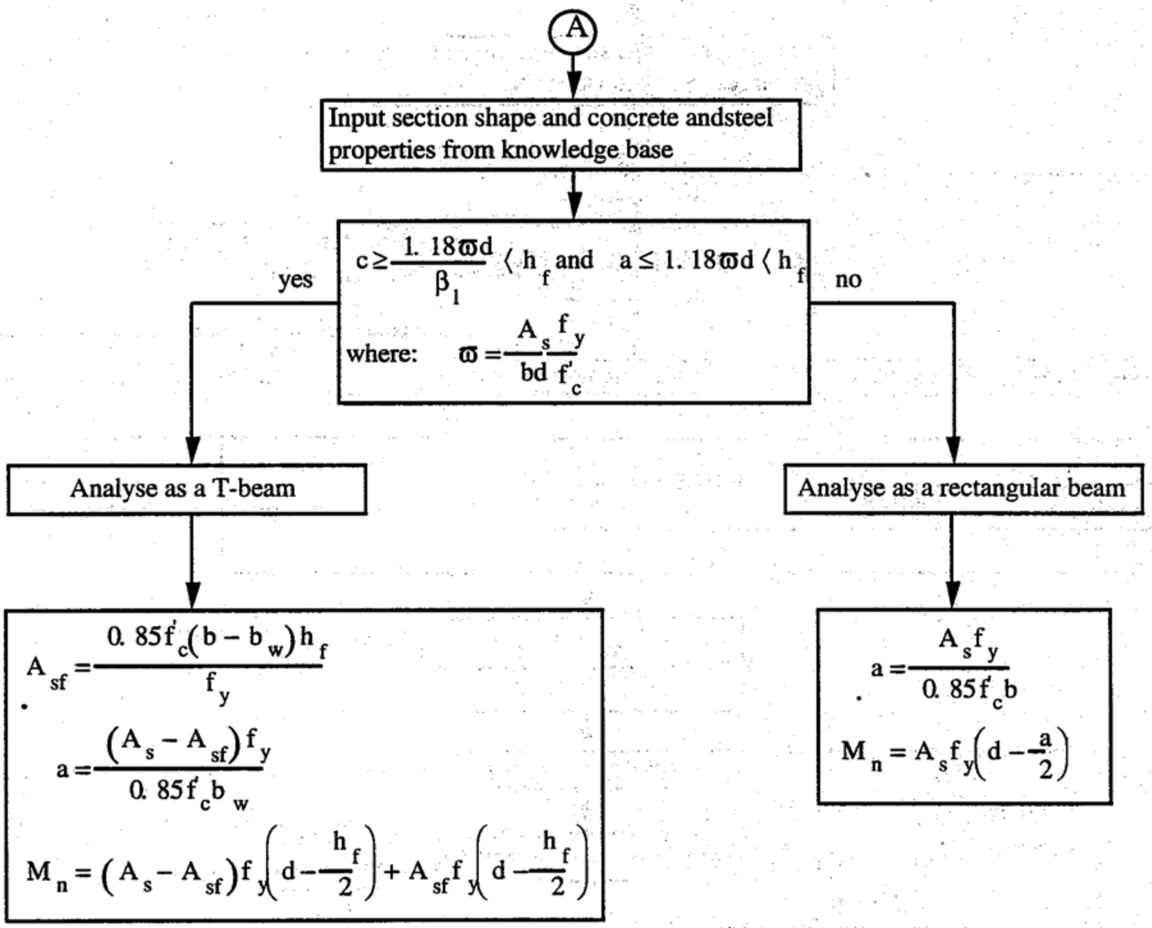
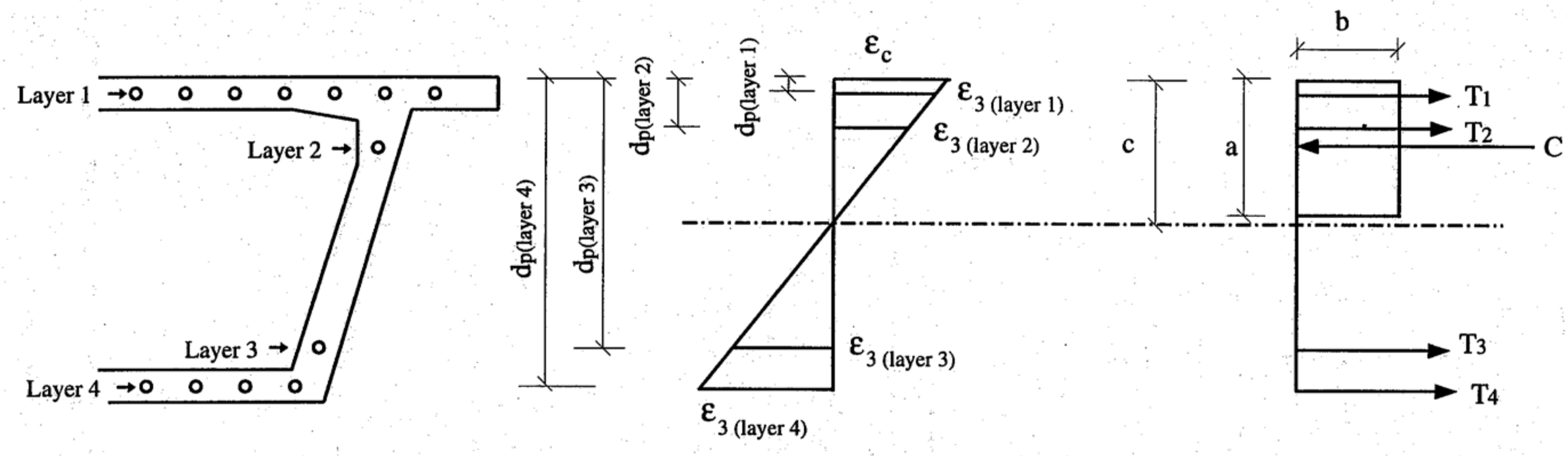


Figure 6.9 (cont'd.) Flow chart for computation of nominal moment [Nawy, 1990]



(a) Box section (b) Strains (c) Stresses and forces

$$\varepsilon_{ps} = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

$$\varepsilon_1 = f_{pe} / E_p$$

$$\varepsilon_2 = \frac{Pe}{Ac\ \ Ec}\left[1 + \frac{e^2}{r^2}\right]$$

$$\varepsilon_{3\,(\text{layer n})} = \varepsilon_c \left[\frac{d_{p(\text{layer } n)} - c}{c}\right]$$

$$T_n = A_{ps(\text{layer } n)} \, . \, f_{ps(\text{layer } n)} \; [\, d_{p(\text{layer } n)} - a/2 \,]$$

$$C = 0.85 \, f'_c \, b \, a$$

Figure 6.10 Strain compatibility for segmental box bridges with multi-layered prestressing

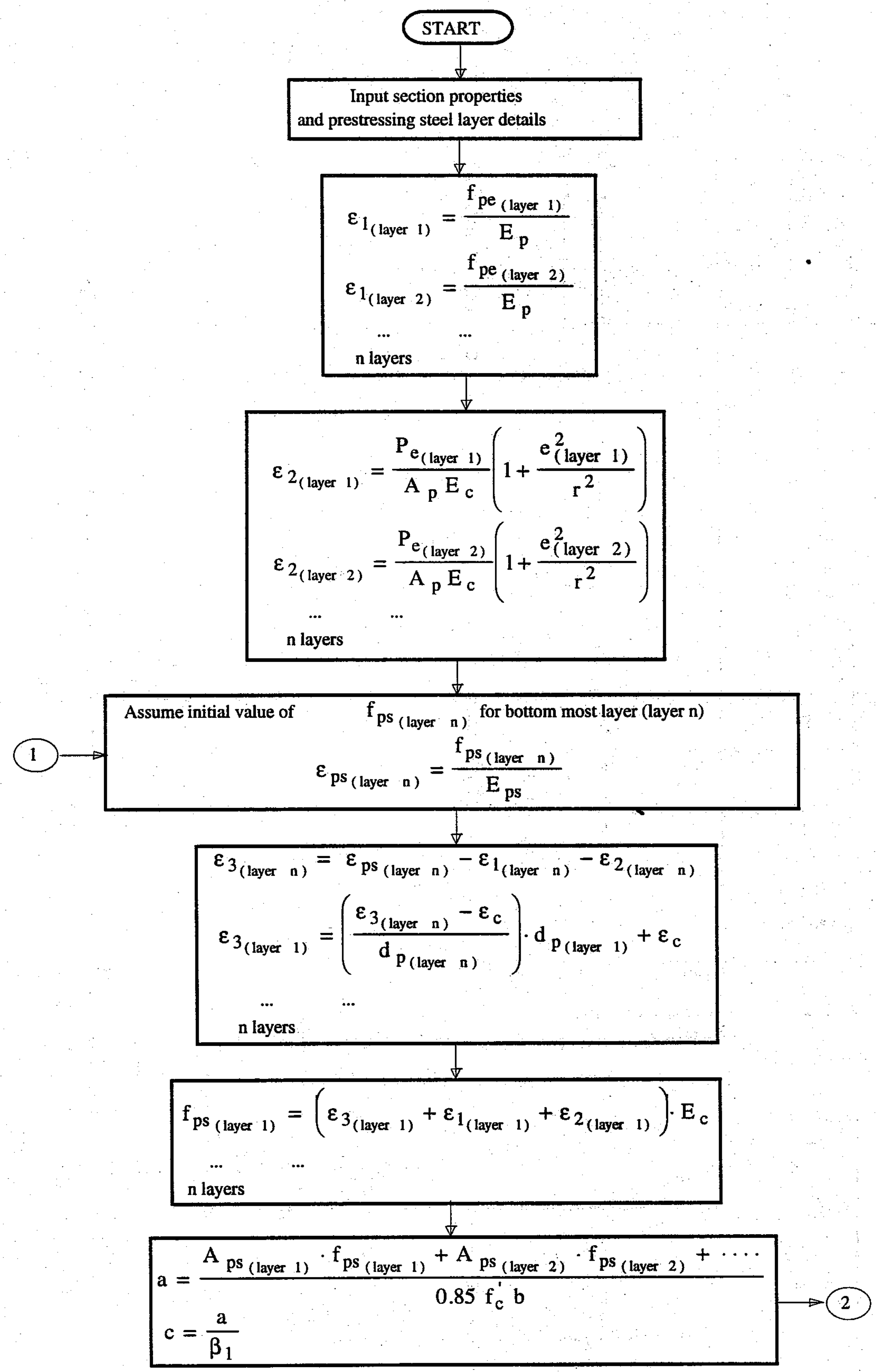


Figure 6.11 Moment capacity computation for prestressed members with multi-layered prestressing based on strain compatibility

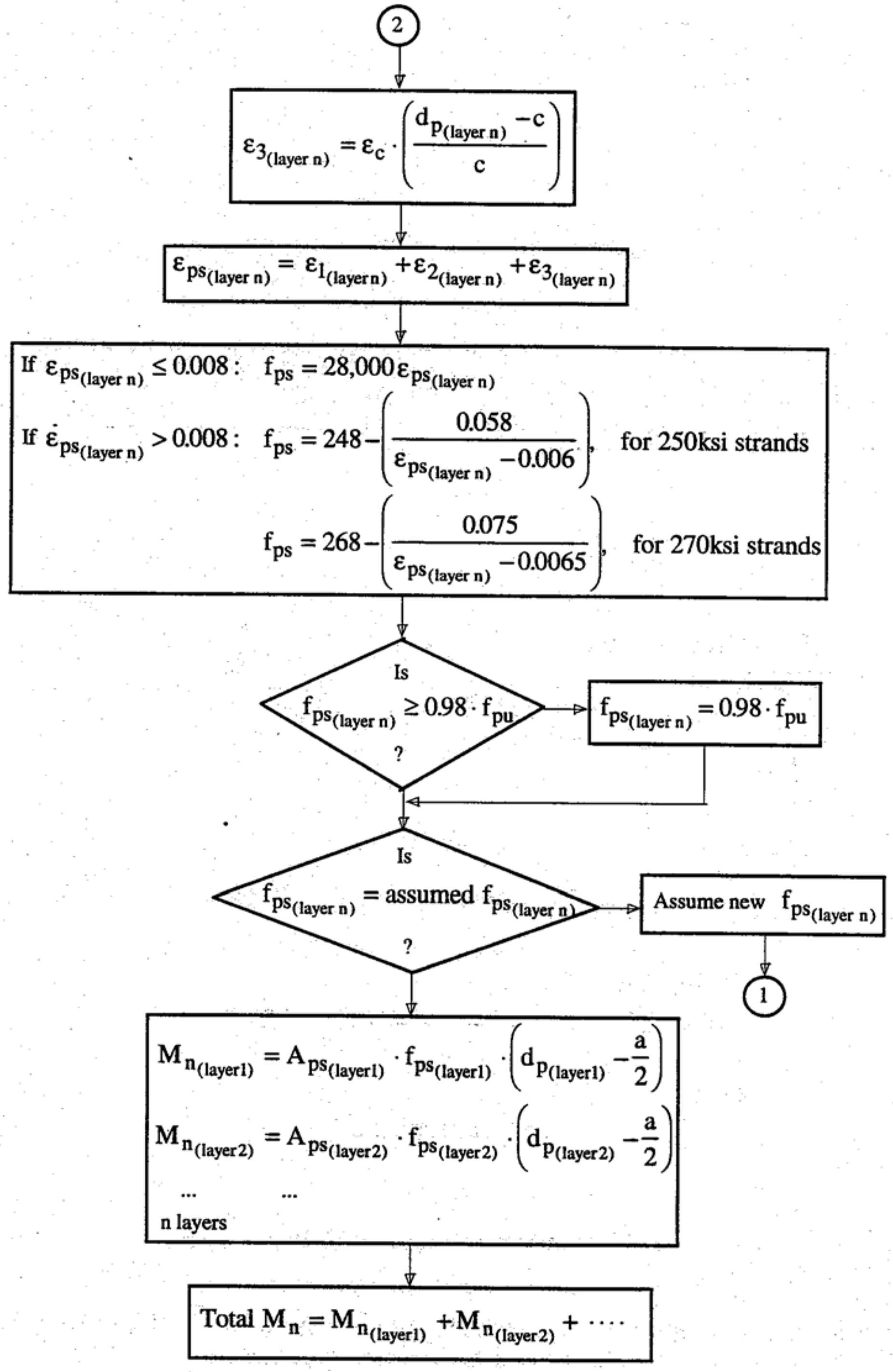


Figure 6.11 (cont'd.) Moment capacity computation for prestressed members with multi-layered prestressing based on strain compatibility

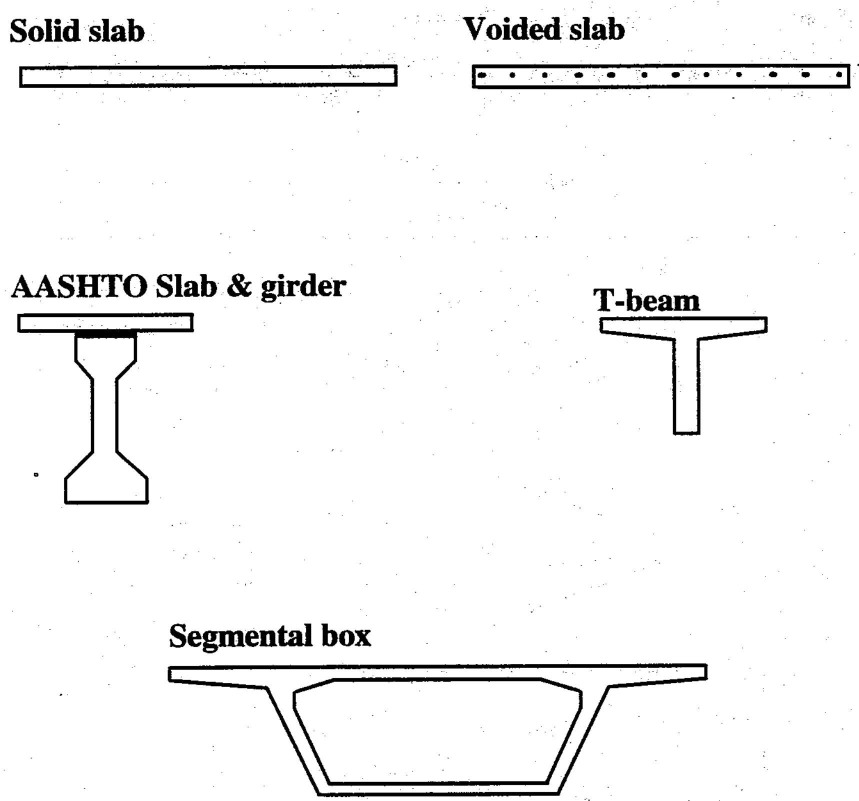


Figure 6.12 Various bridge types incorporated in the REX system

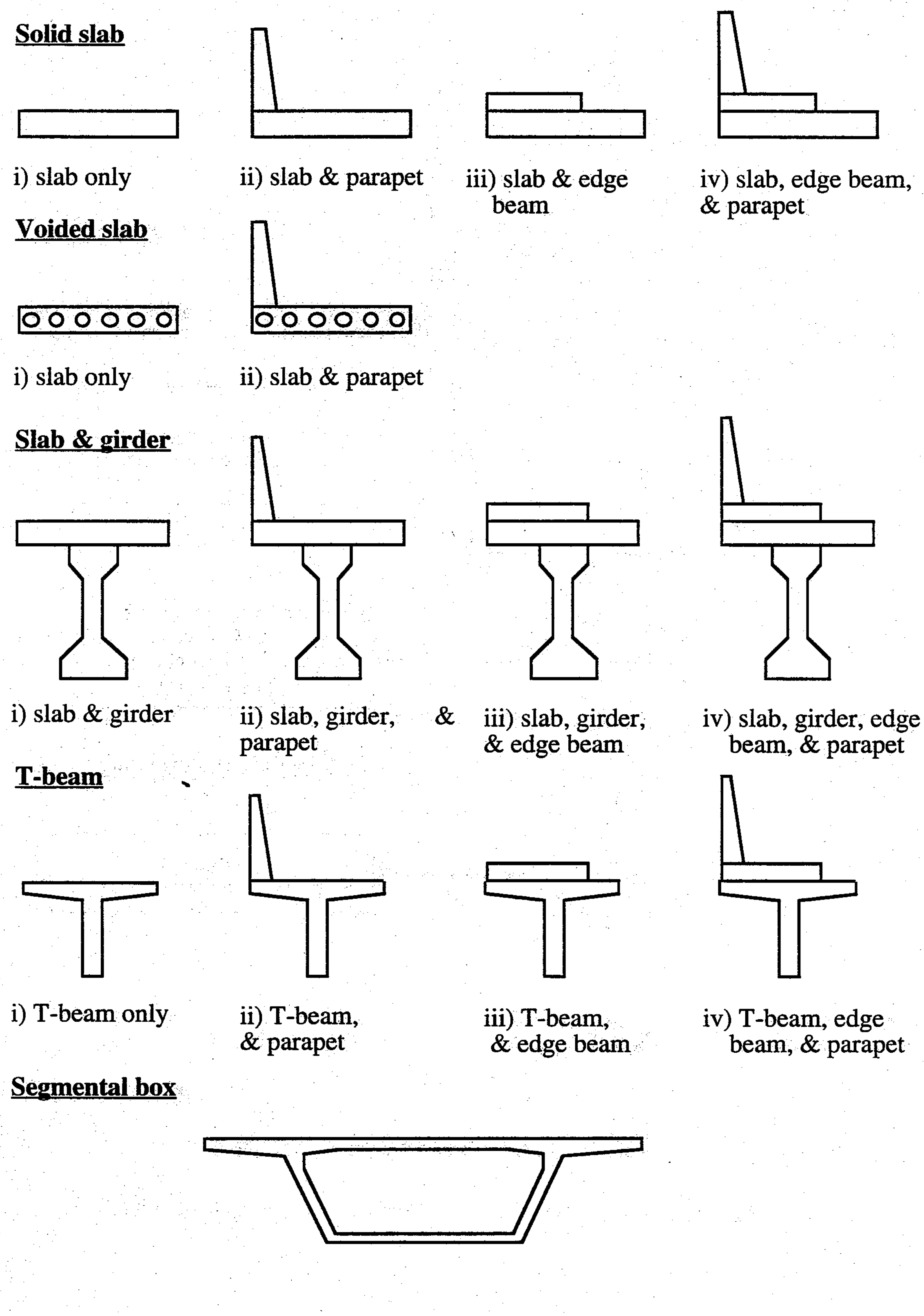


Figure 6.13 Possible combinations of elements in different bridge types

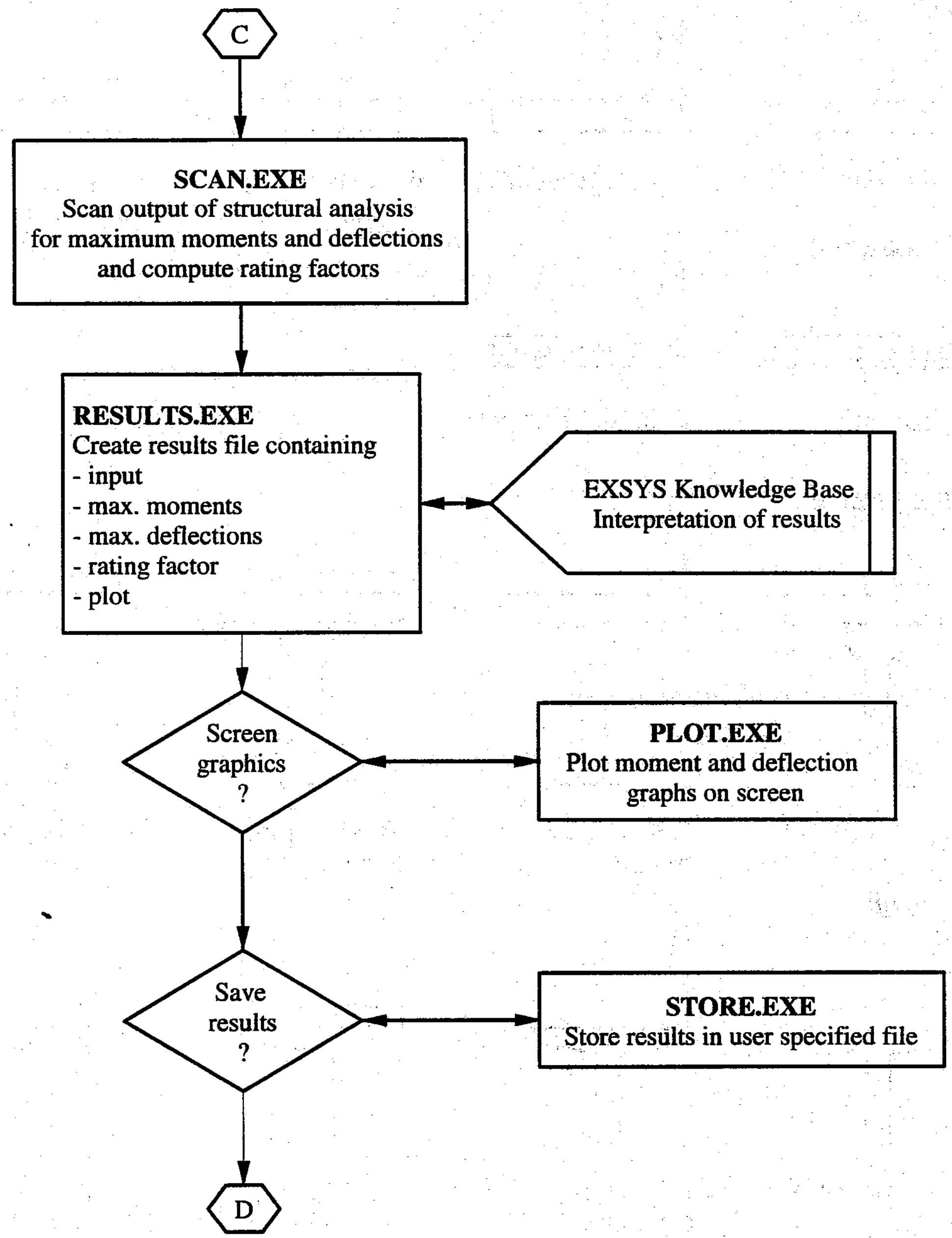


Figure 6.14(a) Flowchart for processing of results for REX-1

The STORE.EXE program allows the user to save the results file under a user specified name.

6.5.2 REX-2

The output for the load rating is prepared by the. program: MAKE-OUT.EXE as soon as the analysis and, rating are completed and-stored in the file RESULT.OUT. The time dependent construction and continuity stresses are computed in the program CREEREXE and stored in the file THVIE-DEROUT. The selection of "OUTPUT file operations" option in the main menu causes the generation of the :final output file "FINALRES.OUT" (Figure 6.14b). The user is also given an option to save this file under a specified name.

The user is given an option to view the maximum positive and negative live load moment envelopes through the program PLOT.EXE:

Illustrative examples for the different bridge types are presented in Chapter 7.

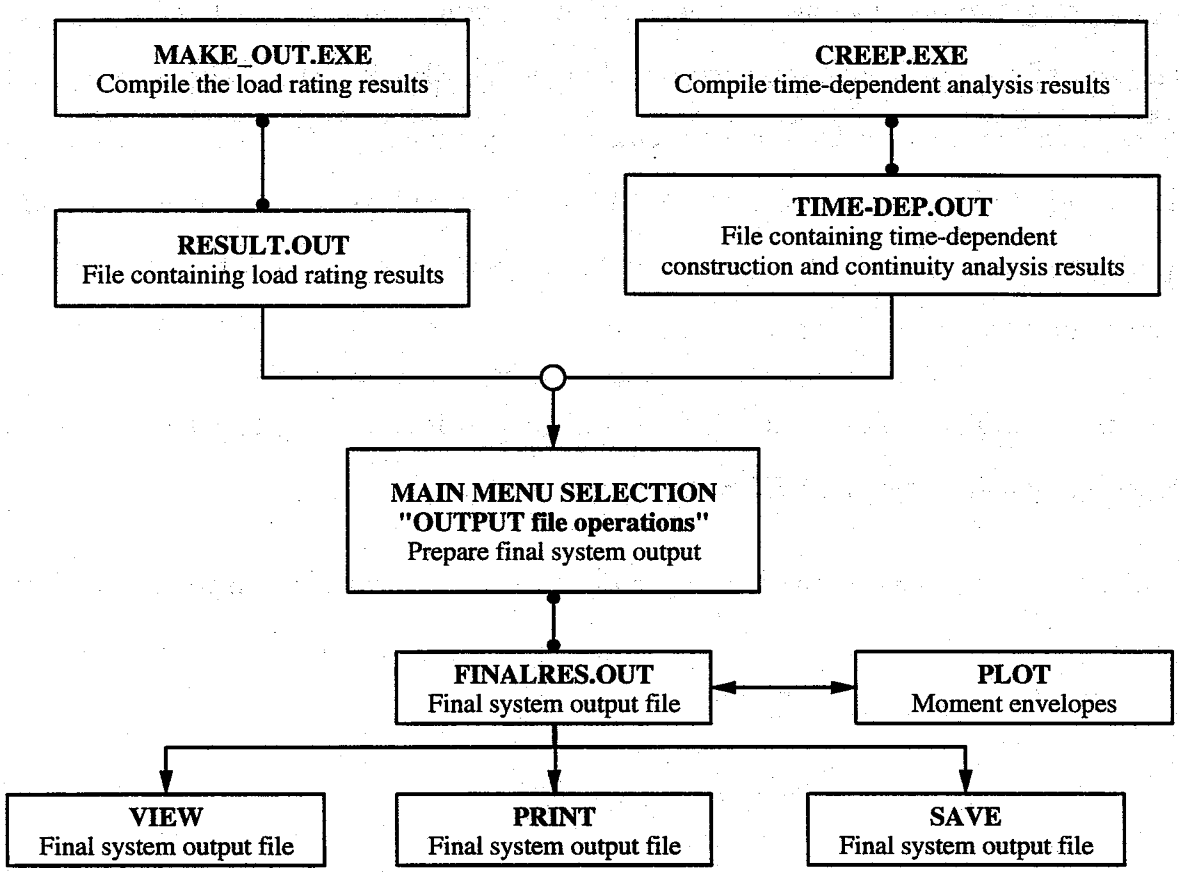


Figure 6.14(b) Flowchart for processing of results for REX-2

CHAPTER 7

ILLUSTRATIVE EXAMPLES

7.1 INTRODUCTION

This chapter illustrates examples for rating of different bridge types using the system REX [Arockiasamy, et al]. The solid slab bridge is an actual bridge in St. John's County, Florida, and the voided slab,: AASHTO girder and slab, and double-T beam bridges are based on the publication "PCI Design Supplement to Short Span Bridges [PCI; 1984]". Examples of existing bridges have also been included for voided slab (Palm Beach County Florida), AASHTO girder and: slab (Palm Beach-County, Florida);: and segmental box bridges (Broward County, Florida).

7.2 SOLID SLAB -BRIDGE

(St. John's County; FDOT Bridge No.780021)

Design Conditions

Simple span of 20 ft x 34 ft width

HS20 live-load- 2 lanes

Solid slab deck: 12 in. thick

Edge beams: 14.5' in. wide x 9 in. deep

Materials

Reinforced concrete: Normal weight

$$f_c = 5000 \text{ psi}$$

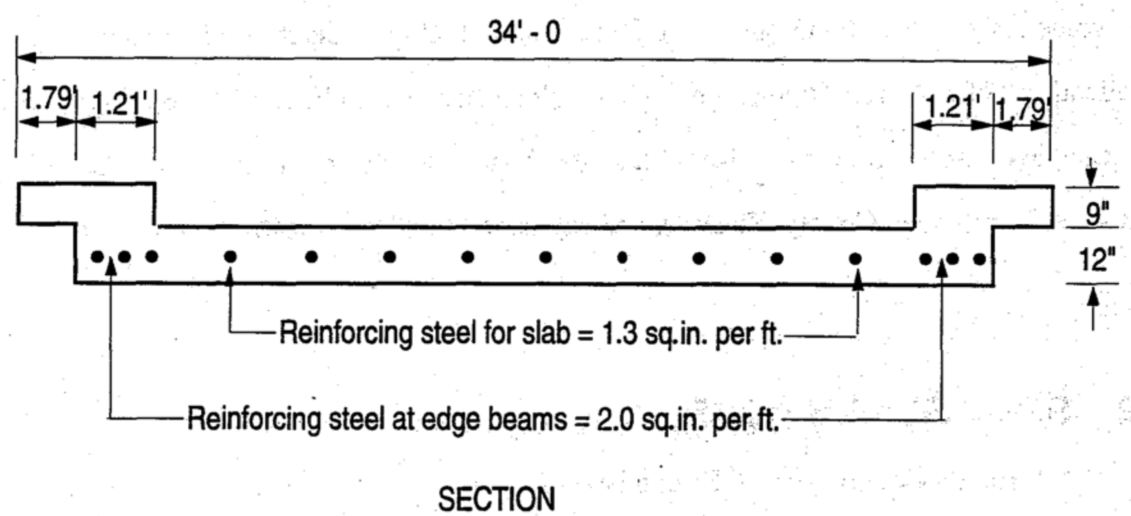


Figure 7.1 Solid slab cross-section

Reinforcing steel:	Edge beams:	A_s	=	2 in^2 @ 19 in. d.
	Slab:	A_s	=	1.3 in^2 @ 10 in. d.
		E_s	=	28 x 10^6 psi
		f_y	=	60,000 psi

USER INTERFACE

CONCRETE PROPERTIES

```
Poisson's ratio of concrete, v .....................  = 0.20
Density of concrete (lb/ft3), w ....................  = 150
Strength of concrete, fc (psi) .....................  = 5000

 Press ESC to exit this screen.
```

SOLID SLAB BRIDGE

```
YEAR BUILT.........................................  = 1970
AGE ...............................................  = 23
RIGHT EDGE BEAM DEPTH (in) ........................  = 9
RIGHT EDGE BEAM WIDTH (FT) ........................  = 1.21
LEFT EDGE BEAM DEPTH (in) .........................  = 9
LEFT EDGE BEAM WIDTH (FT) .........................  = 1.21
RIGHT PARAPET (YES»1;NO»0) ........................  = 1
LEFT PARAPET (YES»1;NO»0) .........................  = 1
BRIDGE LENGTH (ft) ................................  = 20
BRIDGE WIDTH (ft) .................................  = 34
SLAB THICKNESS (IN) ...............................  = 12
OVERLAY UNIT WEIGHT(Asphalt=144;Concrete=150;lb/cu ft) = 0
ENTER THICKNESS OF OVERLAY (IN) ...................  = 0
STEEL (Prestressed»1; Reinforced»0) ...............  = 0
METHOD FOR Rn: ACI»1; AASHTO»2) ...................  = 1

Press ESC to exit this screen.


Enter steel properties for RIGHT EDGE BEAM
```

STEEL PROPERTIES (REINFORCED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .   = 0
Specified yield strength of steel, fy (psi).........   = 60000
Area of tension steel, As (in2) ....................   = 2
Depth of tension steel, d (in) .....................   = 19
Area of compression steel, As'(in2) ................   = 0
Depth of compression steel, d' (in) ................   = 0
If specified yield strength unknown, enter 0

Press ESC to exit this screen.
```

Enter steel properties for SLAB

STEEL PROPERTIES (REINFORCED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .   = 0
Specified yield strength of steel, fy (psi) ........   = 60000
Area of tension steel, As (in2) ....................   = 1.3
Depth of tension steel, d (in)......................   = 10
Area of compression steel, As'(in2) ................   = 0
Depth of compression steel, d' (in) ................   = 0
If specified yield strength unknown, enter 0

Press ESC to exit this screen.
```

Enter steel properties for LEFT EDGE BEAM

STEEL PROPERTIES (REINFORCED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .   = 0
Specified yield strength of steel, fy (psi).........   = 60000
Area of tension steel, As (in2) ....................   = 2
Depth of tension steel, d (in) .....................   = 19
Area of compression steel, As'(in2) ................   = 0
Depth of compression steel, d' (in) ................   = 0
If specified yield strength unknown, enter 0

Press ESC to exit this screen.
```

OUTPUT FILE

FLORIDA BRIDGE RATING
FLORIDA DEPARTMENT OF TRANSPORTATION

<u>INPUT</u>

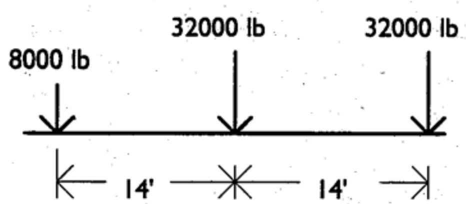
BRIDGE TYPE : SOLID SLAB

DIMENSIONS : LENGTH (ft)........................... 20.00
WIDTH (ft) 34.00

CONCRETE : STRENGTH(SLAB) (psi).................. 5000.00
MODULUS OF ELASTICITY (psi) .... 4.03e+6

LIVE LOAD:

HS 20 Loading



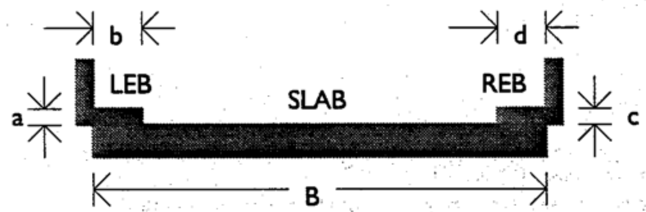
No. of trucks placed on the bridge = 2

Truck #1: Rear axle placed at 21.66 ft. from the left support
9.13 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

Truck #2: Rear axle placed at 21.66 ft. from the left support
24.88 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

TOTAL DEAD LOAD (lbs).............................. 119605.00

SCHEMATIC SHOWING DETAILS OF SOLID SLAB BRIDGE:



LEB : Left edge beam   REB : Right edge beam

<u>Left Edge Beam:</u>
Depth a, in. = 9.00
Width b, ft. = 1.21

<u>Slab:</u>
Depth, in. = 12.00
Width l, ft. = 34.00

<u>Right Edge Beam:</u>
Depth c, in. = 9.00
Width d, ft. = 1.21

Left Parapet:Yes
Right Parapet:Yes

REINFORCEMENT DETAILS: NEAR RIGHT EDGE BEAM:
Area of tension steel, As (in2) .... = 2
Depth of tension steel, d (in) .... = 19
Area of compression steel, As'(in2) .... = 0
Depth of compression steel, d' (in) .... = 0

REINFORCEMENT DETAILS: SOLID SLAB:
Area of tension steel, As (in2) .... = 1.3
Depth of tension steel, d (in)....................... = 10
Area of compression steel, As'(in2) .... = 0
Depth of compression steel, d' (in) .... = 0

REINFORCEMENT DETAILS: NEAR LEFT EDGE BEAM:
Area of tension steel, As (in2) .... = 2
Depth of tension steel, d (in) .... = 19
Area of compression steel, As'(in2) .... = 0
Depth of compression steel, d' (in) .... = 0

<u>RESULTS OF ANALYSIS</u>

Each 'BEAM' represents the group of longitudinal grillage beams from support to support.

CRITICAL RATING FACTORS:
RATING FACTOR = 1.20
NOMINAL MOMENT, Rn(kip-ft) = 178.24
DEAD LOAD MOMENT, MD (kip-ft) = 49.45
LIVE LOAD MOMENT, ML (kip-ft) = 37.07

The above rating factor and moments are computed per foot width of slab.

LOAD AND RESISTANCE FACTORS:

Capacity reduction factor	= 0.85
Live load factor	= 1.60
Dead load factor	= 1.20
Impact Factor	= 1.30

	RATING FACTOR	Rn(kip-ft)	ML(kip-ft)	MD(kip-ft)
BEAM 1	1.20	178.24	37.07	49.45
BEAM 2	4.58	60.03	4.68	5.36
BEAM 3	3.75	60.03	5.58	6.31
BEAM 4	4.58	60.03	4.68	5.36
BEAM 5	1.20	178.24	37.07	49.45

PLOT

BEAM # 1	1	6	11	16	21
Width 5.87					
BEAM # 2	2	7	12	17	22
Width 10.53					
BEAM # 3	3	8	13	18	23
Width 10.53					
BEAM # 4	4	9	14	19	24
Width 5.87					
BEAM # 5	5	10	15	20	25

Length Length Length Length
5.00 5.00 5.00 5.00

DEFLECTIONS (inches)

# 1	0.000	-0.021	-0.028	-0.019	0.000
# 2	0.000	-0.026	-0.035	-0.023	0.000
# 3	0.000	-0.032	-0.042	-0.028	0.000
# 4	0.000	-0.026	-0.035	-0.023	0.000
# 5	0.000	-0.021	-0.028	-0.019	0.000

7.3 VOIDED SLAB BRIDGE

(PCI Handbook Example)

Design Conditions

Simple span of 45 ft x 30 ft width

HS20 live load - 2 lanes

Multi - beam precast sections - TYPE 3 (adjacent units) without wearing surface.

Materials

Concrete:	Normal weight
	f'_c = 5000 psi
	f'_{ci} = 4000 psi (AASHTO 9.22)
Prestressing steel:	11 - 1/2 in. diameter 270 ksi stress - relieved strands @ 19 in. d_p.
	Strand area = 0.153 sq. in / strand
	$E_s = 28 \times 10^6$ psi

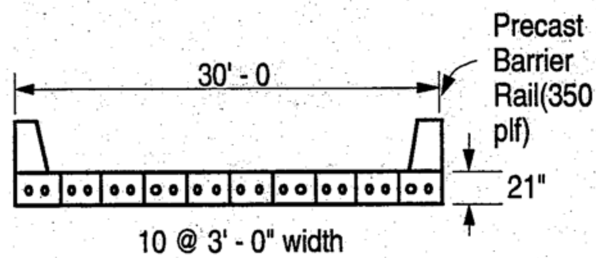
USER INTERFACE

CONCRETE PROPERTIES

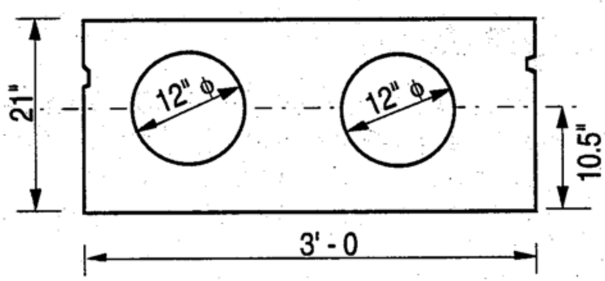
```
Poisson's ratio of concrete, v .....................  = 0.20
Density of concrete (lb/ft3), w ....................  = 150
Strength of concrete, fc (psi) .....................  = 5000
Strength of girder, fcg (psi) ......................  = 5000

Press ESC to exit this screen.
```

VOIDED SLAB BRIDGE

```
YEAR BUILT..........................................  = 1970
BRIDGE LENGTH (ft) .................................  = 45
BRIDGE WIDTH (ft) ..................................  = 30
VOID ELEMENT TYPE(STANDARD>1;NONSTANDARD USER SPECIFIED>0)=1
NUMBER OF ELEMENTS (BEAMS)..........................  = 10
PARAPET (ONE SIDE>1; BOTH SIDES>2; NONE>0) .........  = 2
OVERLAY UNIT WEIGHT(Asphalt=144;Concrete=150;lb/cu ft) = 0
ENTER THICKNESS OF OVERLAY (in).....................  = 0
STEEL (Prestressed>1; Reinforced>0) ................  = 1
METHOD FOR Rn: ACI>1; AASHTO>2......................  = 2

Press ESC to exit this screen.
```



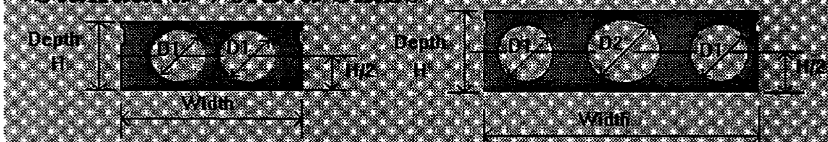
SECTION



VOIDED PRECAST BEAM SECTION

Figure 7.2 Voided slab cross-section

Standard Voided Slabs



Section Properties

Voided Element Type	Width ft.	Depth in.	No. of Voids	Void Dia. in.		Weight lb/ft	Net Area in.^{2}	Ix in.^{4}	S in.^{3}
				D1	D2				
1	3	15	2	8	-	457	439	9,725	1296
2	3	18	2	10	-	511	491	16,514	1836
3	3	21	2	12	-	552	530	25,747	2452
4	4	15	3	8	8	593	569	12,897	1720
5	4	18	3	10	10	654	628	21,855	2428
6	4	21	3	12	10	733	703	34,517	3287

Enter the voided element used in the slab in the above line

Enter steel properties for GIRDER 1 THROUGH 1

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .   = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 1.683
Depth of prestressing tendon, dp (in) ..............   = 19
```

Press ESC to exit this screen.

Enter steel properties for GIRDER 2 THROUGH 9

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .   = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 1.683
Depth of prestressing tendon, dp (in) ..............   = 19
```

Press ESC to exit this screen.

Enter steel properties for GIRDER 10 THROUGH 10

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) ..............  = 1.683
Depth of prestressing tendon, dp (in) ...............  = 19
```

Press ESC to exit this screen.

OUTPUT FILE

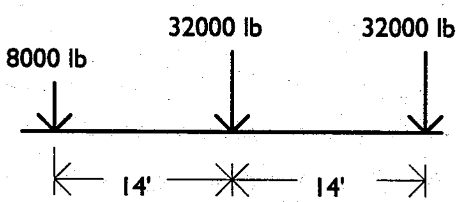
FLORIDA BRIDGE RATING
FLORIDA DEPARTMENT OF TRANSPORTATION

INPUT

```
BRIDGE TYPE : VOIDED SLAB

DIMENSIONS  : LENGTH (ft) ...........................  45.00
              WIDTH (ft) ............................  30.00
              STANDARD VOIDED SECTION SELECTED.......  TYPE 3
CONCRETE   :  STRENGTH(SLAB) (psi) ..................  5000.00
              MODULUS OF ELASTICITY (psi) ...........  4.03e+6
```

LIVE LOAD:

HS 20 Loading



No. of trucks placed on the bridge = 2

```
Truck #1 :  Rear axle placed at 33.66 ft. from the left support
            8.13 ft. from the right edge of the bridge.
            Traveling in the LEFT direction.

Truck #2 :  Rear axle placed at 33.66 ft. from the left support
            21.88 ft. from the right edge of the bridge.
            Traveling in the LEFT direction.

TOTAL DEAD LOAD (lbs)................................  248437.52
```

REINFORCEMENT DETAILS:
Near Right Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 1.68
Depth of prestressing tendons, dp (in) .... = 19.00

Voided Slab:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 1.68
Depth of prestressing tendons, dp (in) .... = 19.00

Near Left Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 1.68
Depth of prestressing tendons, dp (in) .... = 19.00

RESULTS OF ANALYSIS

Each 'BEAM' represents the group of longitudinal grillage beams from support to support.

CRITICAL RATING FACTOR:
RATING FACTOR = 1.62
NOMINAL MOMENT, Rn(kip-ft) = 621.69
DEAD LOAD MOMENT, MD (kip-ft) = 134.20
LIVE LOAD MOMENT, ML (kip-ft) = 109.20

The above rating factor and moments are computed per beam.

LOAD AND RESISTANCE FACTORS:
Capacity reduction factor = 0.85
Live load factor = 1.60
Dead load factor = 1.20
Impact Factor = 1.30

	RATING FACTOR	Rn(kip-ft)	ML(kip-ft)	MD(kip-ft)
BEAM 1	2.02	621.69	350.48	536.80
BEAM 2	1.71	621.69	412.80	536.80
BEAM 3	1.75	621.69	404.40	536.80
BEAM 4	1.62	621.69	436.80	536.80
BEAM 5	1.78	621.69	398.04	536.80
BEAM 6	1.78	621.69	398.04	536.80
BEAM 7	1.62	621.69	436.80	536.80
BEAM 8	1.75	621.69	404.40	536.80
BEAM 9	1.71	621.69	412.80	536.80
BEAM 10	2.02	621.69	350.12	536.80

PLOT

	BEAM # 1	1	11	21	31	41	51
Width 3.00							
	BEAM # 2	2	12	22	32	42	52
Width 3.00							
	BEAM # 3	3	13	23	33	43	53
Width 3.00							
	BEAM # 4	4	14	24	34	44	54
Width 3.00							
	BEAM # 5	5	15	25	35	45	55
Width 3.00							
	BEAM # 6	6	16	26	36	46	56
Width 3.00							
	BEAM # 7	7	17	27	37	47	57
Width 3.00							
	BEAM # 8	8	18	28	38	48	58
Width 3.00							
	BEAM # 9	9	19	29	39	49	59
Width 3.00							
	BEAM # 10	10	20	30	40	50	60
		Length 9.00	Length 9.00	Length 9.00	Length 9.00	Length 9.00	

DEFLECTIONS (inches)

# 1	0.000	-0.175	-0.285	-0.287	-0.178	0.000
# 2	0.000	-0.200	-0.331	-0.335	-0.213	0.000
# 3	0.000	-0.202	-0.332	-0.336	-0.210	0.000
# 4	0.000	-0.213	-0.351	-0.356	-0.226	0.000
# 5	0.000	-0.200	-0.328	-0.331	-0.207	0.000
# 6	0.000	-0.200	-0.328	-0.331	-0.207	0.000
# 7	0.000	-0.213	-0.351	-0.356	-0.226	0.000
# 8	0.000	-0.202	-0.332	-0.336	-0.210	0.000
# 9	0.000	-0.200	-0.331	-0.335	-0.213	0.000
# 10	0.000	-0.175	-0.285	-0.287	-0.179	0.000

7.4 VOIDED SLAB BRIDGE

(Palm Beach County, FDOT Bridge No. 930015)

Design Conditions

Simple span of 30 ft x 48 ft width

SU2 live load - 2 lanes

Multi - beam precast sections - TYPE 4 (adjacent units) without wearing surface.

Materials

Concrete:	Normal weight
	f'_c = 5000 psi
	f'_{ci} = 4000 psi (AASHTO 9.22)
Prestressing steel:	24 - 1/2 in. diameter 270 ksi stress - relieved strands @ 12.5 in. d_p.
	Strand area = 0.153 sq. in / strand
	$E_s = 28 \times 10^6$ psi

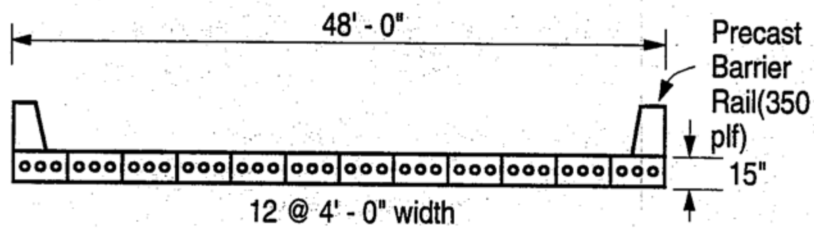
USER INTERFACE

CONCRETE PROPERTIES

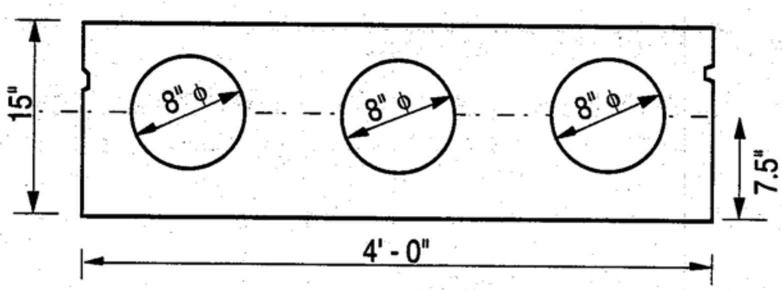
```
Poisson's ratio of concrete, v ......................  = 0.20
Density of concrete (lb/ft3), w .....................  = 150
Strength of concrete, fc (psi) ......................  = 5000
Strength of girder, fcg (psi) .......................  = 5000

Press ESC to exit this screen.
```

VOIDED SLAB BRIDGE

```
YEAR BUILT...........................................  = 1970
BRIDGE LENGTH (ft) ..................................  = 30
BRIDGE WIDTH (ft) ...................................  = 48
VOID ELEMENT TYPE(STANDARD>1;NONSTANDARD USER SPECIFIED>0)=1
NUMBER OF ELEMENTS (BEAMS)...........................  = 12
PARAPET (ONE SIDE>1; BOTH SIDES>2; NONE>0) ..........  = 2
OVERLAY UNIT WEIGHT(Asphalt=144;Concrete=150;lb/cu ft) = 0
ENTER THICKNESS OF OVERLAY (in)......................  = 0
STEEL (Prestressed>1; Reinforced>0) .................  = 1
METHOD FOR Rn: ACI>1; AASHTO>2.......................  = 2

Press ESC to exit this screen.
```



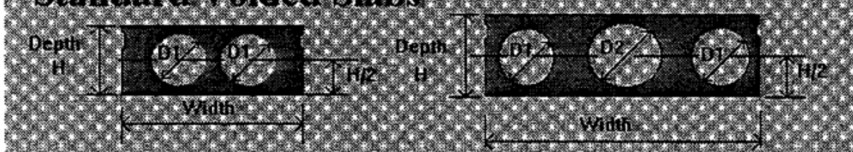
SECTION



VOIDED PRECAST BEAM SECTION

Figure 7.3 Voided slab cross-section

Standard Voided Slabs



Section Properties

Voided Element Type	Width ft.	Depth in.	No. of Voids	Void Dia. in.		Weight lb/ft	Net Area in.^{2}	Ix in.^{4}	S in.^{3}
				D1	D2				
1	3	15	2	8		457	439	9,725	1296
2	3	18	2	10	-	511	491	16,514	1836
3	3	21	2	12	-	552	530	25,747	2452
4	4	15	3	8	8	593	569	12,897	1720
5	4	18	3	10	10	654	628	21,855	2428
6	4	21	3	12	10	733	703	34,517	3287

Enter the voided element used in the slab in the above line

Enter steel properties for GIRDER 1 THROUGH 1

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.67
Depth of prestressing tendon, dp (in) ..............   = 12.50
```

Press ESC to exit this screen.

Enter steel properties for GIRDER 2 THROUGH 9

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.67
Depth of prestressing tendon, dp (in) ..............   = 12.50
```

Press ESC to exit this screen.

Enter steel properties for GIRDER 10 THROUGH 10

PROPERTIES (PRESTRESSED SECTIONS)

If nominal resistance is known enter value (kip-ft) . . = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .... = 3.67
Depth of prestressing tendon, dp (in) .... = 12.50

Press ESC to exit this screen.

OUTPUT FILE

FLORIDA BRIDGE RATING
FLORIDA DEPARTMENT OF TRANSPORTATION

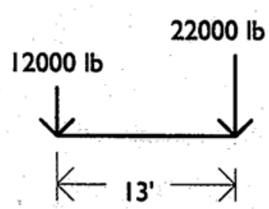
INPUT

BRIDGE TYPE : VOIDED SLAB

DIMENSIONS : LENGTH (ft) 30.00
WIDTH (ft) 48.00
STANDARD VOIDED SECTION SELECTED....... TYPE 4
CONCRETE : STRENGTH(SLAB) (psi) 5000.00
MODULUS OF ELASTICITY (psi) .... 4.03e+6

LIVE LOAD:

SU2 Loading



No. of trucks placed on the bridge = 2

Truck #1 : Rear axle placed at 17.29 ft. from the left support
12.63 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

Truck #2 : Rear axle placed at 17.29 ft. from the left support
35.38 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

TOTAL DEAD LOAD (lbs)................................ 213375.02

REINFORCEMENT DETAILS:

Near Right Edge Beam:

Prestressing Steel

Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 12.50

Voided Slab:

Prestressing Steel

Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 12.50

Near Left Edge Beam:

Prestressing Steel

Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 12.50

RESULTS OF ANALYSIS

Each 'BEAM' represents the group of longitudinal grillage beams from support to support.

CRITICAL RATING FACTOR:

RATING FACTOR = 4.53
NOMINAL MOMENT, Rn(kip-ft) = 719.40
DEAD LOAD MOMENT, MD (kip-ft) = 64.01
LIVE LOAD MOMENT, ML (kip-ft) = 56.80

The above rating factor and moments are computed per beam.

LOAD AND RESISTANCE FACTORS:

Capacity reduction factor = 0.85
Live load factor = 1.60
Dead load factor = 1.20
Impact Factor = 1.30

	RATING FACTOR	Rn(kip-ft)	ML(kip-ft)	MD(kip-ft)
BEAM 1	44.34	719.40	17.39	192.03
BEAM 2	12.80	719.40	60.27	192.03
BEAM 3	4.53	719.40	170.40	192.03
BEAM 4	5.57	719.40	138.45	192.03
BEAM 5	7.46	719.40	103.35	192.03
BEAM 6	27.09	719.40	28.46	192.03
BEAM 7	27.09	719.40	28.47	192.03
BEAM 8	7.46	719.40	103.35	192.03
BEAM 9	5.57	719.40	138.45	192.03
BEAM 10	4.53	719.40	170.40	192.03
BEAM 11	12.79	719.40	60.30	192.03
BEAM 12	44.46	719.40	17.35	192.03

PLOT

	BEAM # 1	1	13	25	37	49	61
Width 4.00							
	BEAM # 2	2	14	26	38	50	62
Width 4.00							
	BEAM # 3	3	15	27	39	51	63
Width 4.00							
	BEAM # 4	4	16	28	40	52	64
Width 4.00							
	BEAM # 5	5	17	29	41	53	65
Width 4.00							
	BEAM # 6	6	18	30	42	54	66
Width 4.00							
	BEAM # 7	7	19	31	43	55	67
Width 4.00							
	BEAM # 8	8	20	32	44	56	68
Width 4.00							
	BEAM # 9	9	21	33	45	57	69
Width 4.00							
	BEAM # 10	10	22	34	46	58	70
Width 4.00							
	BEAM # 11	11	23	35	47	59	71
Width 4.00							
	BEAM # 12	12	24	36	48	60	72
		Length 6.00	Length 6.00	Length 6.00	Length 6.00	Length 6.00	

DEFLECTIONS (inches)

# 1	0.000	-0.010	-0.017	-0.017	-0.010	0.000
# 2	0.000	-0.036	-0.057	-0.057	-0.035	0.000
# 3	0.000	-0.087	-0.142	-0.145	-0.089	0.000
# 4	0.000	-0.073	-0.119	-0.121	-0.074	0.000
# 5	0.000	-0.056	-0.091	-0.092	-0.056	0.000

```
# 6  | 0.000  -0.017   -0.028  -0.028  -0.017  0.000
# 7  | 0.000  -0.017   -0.028  -0.028  -0.017  0.000
# 8  | 0.000  -0.056   -0.091  -0.092  -0.056  0.000
# 9  | 0.000  -0.073   -0.119  -0.121  -0.074  0.000
# 10 | 0.000  -0.087   -0.142  -0.145  -0.089  0.000
# 11 | 0.000  -0.036   -0.057  -0.057  -0.035  0.000
# 12 | 0.000  -0.010   -0.017  -0.017  -0.010  0.000
```

According to the FDOT load test results, this bridge has an operating rating factor of 3.23.

7.5 AASHTO GIRDER AND SLAB BRIDGE

(PCI Handbook Example)

Design Conditions

Simple span of 75 ft x 30 ft width

HS20 live load - 2 lanes

PCI standard I - Girders at 8 ft spacing

Composite construction with 7 - 1/2 in. deck slab

2 in. future wearing surface.

Materials

Precast concrete:	Normal weight	
	f'_c	= 5000 psi; f'_{ci}= 4000 psi (AASHTO 9.22)
Cast - in - place concrete:		Normal weight
	f'_c	= 4000 psi
Prestressing steel:	24 - 1/2 in. diameter 270 ksi stress - relieved strands @ 57.5 in.	
	Strand area = 0.153 sq. in. / strand	
	E_s	= 28 x 10^6 psi
Reinforcing bars:	f_y	= 60,000 psi

USER INTERFACE

CONCRETE PROPERTIES

```
Poisson's ratio of concrete, v ......................  = 0.20
Density of concrete (lb/ft3), w .....................  = 150
Strength of concrete, fc (psi) ......................  = 4000
Strength of girder, fcg (psi) .......................  = 5000

Press ESC to exit this screen.
```

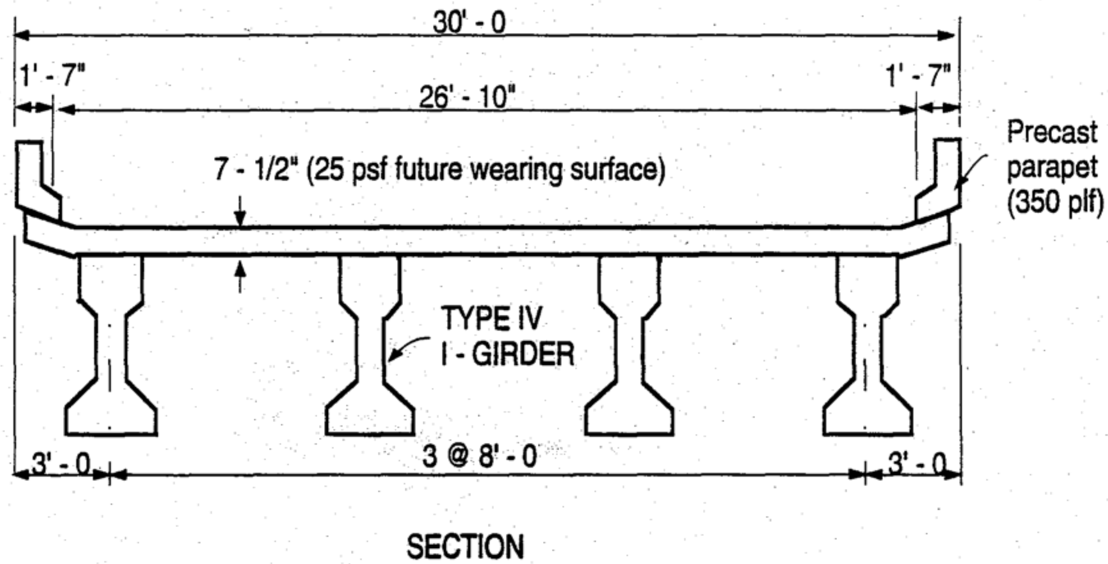
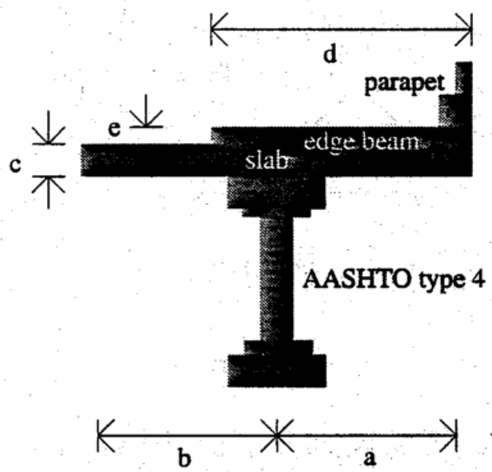


Figure 7.4 AASHTO girder and slab cross-section

AASHTO GIRDER & SLAB BRIDGE

```
YEAR BUILT.........................................  = 1970
AGE................................................  = 23
BRIDGE LENGTH (ft) ................................  = 75
BRIDGE WIDTH (ft) .................................  = 30
AASHTO GIRDER TYPE (1 through 6)...................  = 4
ENTER SPACING OF INTERIOR GIRDERS (ft).............  = 8
NUMBER OF GIRDERS..................................  = 2
OVERLAY UNIT WEIGHT(Asphalt=144;Concrete=150;lb/cu ft) = 0
ENTER THICKNESS OF OVERLAY (in)....................  = 0
STEEL (Prestressed>1; Reinforced>0) ...............  = 1
METHOD FOR Rn: ACI>1; AASHTO>2.....................  = 2

Press ESC to exit this screen.
```

Enter the dimensions of the right exterior member



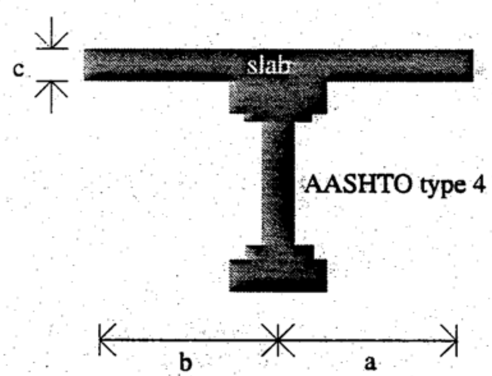

```
a>SLAB WIDTH RT.OF CTRLINE,ft=3     b>SLAB WIDTH LT.OF CTRLINE,ft=4
c> SLAB THICKNESS, in          =7.5
d> WIDTH OF EDGE BEAM, ft      =0    e> THICKNESS OF EDGE BEAM,in =0
f> PARAPET? (YES=1;NO=0)       =1
Press ESC to exit this screen.
```

Enter steel properties for GIRDER 1 THROUGH 1

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.672
Depth of prestressing tendon, dp (in) ..............   = 57.5

Press ESC to exit this screen.
```

Enter the dimensions of the intermediate members

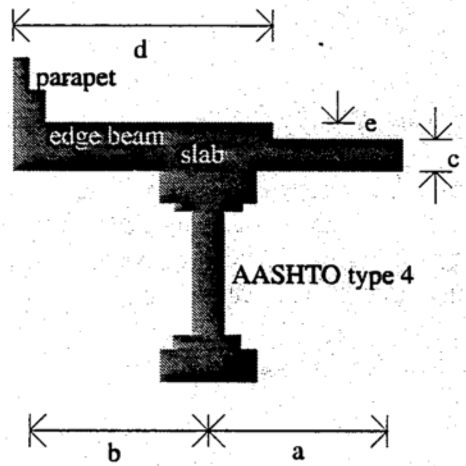



```
a>SLAB WIDTH RT.OF CTRLINE,ft=4      b>SLAB WIDTH LT.OF CTRLINE,ft=4
c> SLAB THICKNESS, in        =7.5
Press ESC to exit this screen.


Enter steel properties for GIRDER 2 THROUGH 3
```

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.672
Depth of prestressing tendon, dp (in) ..............   = 57.5

Press ESC to exit this screen.
```

Enter the dimensions of the left exterior member




```
a>SLAB WIDTH RT.OF CTRLINE,ft=4      b>SLAB WIDTH LT.OF CTRLINE,ft=3
c> SLAB THICKNESS, in          =7.5
d> WIDTH OF EDGE BEAM, ft      =0    e> THICKNESS OF EDGE BEAM,in =0
f> PARAPET? (YES=1;NO=0)       =1
Press ESC to exit this screen.
```

Enter steel properties for GIRDER 4 THROUGH 4

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) ..............  = 3.672
Depth of prestressing tendon, dp (in) ...............  = 57.5
```

Press ESC to exit this screen.

OUTPUT FILE

FLORIDA BRIDGE RATING
FLORIDA DEPARTMENT OF TRANSPORTATION

INPUT

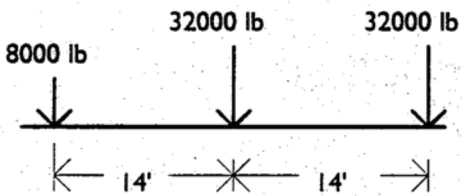
BRIDGE TYPE : SLAB & GIRDER: TYPE 4

```
DIMENSIONS   : LENGTH (ft) ..........................  75.00
               WIDTH (ft) ...........................  30.00
               NO. OF GIRDERS .......................  4
               GIRDER SPACING (ft) ..................  8.00
```

```
CONCRETE     : STRENGTH(SLAB) (psi) ..................  4000.00
               MODULUS OF ELASTICITY (psi) ...........  3.60e+6
               STRENGTH(GIRDERS) (psi) ...............  5000.00
               MODULUS OF ELASTICITY(GIRDER) (psi) ...  4.03e+6
```

LIVE LOAD:

HS 20 Loading



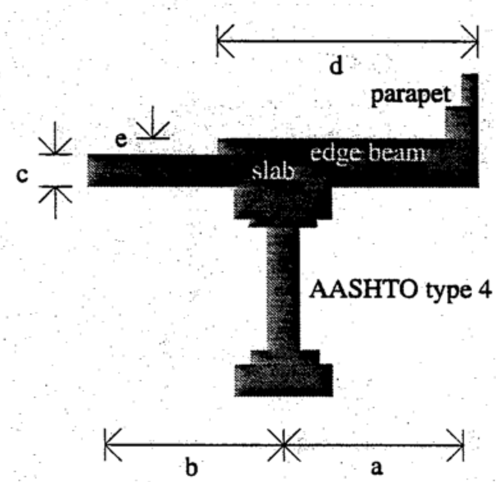
No. of trucks placed on the bridge = 2

Truck #1: Rear axle placed at 48.66 ft. from the left support
8.13 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

Truck #2: Rear axle placed at 48.66 ft. from the left support
21.88 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

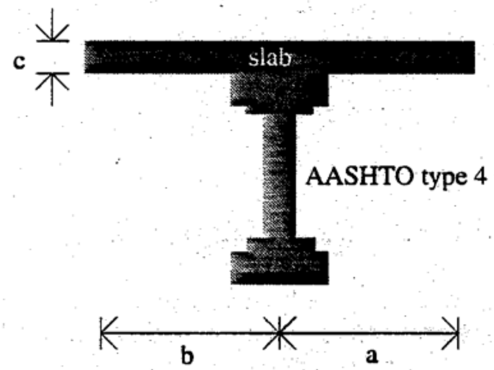
TOTAL DEAD LOAD (lbs) 480780.94

Dimensions of the right exterior member:



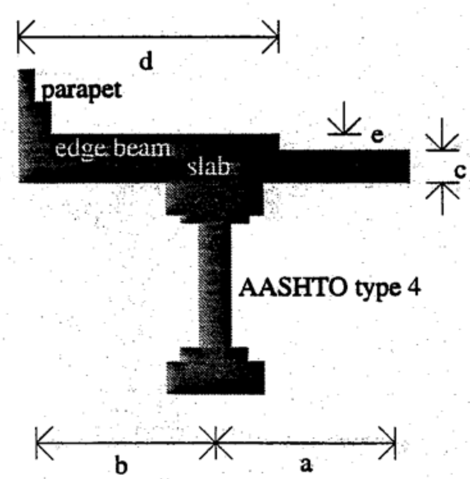
```
a> SLAB WIDTH RT OF CTRLINE, ft          =    3.00
b> SLAB WIDTH LT OF CTRLINE, ft          =    4.00
c> SLAB THICKNESS, in                    =    7.50
d> WIDTH OF EDGE BEAM, ft                =    0.00
e> THICKNESS OF EDGE BEAM, in            =    0.00
f> PARAPET? (YES=1;NO=0)                 =    1
```

Dimensions of the interior members:




```
a> SLAB WIDTH RT OF CTRLINE, ft          =    4.00
b> SLAB WIDTH LT OF CTRLINE, ft          =    4.00
c> SLAB THICKNESS, in                    =    7.50
d> No. of intermediate girders           =    2
```

Dimensions of the left exterior member:



```
a> SLAB WIDTH RT OF CTRLINE, ft          =    4.00
b> SLAB WIDTH LT OF CTRLINE, ft          =    3.00
c> SLAB THICKNESS, in                    =    7.50
d> WIDTH OF EDGE BEAM, ft                =    0.00
e> THICKNESS OF EDGE BEAM, in            =    0.00
f> PARAPET? (YES=1;NO=0)                 =    1
```

Reinforcement Details
Near Right Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 57.50

Girder and Slab:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 57.50

Near Left Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 57.50

RESULTS OF ANALYSIS

Each 'BEAM' represents the group of longitudinal grillage beams from support to support.

CRITICAL RATING FACTOR:
RATING FACTOR = 2.10
NOMINAL MOMENT, Rn(kip-ft) = 4550.20
DEAD LOAD MOMENT, MD (kip-ft) = 1296.00
LIVE LOAD MOMENT, ML (kip-ft) = 530.00

LOAD AND RESISTANCE FACTORS:
Capacity reduction factor = 0.85
Live load factor = 1.60
Dead load factor = 1.20
Impact Factor = 1.30

	RATING FACTOR	Rn(kip-ft)	ML(kip-ft)	MD(kip-ft)
BEAM 1	2.10	4550.20	530.00	1296.00
BEAM 2	2.47	4550.20	528.70	958.00
BEAM 3	2.47	4550.20	528.70	958.00
BEAM 4	2.10	4550.20	530.00	1296.00

PLOT

```
     BEAM # 1       1    5    9    13   17   21   25
Width
8.00
     BEAM # 2       2    6    10   14   18   22   26
Width
8.00
     BEAM # 3       3    7    11   15   19   23   27
Width
8.00
     BEAM # 4       4    8    12   16   20   24   28
                    Length
                    12.50 12.50 12.50 12.50 12.50 12.50
```

DEFLECTIONS (inches)

# 1	0.000	-0.061	-0.107	-0.126	-0.109	-0.063	0.000
# 2	0.000	-0.089	-0.157	-0.185	-0.161	-0.093	0.000
# 3	0.000	-0.089	-0.157	-0.185	-0.161	-0.093	0.000
# 4	0.000	-0.061	-0.107	-0.126	-0.109	-0.063	0.000

7.6 AASHTO GIRDER AND SLAB BRIDGE

(Palm Beach County, FDOT Bridge No. 930247)

Design Conditions

Simple span of 102 ft x 30 ft width

SU2 live load - 2 lanes

AASHTO standard (Type IV) I - Girders at 6 ft. 4 in. spacing

Composite construction with 7 in. deck slab

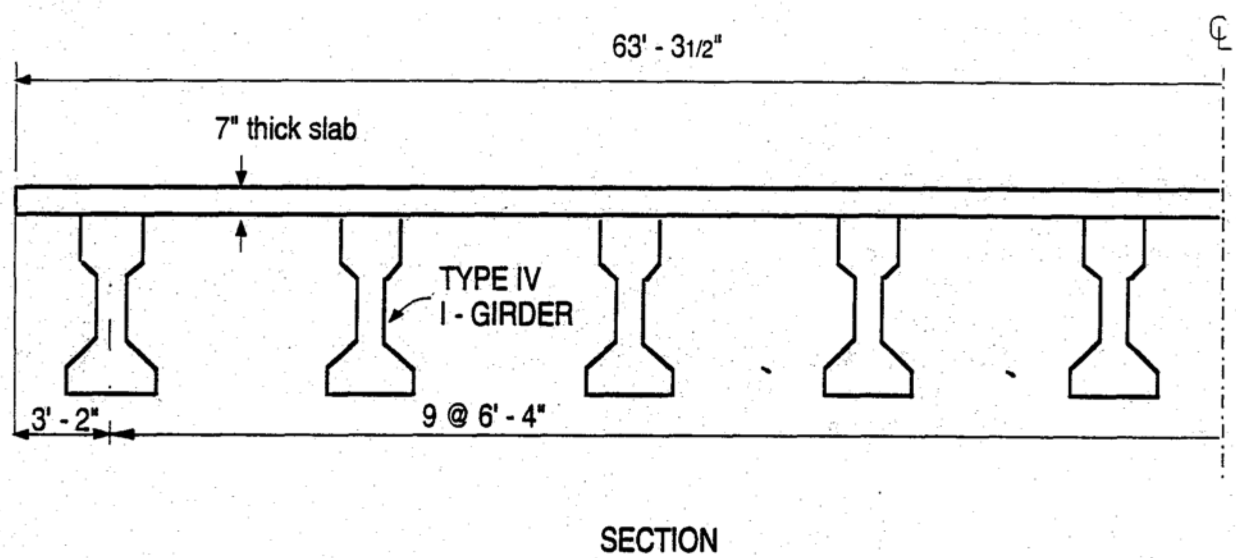


Figure 7.5 AASHTO girder and slab cross-section

Materials

Precast concrete: Normal weight

f'_c = 5500 psi; f'_{ci}= 4000 psi (AASHTO 9.22)

Cast - in - place concrete: Normal weight

f'_c = 5500 psi

Prestressing steel: 16 - 1/2 in. diameter 270 ksi stress - relieved strands @ 57.56 in.

Strand area = 0.153 sq. in./ strand

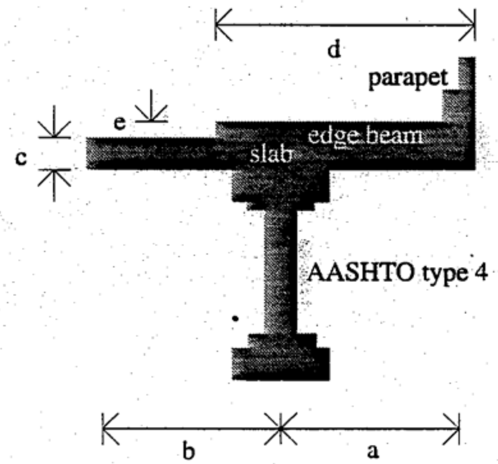
$E_s = 28 \times 10^6$ psi

USER INTERFACE

```
CONCRETE PROPERTIES

Poisson's ratio of concrete, v ......................  = 0.20
Density of concrete (lb/ft3), w .....................  = 150
Strength of concrete, fc (psi) ......................  = 5500
Strength of girder, fcg (psi) .......................  = 5500

Press ESC to exit this screen.
```

```
AASHTO GIRDER & SLAB BRIDGE

YEAR BUILT.............................................  = 1970
AGE....................................................  = 23
BRIDGE LENGTH (ft) ....................................  = 102
BRIDGE WIDTH (ft) .....................................  = 63.33
AASHTO GIRDER TYPE (1 through 6).......................  = 4
ENTER SPACING OF INTERIOR GIRDERS (ft).................  = 6.33
NUMBER OF GIRDERS......................................  = 10
OVERLAY UNIT WEIGHT(Asphalt=144;Concrete=150;lb/cu ft)  = 0
ENTER THICKNESS OF OVERLAY (in)........................  = 0
STEEL (Prestressed>1; Reinforced>0) ...................  = 1
METHOD FOR Rn: ACI>1; AASHTO>2.........................  = 2

Press ESC to exit this screen.
```

Enter the dimensions of the right exterior member



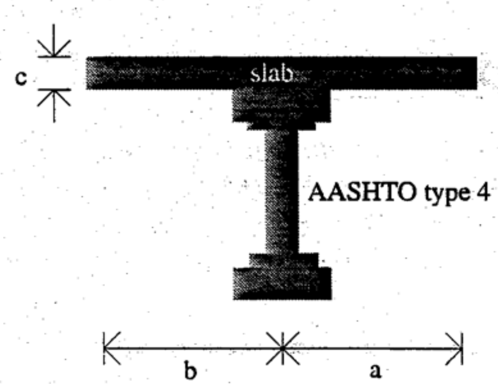

```
a>SLAB WIDTH RT.OF CTRLINE,ft=3.17  b>SLAB WIDTH LT.OF CTRLINE,ft=3.17
c> SLAB THICKNESS, in          =7.0
d> WIDTH OF EDGE BEAM, ft      =0      e> THICKNESS OF EDGE BEAM,in =0
f> PARAPET? (YES=1;NO=0)       =0
Press ESC to exit this screen.
```

Enter steel properties for GIRDER 1 THROUGH 1

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .   = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.67
Depth of prestressing tendon, dp (in) ..............   = 57.56

Press ESC to exit this screen.
```

Enter the dimensions of the intermediate members



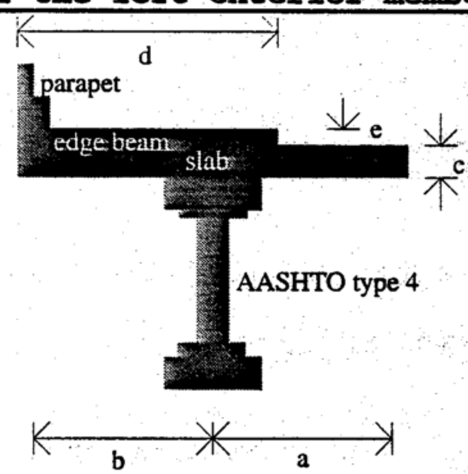
```
a>SLAB WIDTH RT.OF CTRLINE,ft=3.17  b>SLAB WIDTH LT.OF CTRLINE,ft=3.17
c> SLAB THICKNESS, in        =7.0
Press ESC to exit this screen.
```

```
Enter steel properties for GIRDER 2 THROUGH 3
```

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.67
Depth of prestressing tendon, dp (in) ..............   = 57.56

Press ESC to exit this screen.
```

Enter the dimensions of the left exterior member




```
a>SLAB WIDTH RT.OF CTRLINE,ft=3.17  b>SLAB WIDTH LT.OF CTRLINE,ft=3.17
c> SLAB THICKNESS, in        =7.0
d> WIDTH OF EDGE BEAM, ft    =0     e> THICKNESS OF EDGE BEAM,in =0
f> PARAPET? (YES=1;NO=0)     =0
Press ESC to exit this screen.
```

```
Enter steel properties for GIRDER 4 THROUGH 4
```

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 3.67
Depth of prestressing tendon, dp (in) ..............   = 57.56

Press ESC to exit this screen.
```

OUTPUT FILE

FLORIDA BRIDGE RATING
FLORIDA DEPARTMENT OF TRANSPORTATION

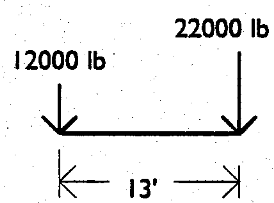
INPUT

BRIDGE TYPE : SLAB & GIRDER: TYPE 4

DIMENSIONS :	LENGTH (ft)	102.00
	WIDTH (ft)	63.33
	NO. OF GIRDERS	10
	GIRDER SPACING (ft)	6.33
CONCRETE :	STRENGTH(SLAB) (psi)	5500.00
	MODULUS OF ELASTICITY (psi)	4.23e+6
	STRENGTH(GIRDERS) (psi)	5500.00
	MODULUS OF ELASTICITY(GIRDER) (psi) ...	4.23e+6

LIVE LOAD:

SU2 Loading



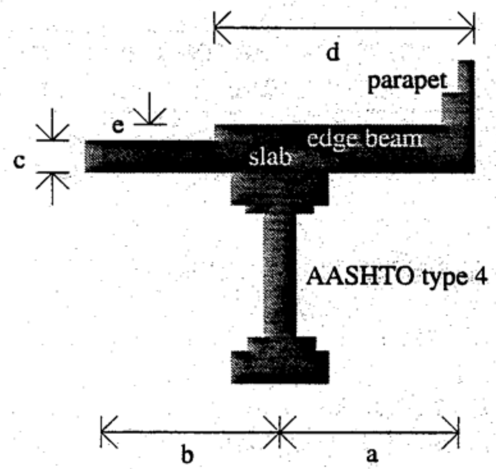
No. of trucks placed on the bridge = 2

Truck #1: Rear axle placed at 53.29 ft. from the left support
16.46 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

Truck #2: Rear axle placed at 53.29 ft. from the left support
46.87 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

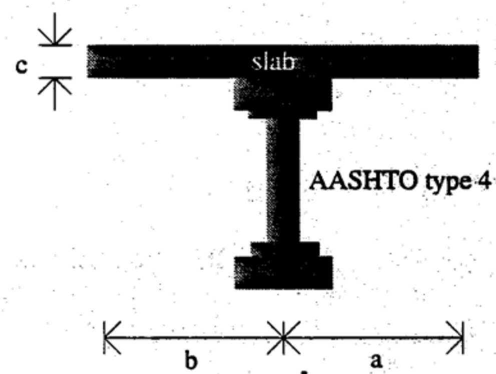
TOTAL DEAD LOAD (lbs) 1403562.38

Dimensions of the right exterior member:



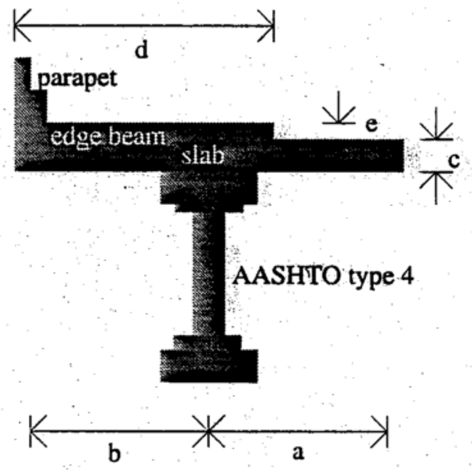

```
a> SLAB WIDTH RT OF CTRLINE, ft          =    3.17
b> SLAB WIDTH LT OF CTRLINE, ft          =    3.17
c> SLAB THICKNESS, in                    =    7.00
d> WIDTH OF EDGE BEAM, ft                =    0.00
e> THICKNESS OF EDGE BEAM, in            =    0.00
f> PARAPET? (YES=1;NO=0)                 =    0
```

Dimensions of the interior members:




```
a> SLAB WIDTH RT OF CTRLINE, ft          =    3.17
b> SLAB WIDTH LT OF CTRLINE, ft          =    3.17
c> SLAB THICKNESS, in                    =    7.00
d> No. of intermediate girders           =    2
```

Dimensions of the left exterior member:




```
a> SLAB WIDTH RT OF CTRLINE, ft          =    3.17
b> SLAB WIDTH LT OF CTRLINE, ft          =    3.17
c> SLAB THICKNESS, in                    =    7.00
d> WIDTH OF EDGE BEAM, ft                =    0.00
e> THICKNESS OF EDGE BEAM, in            =    0.00
f> PARAPET? (YES=1;NO=0)                 =    0
```

Reinforcement Details
Near Right Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 57.56

Girder and Slab:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 57.56

Near Left Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 3.67
Depth of prestressing tendons, dp (in) .... = 57.56

RESULTS OF ANALYSIS

Each 'BEAM' represents the group of longitudinal grillage beams from support to support.

CRITICAL RATING FACTOR:

RATING FACTOR	= 4.14
NOMINAL MOMENT, Rn(kip-ft)	= 4600.65
DEAD LOAD MOMENT, MD (kip-ft)	= 1790.00
LIVE LOAD MOMENT, ML (kip-ft)	= 204.80

LOAD AND RESISTANCE FACTORS:

Capacity reduction factor	= 0.85
Live load factor	= 1.60
Dead load factor	= 1.20
Impact Factor	= 1.30

	RATING FACTOR	Rn(kip-ft)	ML(kip-ft)	MD(kip-ft)
BEAM 1	9.22	4600.65	91.91	1790.00
BEAM 2	5.40	4600.65	156.80	1790.00
BEAM 3	4.14	4600.65	204.80	1790.00
BEAM 4	4.61	4600.65	183.80	1790.00
BEAM 5	6.03	4600.65	140.50	1790.00
BEAM 6	6.03	4600.65	140.50	1790.00
BEAM 7	4.61	4600.65	183.90	1790.00
BEAM 8	4.14	4600.65	204.80	1790.00
BEAM 9	5.41	4600.65	156.60	1790.00
BEAM 10	9.23	4600.65	91.79	1790.00

PLOT

```
     BEAM #1  1   11   21   31   41   51   61   71   81   91   101
Width
6.33
     BEAM #2  2   12   22   32   42   52   62   72   82   92   102
Width
6.33
     BEAM #3  3   13   23   33   43   53   63   73   83   93   103
Width
6.33
     BEAM #4  4   14   24   34   44   54   64   74   84   94   104
Width
6.33
     BEAM #5  5   15   25   35   45   55   65   75   85   95   105
Width
6.33
     BEAM #6  6   16   26   36   46   56   66   76   86   96   106
Width
6.33
     BEAM #7  7   17   27   37   47   57   67   77   87   97   107
Width
6.33
     BEAM #8  8   18   28   38   48   58   68   78   88   98   108
```

```
Width
6.33
     BEAM #9  9   19   29   39   49   59   69   79   89   99   109
Width
6.33
     BEAM #10 10  20   30   40   50   60   70   80   90   100  110
Lengths of all elements
12.50
```

```
DEFLECTIONS (inches)                            symmetric about
                                                  midspan
# 1  0.000  -0.020  -0.038  -0.052   -0.061  -0.064
# 2  0.000  -0.030  -0.057  -0.079   -0.094  -0.098
# 3  0.000  -0.035  -0.068  -0.095   -0.113  -0.119
# 4  0.000  -0.034  -0.065  -0.091   -0.108  -0.113
# 5  0.000  -0.030  -0.058  -0.080   -0.093  -0.098
# 6  0.000  -0.030  -0.058  -0.080   -0.093  -0.098
# 7  0.000  -0.034  -0.065  -0.091   -0.108  -0.113
# 8  0.000  -0.035  -0.068  -0.095   -0.113  -0.119
# 9  0.000  -0.030  -0.057  -0.079   -0.094  -0.098
# 10 0.000  -0.020  -0.038  -0.052   -0.061  -0.064
```

According to the FDOT load test results, this bridge has an operating rating factor of 2.58.

7.7 DOUBLE-T BRIDGE

(PCI Handbook Example)

Design Conditions

Simple span of 40 ft x 30 ft width

HS20 live load - 2 lanes

Double stemmed precast sections (adjacent units) with cast-in-place composite deck slab.

Materials

Precast concrete: Normal weight

f'_c = 5000 psi

f'_{ci} = 4000 psi (AASHTO 9.22)

Cast - in - place concrete: Normal weight

f'_c = 4000 psi

Prestressing steel: 6 - 1/2 in. diameter 270 ksi stress - relieved strands per stem @ 26in.

Strand area = 0.153 sq. in. / strand

E_s = 28×10^6 psi

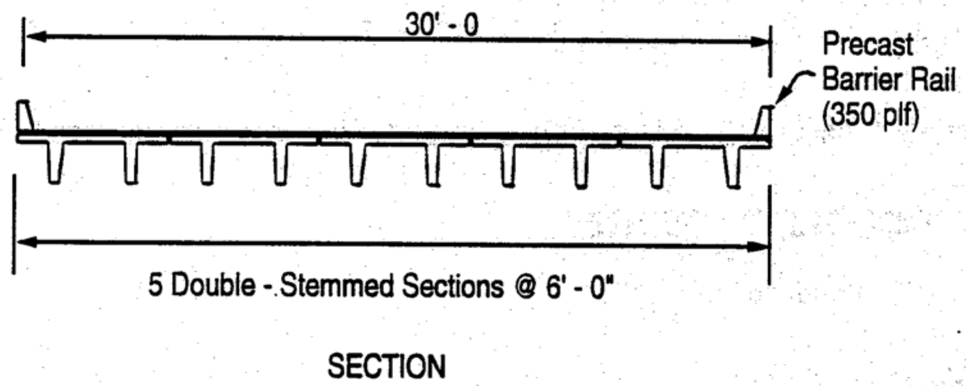
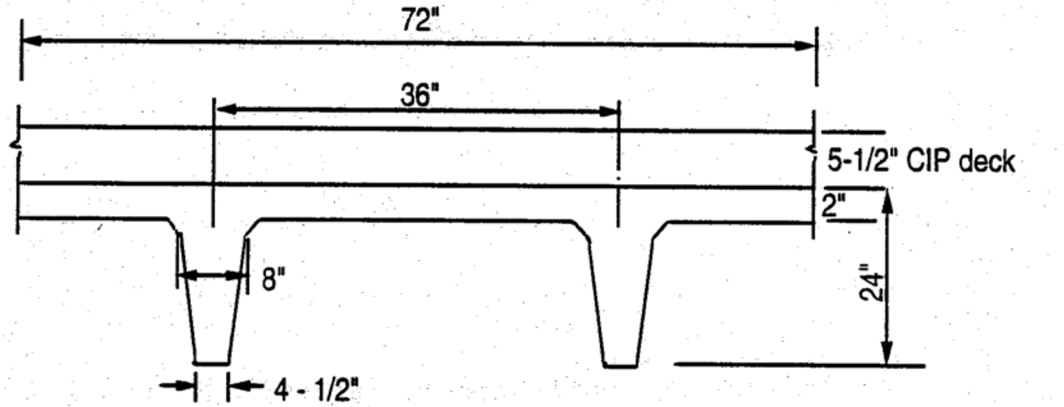


Figure 7.6(a) Double-T cross-section



DOUBLE STEMMED BEAM SECTION

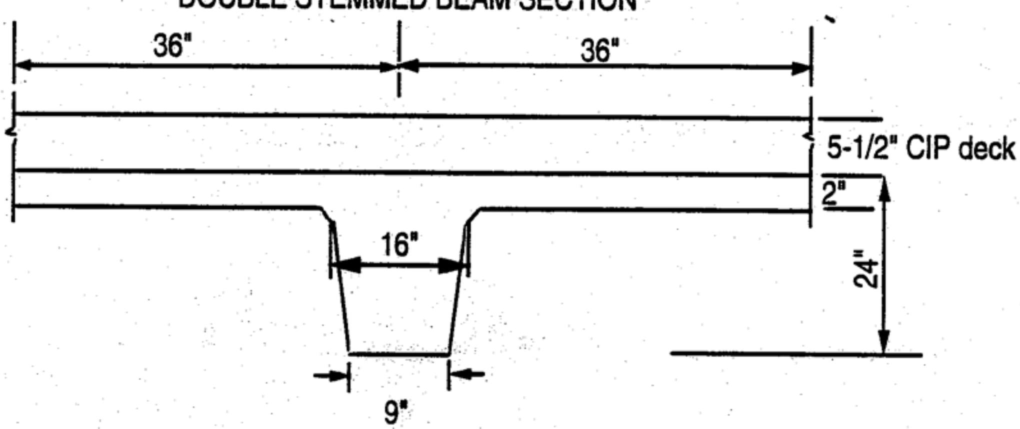


Figure 7.6(b) T-beam idealization of the Double-T cross-section

USER INTERFACE

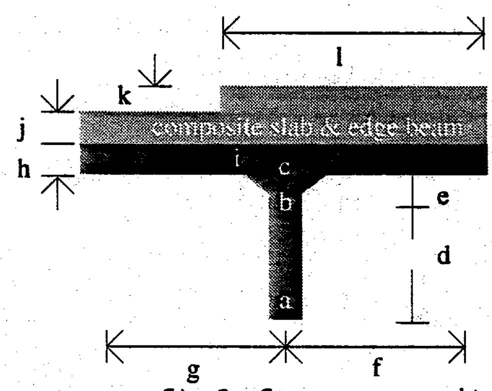
CONCRETE PROPERTIES

```
Poisson's ratio of concrete, v ......................  = 0.20
Density of concrete (lb/ft3), w .....................  = 150
Strength of concrete, fc (psi) ......................  = 4000
Strength of girder, fcg (psi) .......................  = 5000

Press ESC to exit this screen.
```

T-BEAM BRIDGE

```
YEAR BUILT..........................................  = 1970
AGE.................................................  = 23
BRIDGE LENGTH (ft) .................................  = 40
BRIDGE WIDTH (ft) ..................................  = 30
ENTER SPACING OF INTERIOR GIRDERS (ft)..............  = 6
NUMBER OF BEAMS.....................................  = 5
OVERLAY UNIT WEIGHT(Asphalt=144;Concrete=150;lb/cu ft) = 0
ENTER THICKNESS OF OVERLAY (in).....................  = 0
STEEL (Prestressed>1; Reinforced>0) ................  = 1
METHOD FOR Rn: ACI>1; AASHTO>2......................  = 2

Press ESC to exit this screen.
```

Enter the dimensions of the right exterior member



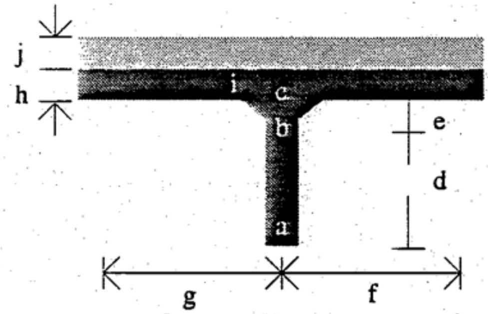

```
          a)=9 in.         f)=3 ft.        j)=5.5 in.
          b)=16 in.        g)=3 in.        k)=0 in.
          c)=16 in.        h)=2 in.        l)=0 ft.
          d)=22 in.        i)=2 in.
          e)=0 in.
          m)PARAPET? (YES=1;NO=0)=1
Press ESC to exit this screen.
```

Enter steel properties for GIRDER 1 THROUGH 1

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 1.836
Depth of prestressing tendon, dp (in) ..............   = 26
Press ESC to exit this screen.
```

Enter the dimensions of the intermediate members



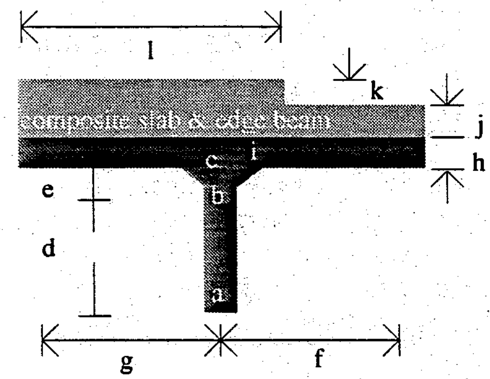

```
             a)=9 in.          f)=3 ft.       j)=5.5 in.
             b)=16 in.         g)=3 in.
             c)=16 in.         h)=2 in.
             d)=22 in.         i)=2 in.
             e)=0 in.
Press ESC to exit this screen.
```

Enter steel properties for GIRDER 2 THROUGH 4

PROPERTIES (PRESTRESSED SECTIONS)

```
If nominal resistance is known enter value (kip-ft) .  = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .............   = 1.836
Depth of prestressing tendon, dp (in) ..............   = 26
Press ESC to exit this screen.
```

Enter the dimensions of the left exterior member



a)=9 in.	f)=3 ft.	j)=5.5 in.
b)=16 in.	g)=3 in.	k)=0 in.
c)=16 in.	h)=2 in.	l)=0 ft.
d)=22 in.	i)=2 in.	
e)=0 in.		

m)PARAPET? (YES=1;NO=0)=1

Press ESC to exit this screen.

Enter steel properties for GIRDER 5 THROUGH 5

PROPERTIES (PRESTRESSED SECTIONS)

If nominal resistance is known enter value (kip-ft) . = 0
Specified tensile str. of prestressing steel,fpu (psi) = 270000
Area of prestressing tendon, Aps (in2) .... = 1.836
Depth of prestressing tendon, dp (in) .... = 26
Press ESC to exit this screen.

OUTPUT FILE

FLORIDA BRIDGE RATING
FLORIDA DEPARTMENT OF TRANSPORTATION

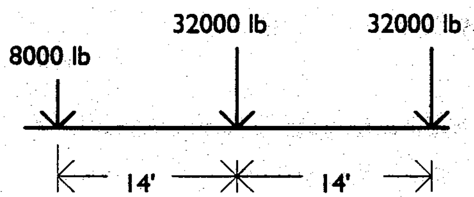
INPUT

BRIDGE TYPE : T-BEAM

DIMENSIONS	: LENGTH (ft)	40.00
	WIDTH (ft)	30.00
	NO. OF T-BEAM	5
	BEAM SPACING (ft)	6.00
CONCRETE	: STRENGTH(SLAB) (psi)	4000.00
	MODULUS OF ELASTICITY (psi)	3.60e+6

LIVE LOAD:

HS 20 Loading



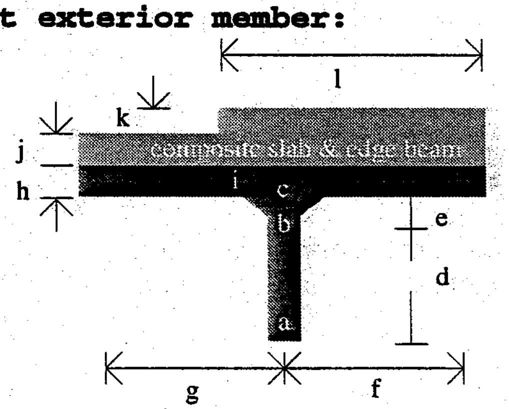
No. of trucks placed on the bridge = 2

Truck #1: Rear axle placed at 31.66 ft. from the left support
8.13 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

Truck #2: Rear axle placed at 31.66 ft. from the left support
21.88 ft. from the right edge of the bridge.
Traveling in the LEFT direction.

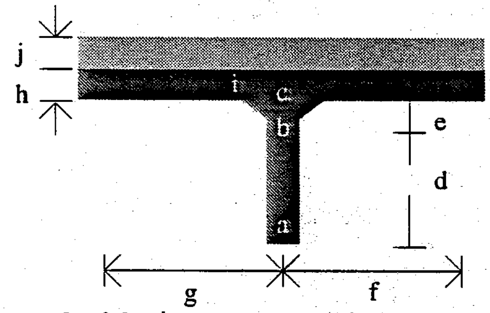
TOTAL DEAD LOAD (lbs) 194083.36

Dimensions of the right exterior member:



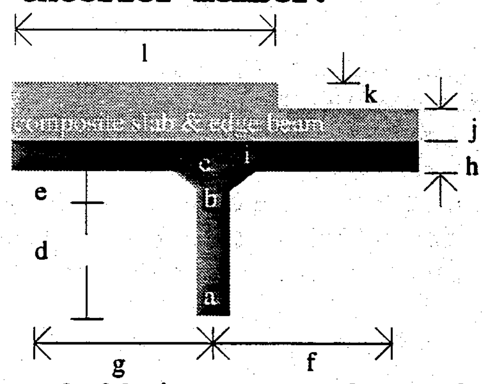
a = 9.00 in.	b = 16.00 in.
c = 16.00 in.	d = 22.00 in.
e = 0.00 in.	f = 3.00 ft.
g = 3.00 in.	h = 2.00 in.
i = 2.00 in.	j = 5.50 in.
k = 0.00 in.	l = 0.00 ft.

Dimensions of the interior members:



a = 9.00 in.	b = 16.00 in.
c = 16.00 in.	d = 22.00 in.
e = 0.00 in.	f = 3.00 ft.
g = 3.00 in.	h = 2.00 in.
i = 2.00 in.	j = 5.50 in.

Dimensions of the left exterior member:



a = 9.00 in.	b = 16.00 in.
c = 16.00 in.	d = 22.00 in.
e = 0.00 in.	f = 3.00 ft.
g = 3.00 in.	h = 2.00 in.
i = 2.00 in.	j = 5.50 in.
k = 0.00 in.	l = 0.00 ft.

Reinforcement Details
Near Right Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 1.84
Depth of prestressing tendons, dp (in) .... = 26.00

Girder and Slab:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 1.84
Depth of prestressing tendons, dp (in) .... = 26.00

Near Left Edge Beam:
Prestressing Steel
Area of prestressing tendons, Aps (in2) .... = 1.84
Depth of prestressing tendons, dp (in) .... = 26.00

RESULTS OF ANALYSIS

Each 'BEAM' represents the group of longitudinal grillage beams from support to support.

CRITICAL RATING FACTOR:

RATING FACTOR	= 1.00
NOMINAL MOMENT, Rn(kip-ft)	= 998.62
DEAD LOAD MOMENT, MD (kip-ft)	= 297.50
LIVE LOAD MOMENT, ML (kip-ft)	= 236.90

LOAD AND RESISTANCE FACTORS:

Capacity reduction factor	= 0.85
Live load factor	= 1.60
Dead load factor	= 1.20
Impact Factor	= 1.30

	RATING FACTOR	Rn(kip-ft)	ML(kip-ft)	MD(kip-ft)
BEAM 1	1.00	998.62	236.90	297.50
BEAM 2	2.79	998.62	121.70	119.20
BEAM 3	2.28	998.62	144.50	137.00
BEAM 4	2.79	998.62	121.70	119.20
BEAM 5	1.00	998.62	236.90	297.50

PLOT

```
     BEAM # 1      1         6         11        16       21
Width
6.00
     BEAM # 2      2         7         12        17       22
Width
6.00
     BEAM # 3      3         8         13        18       23
Width
6.00
     BEAM # 4      4         9         14        19       24
Width
6.00
     BEAM # 5      5         10        15        20       25
                     Length    Length    Length    Length
                     10.00     10.00     10.00     10.00
```

DEFLECTIONS (inches)

# 1	0.000	-0.066	-0.096	-0.069	0.000
# 2	0.000	-0.129	-0.190	-0.140	0.000
# 3	0.000	-0.153	-0.225	-0.165	0.000
# 4	0.000	-0.129	-0.190	-0.140	0.000
# 5	0.000	-0.066	-0.096	-0.069	0.000

7.8 SEGMENTAL BOX BRIDGE

(Broward County, FDOT Bridge No. 860509)

Design Conditions

Four spans, continuous: Span 1 =60 ft.; Span 2 =126 ft.; Span 3 =172 ft.; Span 4 =102 ft.

Number of segments: Span 1 : 5; Span 2 : 11; Span 3 : 16; Span 4 : 9

FDOT204 live load - 2 lanes

Bridge layout and segment cross-section details are as per drawings in Figures 7.7 (a) through (d).

Materials

Precast concrete:

Normal weight

f'_c = 5500 psi

Prestressing steel:

Tendon Type 1: 9 - 0.6 in. diameter strands.

Tendon Type 2: 12 - 0.6 in. diameter strands.

Tendon Type 3: 1 in. diameter threaded bar.

All strands 270 ksi stress - relieved with 60% effective prestress.

Prestressing Steel Details

Prestressing is as per drawings in Figures 7.7 (e) and (f). Prestressing details at typical sections are given in the table below:

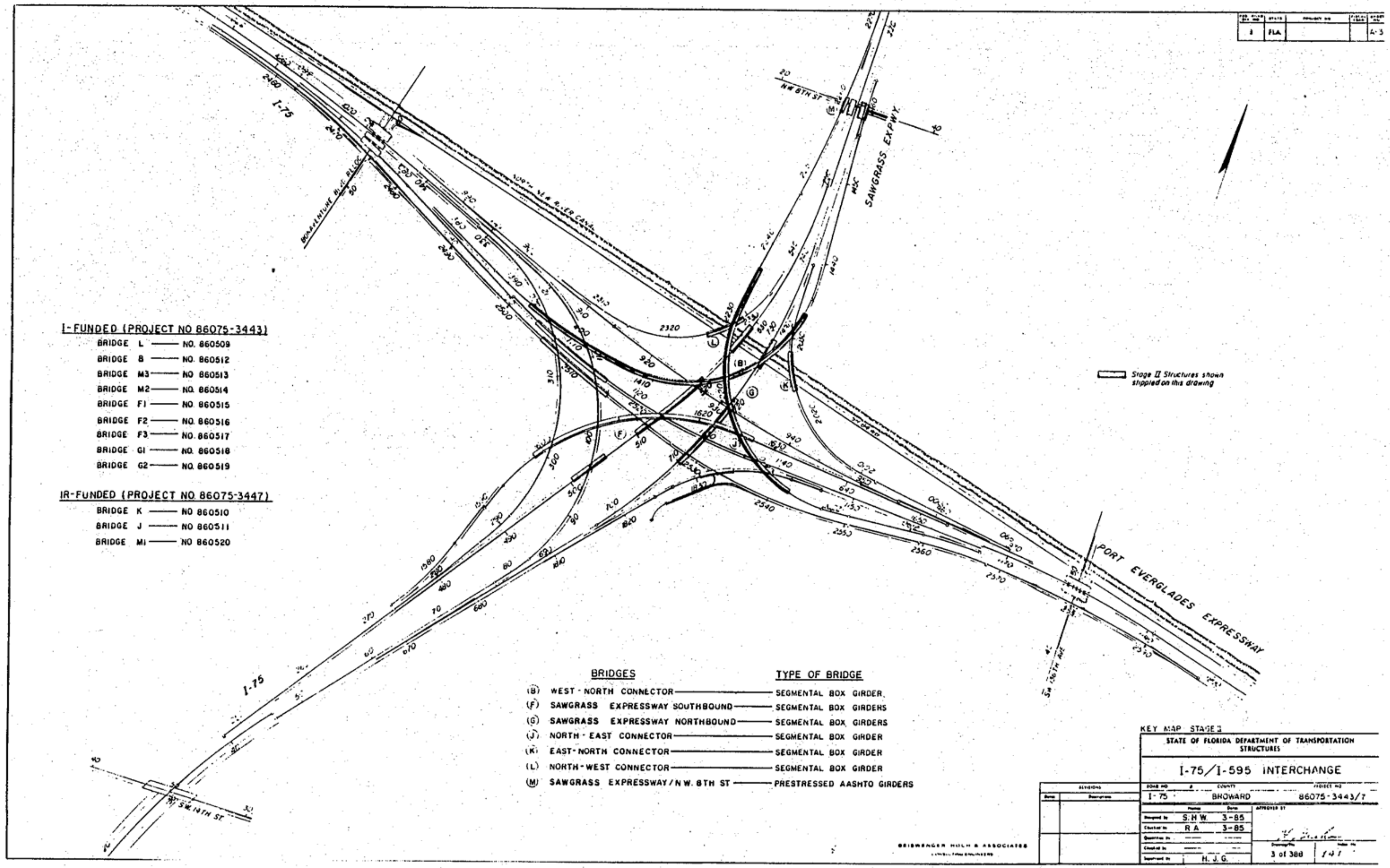


Figure 7.7 (a) Map showing the location of the segmental box bridge (FDOT bridge no. 860509)

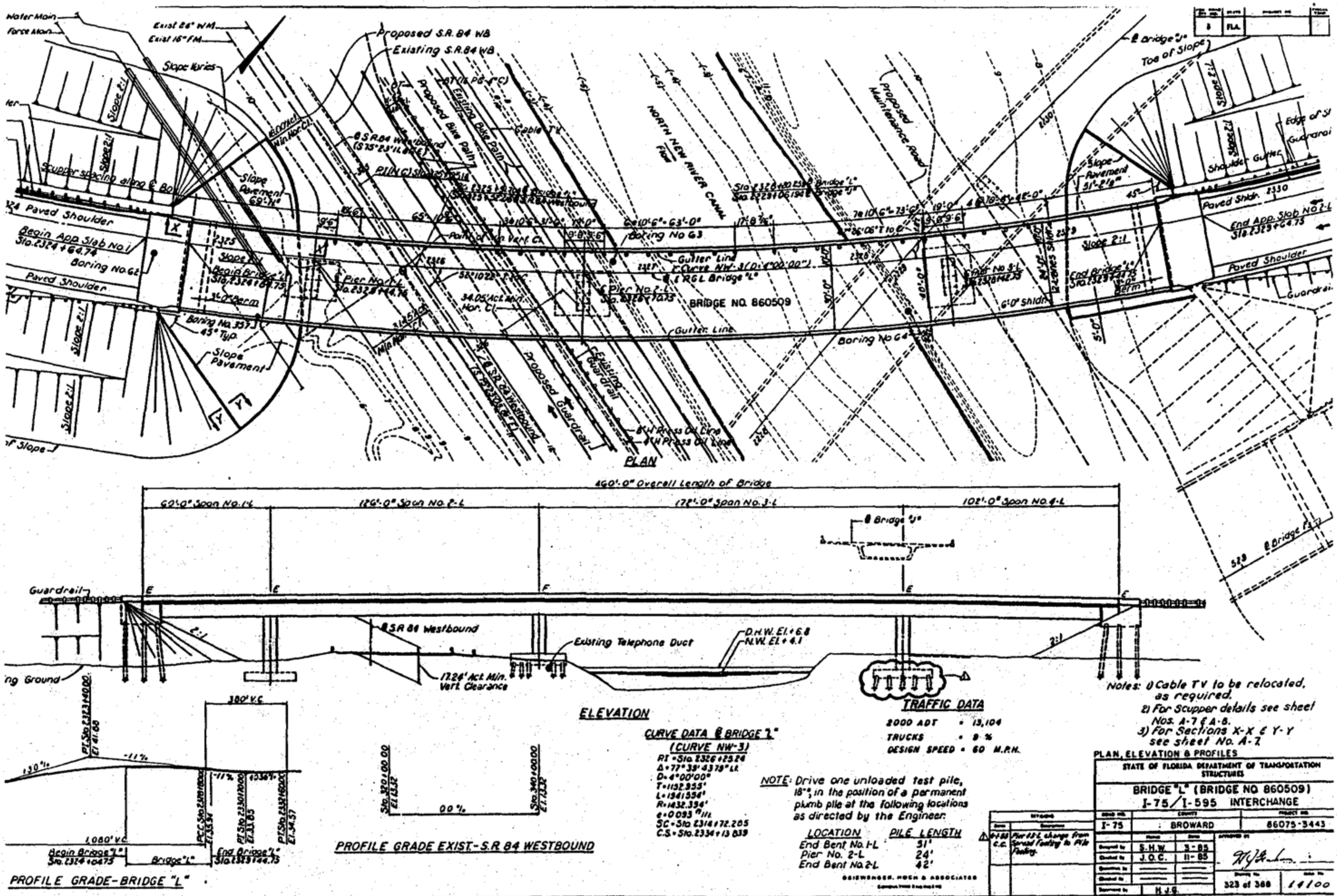
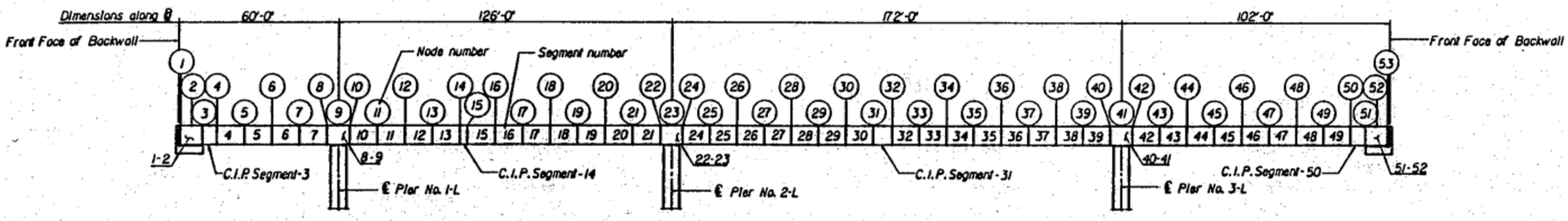
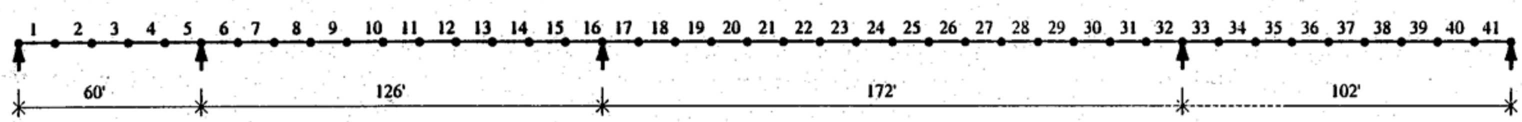


Figure 7.7 (b) Plan and elevation of the segmental box bridge



(i) Actual segment numbering for the bridge



(ii) Idealized bridge for computer analysis

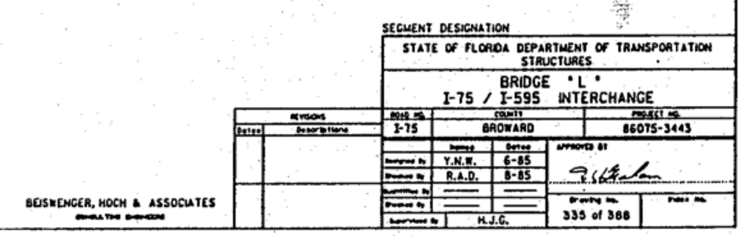


Figure 7.7 (c) Segment designations

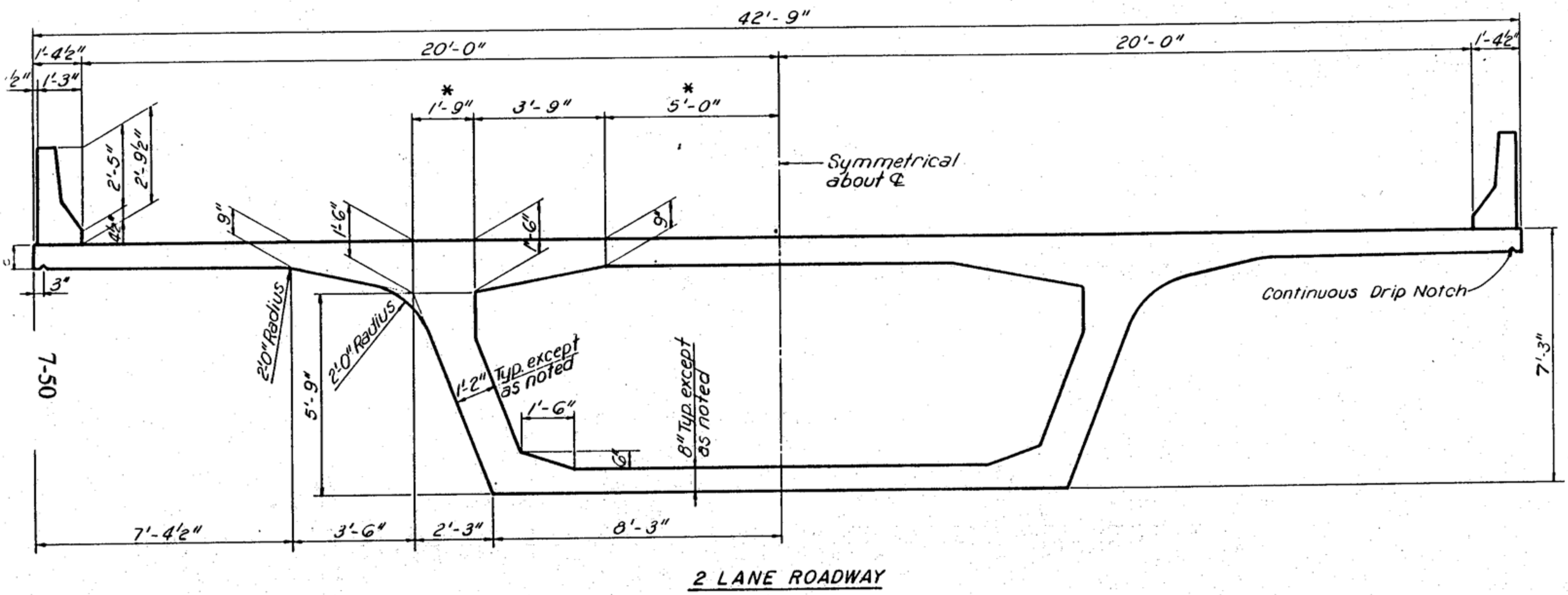


Figure 7.7 (d) Segmental box girder cross-section

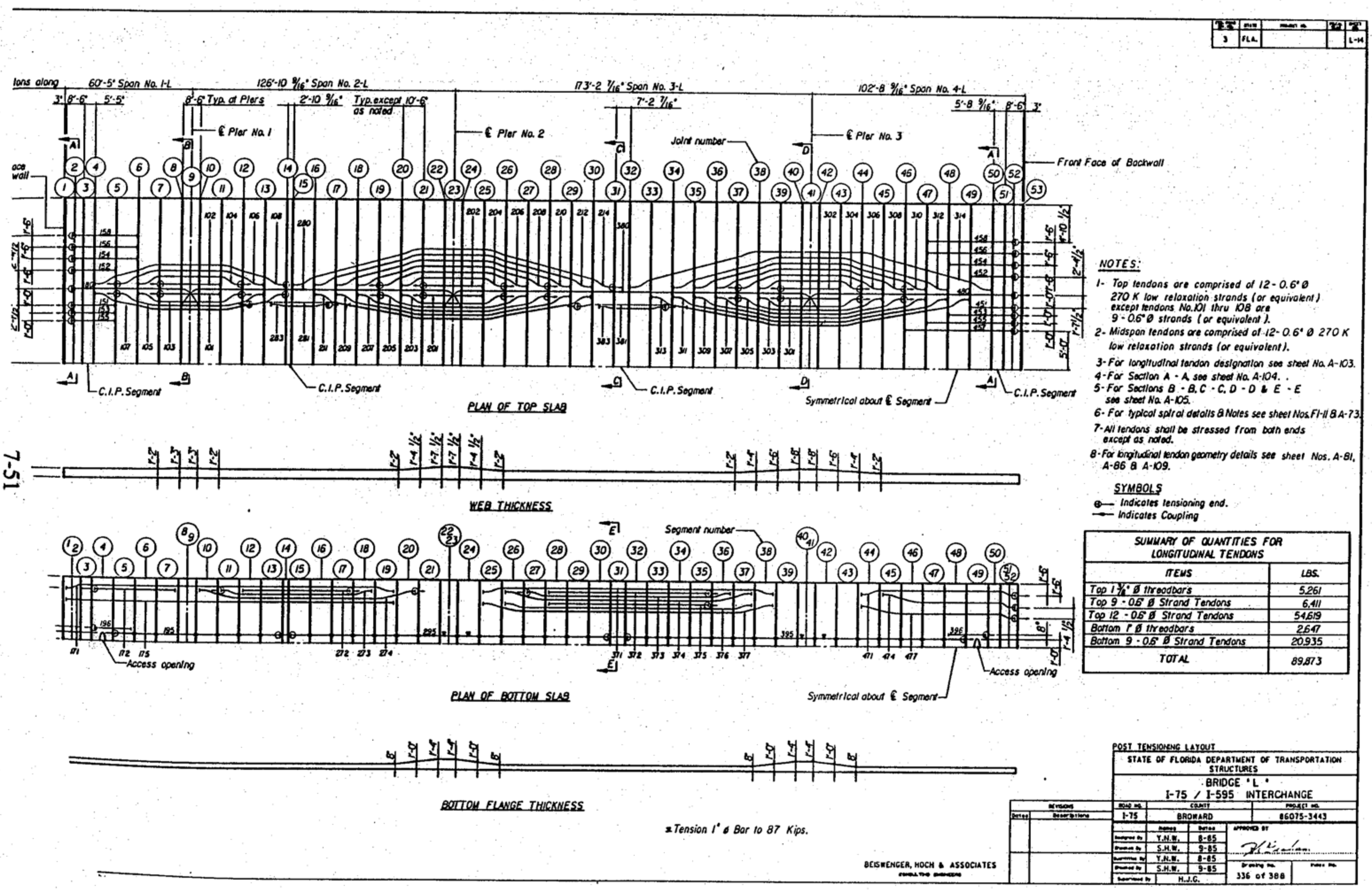


Figure 7.7 (e) Prestressing steel layout

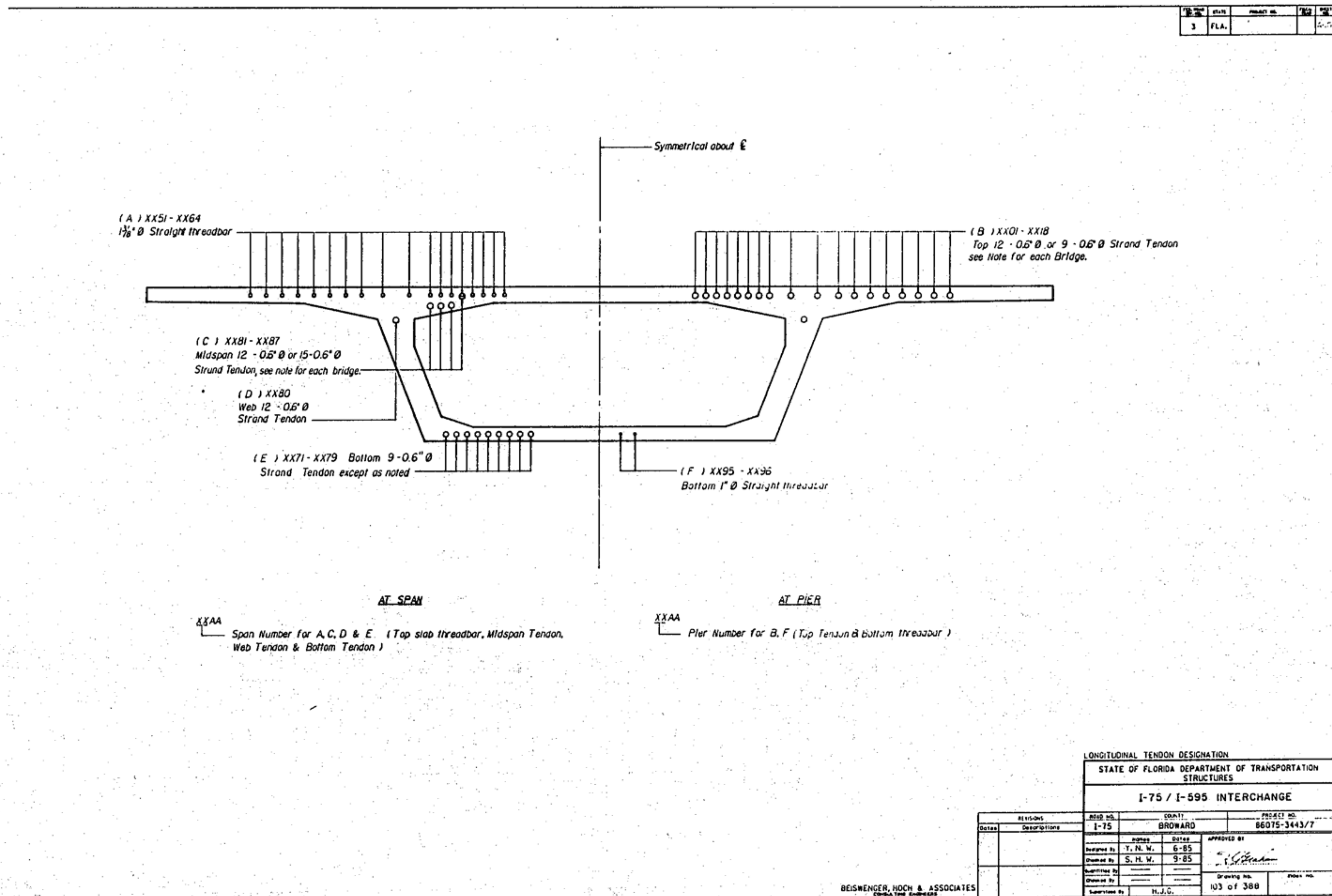


Figure 7.7 (f) Longitudinal tendon designation

Section from left support (ft)	No. of tendons	Prestressing steel type	Depth at which steel provided from compression flange (ft)
24	10	1	1.541
	6	1	6.920
	2	3	6.920
60	16	1	6.828
128	12	2	1.541
	10	1	6.920
	2	3	6.920
186	13	2	6.828
272	2	2	1.541
	14	2	6.920
358	28	2	6.828
414	18	2	1.541
	6	1	6.920
	2	3	6.920

Cantilever Construction Details

Construction sequence is specified in Figures 7.7 (g) and (h). The construction stages are tabulated below:

Day of segment erection	Erected segments (Suffix L: erected to the left of support R: erected to the right of support C: closure segment)
1	4L 5L 6R 7R
7	1C 2L 3L 8R 9R
14	15L 16L 17R 18R
21	13L 14L 19R 20R
28	10C 11L 12L 21R 22R
35	31L 32L 33R 34R
42	29L 30L 35R 36R
49	27L 28L 37R 38R
56	25L 26L 39R 40R 41C
63	23L 24L

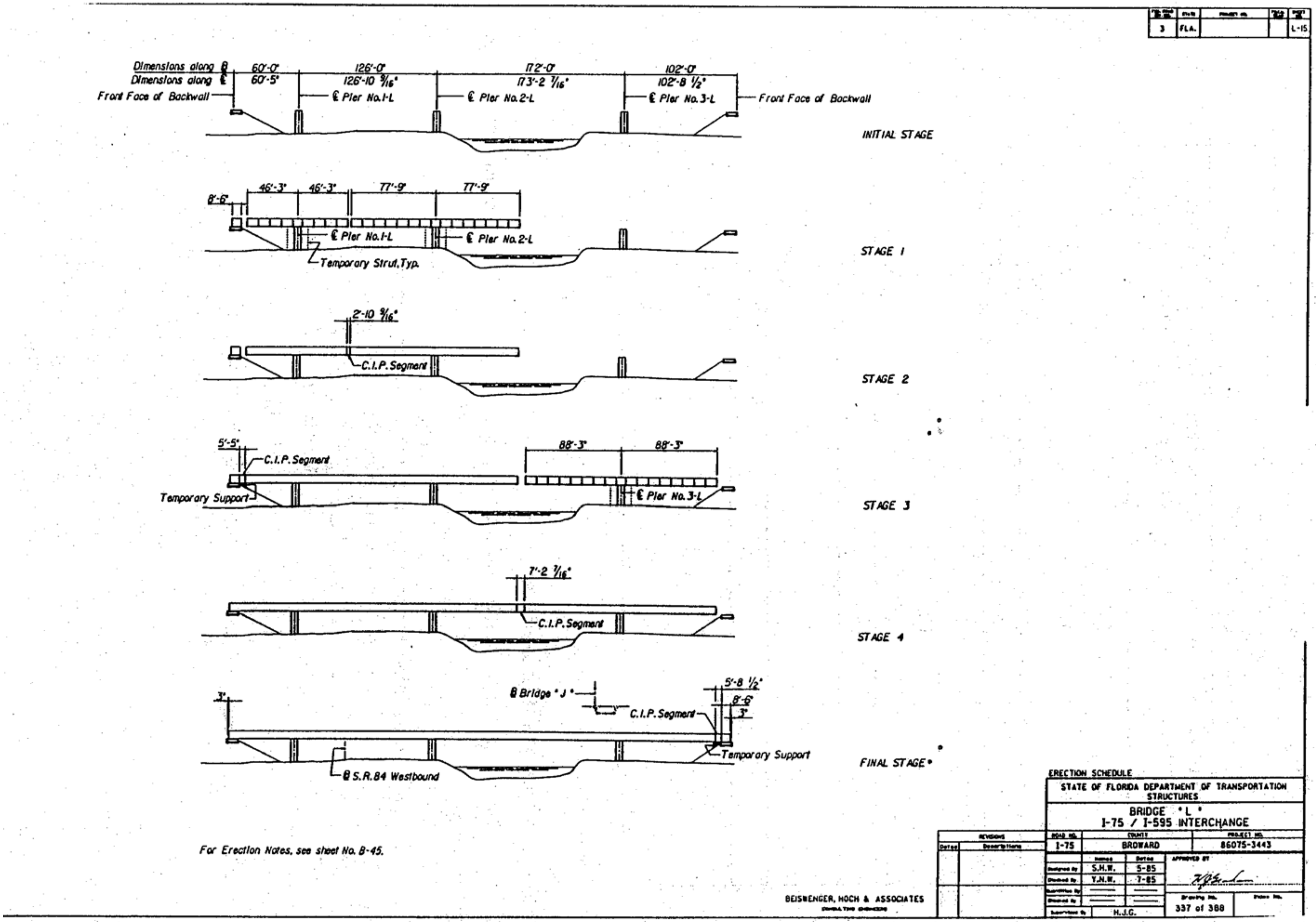


Figure 7.7 (g) Segment erection schedule

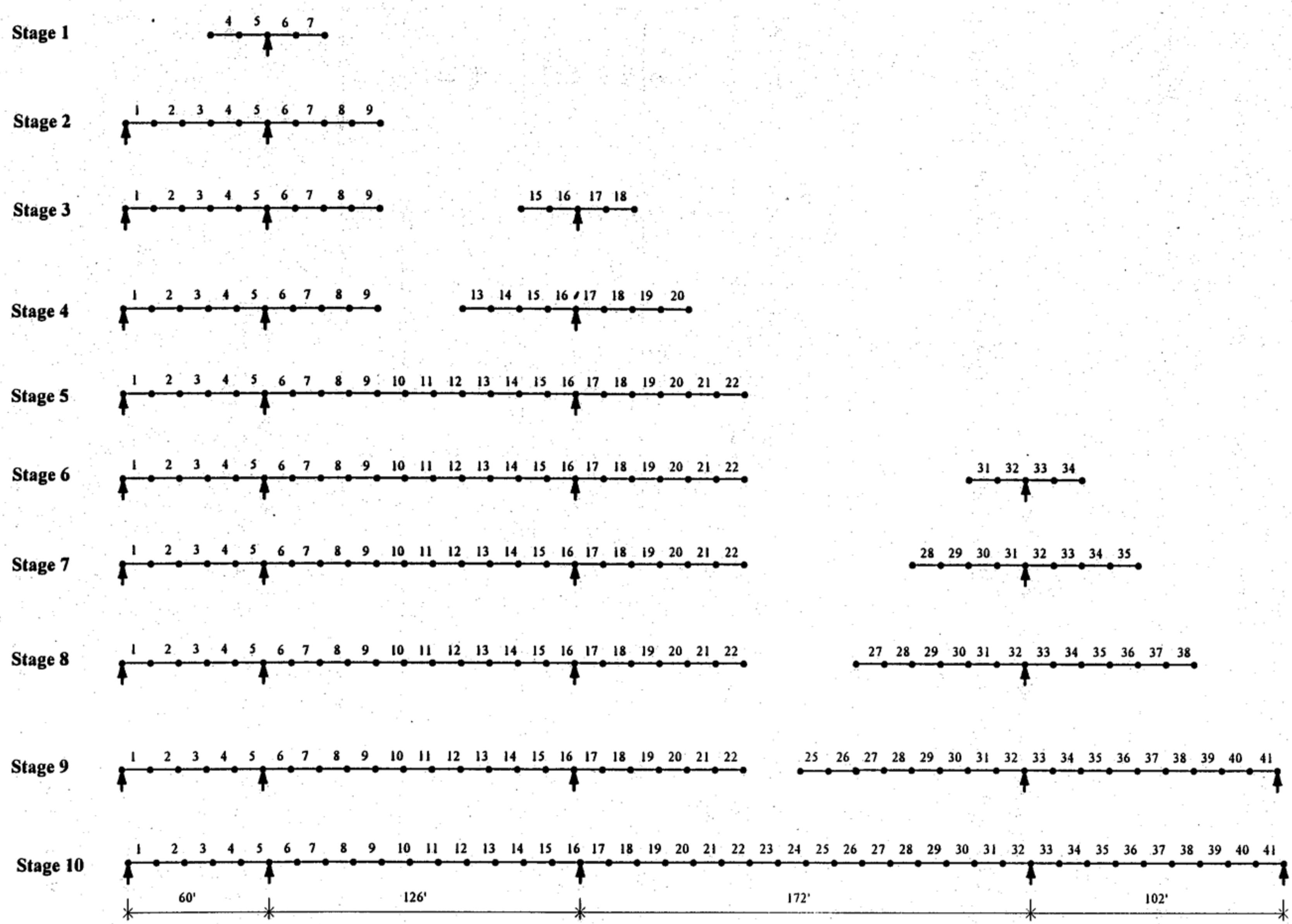


Figure 7.7 (h) Detailed construction sequence for computer analysis

Prestressing steel for cantilever construction:

Segments 1 through 9 :

Area of prestressing steel =7.74 in ^{2} provided @ 2ft. depth from top flange.

Segments 10 through 41 :

Area of prestressing steel =7.74 in ^{2} provided @ 2ft. depth from top flange.

Continuity Tendon Details

Span #	Construction stage in which spans made continuous	No. of tendons	Prestressing steel type	Depth at which steel provided from top flange (ft)	Starts to the left of segment #	Ends to the right of segment #
1	2	2	1	6.92	2	3
		2	1	6.92	2	5
		4	1	6.92	1	5
2	5	2	1	6.92	6	14
		2	1	6.92	8	12
		2	1	6.92	7	13
		4	1	6.92	6	15
3	10	4	1	6.92	18	31
		4	1	6.92	21	28
		4	1	6.92	19	30
		2	1	6.92	20	29
4	9	4	1	6.92	35	41
		2	1	6.92	36	41

Concrete Factors Required for Time-Dependent Analysis

Ultimate creep = 3.0

Aging coefficient = 0.80

Shrinkage = $-300\text{x}10^{-6}$

Tensile strength = $7.5\sqrt{f'_c}$

Age of the bridge = 5 years

OUTPUT FILE

FLORIDA DEPARTMENT OF TRANSPORTATION

Load Rating and Time-Dependent Stress Computation for Segmental Box Bridges

RATING SUMMARY:
================

```
Rating vehicle = HS20
Load and resistance factors: Live load factor,           LLF = 1.20
                             Dead load factor,           DLF = 1.60
                             Impact factor,              I   = 1.30
                             Capacity reduction factor,  PHI = 0.85

Number of spans in the bridge = 4
Number of lanes on the bridge = 2

Rating factor computation based on :
------------------------------------
(a) Operating rating = (PHI*MN - DLF*MD)/(I*LLF*ML)
(b) Inventory rating = (PHI*MN - DLF*MD)/(5/3)*(I*LLF*ML)

        where   MN: moment capacity
                ML: live load moment
                MD: dead load moment

+M : rating for maximum positive moment (near midspan).
-M : rating for maximum negative moment (over support).
 All distances are measured from the extreme left support to the front
axle of the truck.
 L : truck travelling in the left direction.
 R : truck travelling in the right direction.
```

Span#		Max.ML (kip-ft)	@dist (ft)	truck@ (ft)	Max.MD (kip-ft)	Mom.Capacity (kip-ft)	Oper.RF	Inv.RF
1	+M	1380.80	24	10L	1453.09	27185.33	9.65	5.79
	-M	-1978.00	60	91L	-7514.66	54769.11	11.19	6.71
2	+M	2512.00	128	114L	4522.73	42436.12	7.36	4.41
	-M	-2344.20	186	267R	-22688.72	59227.95	3.84	2.30
3	+M	3462.40	272	286R	15985.26	49461.30	3.05	1.83
	-M	-2374.20	358	276L	-21681.38	124106.04	19.12	11.47

4	+M	2614.40	414	428R	3621.59	30958.58	5.03	3.02
	-M	-2374.20	358	276L	-21681.38	124106.04	19.12	11.47
Rating at user defined section:								
3	+M	3462.40	272	286R	15985.26	49461.30	3.05	1.83
	-M	-411.59	272	156R	15985.26	49461.30	25.64	15.39

Live Load Stresses :

Span #	Section @ dist(ft)		Stresses (ksf) Top	Bottom
1	60.0	-M	4.962	-11.232
		+M	-1.992	4.509
	24.0	-M	1.985	-4.493
		+M	-3.463	7.840
2	186.0	-M	5.880	-13.311
		+M	-0.870	1.969
	128.7	-M	2.302	-5.211
		+M	-6.301	14.263
3	358.0	-M	5.955	-13.481
		+M	-0.945	2.138
	272.0	-M	1.032	-2.337
		+M	-8.685	19.660
4	358.0	-M	5.955	-13.481
		+M	-0.945	2.138
	414.7	-M	2.647	-5.992
		+M	-6.558	14.845
User defined node :				
5	272.0	-M	-1.032	2.337
		+M	8.685	-19.660

Stresses due to time-dependent forces and continuity of tendons:

[Tensile stresses are positive; Compressive stresses are negative]

Section #9 is the user defined section.

SECTION # : 1

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-4.390000e-005	2.865640e-013	0.000000e+000	0.000000e+000
2	4.784380e-005	-6.660380e-005	2.829160e+001	-6.808910e+001
3	-2.156170e-006	-6.660380e-005	2.829160e+001	-6.808910e+001
4	-5.215620e-005	-6.660380e-005	2.829160e+001	-6.808910e+001
5	-1.626580e-004	-5.469650e-005	1.809730e+001	-6.373760e+001
6	-2.126580e-004	-5.469650e-005	1.809730e+001	-6.373760e+001
7	-2.626580e-004	-5.469650e-005	1.809730e+001	-6.373760e+001
8	-3.126580e-004	-5.469650e-005	1.809730e+001	-6.373760e+001
9	-3.626580e-004	-5.469650e-005	1.809720e+001	-6.373760e+001
10	1.260400e-004	-2.087760e-004	5.888630e+001	-8.114840e+001

SECTION # : 2

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-1.807380e-004	1.818150e-005	-4.958100e+001	-1.819680e+000
2	-1.488960e-004	-1.039930e-004	-3.324570e+001	-1.622800e+002
3	-1.988960e-004	-1.039930e-004	-3.324570e+001	-1.622800e+002
4	-2.488960e-004	-1.039930e-004	-3.324570e+001	-1.622800e+002
5	-9.059600e-004	1.647380e-004	-1.355330e+002	6.371150e+001
6	-9.559600e-004	1.647380e-004	-1.355330e+002	6.371150e+001
7	-1.005960e-003	1.647380e-004	-1.355330e+002	6.371150e+001
8	-1.055960e-003	1.647380e-004	-1.355330e+002	6.371150e+001
9	-1.105960e-003	1.647380e-004	-1.355330e+002	6.371150e+001
10	-3.075080e-004	-1.348920e-004	-7.860580e+001	7.460970e+000

SECTION # : 3

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-1.842380e-004	1.982620e-005	-5.084930e+001	1.232610e+000
2	-3.586570e-004	-5.428640e-006	-7.568280e+001	-6.014660e+001
3	-4.086570e-004	-5.428640e-006	-7.568280e+001	-6.014660e+001
4	-4.586570e-004	-5.428640e-006	-7.568280e+001	-6.014660e+001
5	-8.638610e-004	1.449560e-004	-1.355330e+002	6.371150e+001
6	-9.138610e-004	1.449560e-004	-1.355330e+002	6.371150e+001
7	-9.638610e-004	1.449560e-004	-1.355330e+002	6.371150e+001
8	-1.013860e-003	1.449560e-004	-1.355330e+002	6.371150e+001
9	-1.063860e-003	1.449560e-004	-1.355330e+002	6.371150e+001
10	-2.654090e-004	-1.546740e-004	-7.860580e+001	7.460950e+000

SECTION # : 4

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-4.390000e-005	2.865640e-013	0.000000e+000	0.000000e+000
2	-9.390000e-005	1.417850e-012	-1.377900e-006	0.000000e+000
3	-5.340270e-004	6.281840e-005	-7.212640e+001	1.207380e+001
4	-8.470040e-004	5.934080e-005	-1.182390e+002	-3.845970e+001
5	-1.099120e-003	2.209710e-005	-1.522940e+002	-1.180110e+002
6	-1.149120e-003	2.209710e-005	-1.522940e+002	-1.180110e+002
7	-1.199120e-003	2.209710e-005	-1.522940e+002	-1.180110e+002
8	-1.249120e-003	2.209710e-005	-1.522940e+002	-1.180110e+002
9	-1.299120e-003	2.209710e-005	-1.522940e+002	-1.180110e+002

10	-1.724930e-003	2.977360e-004	-1.591510e+002	-2.075280e+001

SECTION # : 5

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-4.390000e-005	2.865640e-013	0.000000e+000	0.000000e+000
2	-9.390000e-005	1.417850e-012	-1.377900e-006	0.000000e+000
3	-5.424150e-004	6.676000e-005	-7.367730e+001	1.580630e+001
4	-8.819250e-004	7.574990e-005	-1.244420e+002	-2.353020e+001
5	-1.097220e-003	2.120660e-005	-1.522940e+002	-1.180120e+002
6	-1.147220e-003	2.120660e-005	-1.522940e+002	-1.180120e+002
7	-1.197220e-003	2.120660e-005	-1.522940e+002	-1.180120e+002
8	-1.247220e-003	2.120660e-005	-1.522940e+002	-1.180120e+002
9	-1.297220e-003	2.120660e-005	-1.522940e+002	-1.180120e+002
10	-1.723040e-003	2.968460e-004	-1.591510e+002	-2.075280e+001

SECTION # : 6

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-4.390000e-005	2.865640e-013	0.000000e+000	0.000000e+000
2	-9.390000e-005	1.417850e-012	-1.377900e-006	0.000000e+000
3	-1.439000e-004	1.586260e-012	-2.150400e-006	0.000000e+000
4	-1.939000e-004	1.345670e-012	-1.687870e-006	0.000000e+000
5	-2.439000e-004	2.103140e-012	-2.669270e-006	0.000000e+000
6	-7.452150e-004	7.560510e-005	-7.367730e+001	1.580620e+001
7	-1.114360e-003	8.551570e-005	-1.244420e+002	-2.352990e+001
8	-1.343350e-003	2.646380e-005	-1.522960e+002	-1.180080e+002
9	-1.425710e-003	-1.042010e-004	-1.572380e+002	-2.676260e+002
10	-4.175240e-003	1.049530e-003	-2.851610e+002	4.024520e+001

SECTION # : 7

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-4.390000e-005	2.865640e-013	0.000000e+000	0.000000e+000
2	-9.390000e-005	1.417850e-012	-1.377900e-006	0.000000e+000
3	-1.439000e-004	1.586260e-012	-2.150400e-006	0.000000e+000
4	-1.939000e-004	1.345670e-012	-1.687870e-006	0.000000e+000
5	-2.439000e-004	2.103140e-012	-2.669270e-006	0.000000e+000
6	-7.373920e-004	7.192940e-005	-7.240020e+001	1.273280e+001
7	-1.082460e-003	7.052240e-005	-1.193340e+002	-3.582380e+001
8	-1.270430e-003	-7.800600e-006	-1.408050e+002	-1.456620e+002
9	-1.428030e-003	-1.031120e-004	-1.572380e+002	-2.676260e+002
10	-4.177560e-003	1.050620e-003	-2.851610e+002	4.024530e+001

SECTION # : 8

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-4.390000e-005	2.865640e-013	0.000000e+000	0.000000e+000
2	-9.390000e-005	1.417850e-012	-1.377900e-006	0.000000e+000
3	-1.439000e-004	1.586260e-012	-2.150400e-006	0.000000e+000
4	-1.939000e-004	1.345670e-012	-1.687870e-006	0.000000e+000
5	-2.439000e-004	2.103140e-012	-2.669270e-006	0.000000e+000
6	-2.939000e-004	2.721630e-012	-3.781020e-006	0.000000e+000
7	-3.439000e-004	3.457770e-012	-4.552170e-006	0.000000e+000

```
    8  -3.939000e-004   4.804700e-012   -5.481060e-006   0.000000e+000
    9  -1.660250e-004  -1.305700e-004   4.243720e+001   -1.021340e+002
   10  -4.602270e-004  -1.305700e-004   4.243720e+001   -1.021330e+002
```

SECTION # : 9

```
STAGE #     Strain          Curvature        Stress(Top)      Stress(Bottom)
    1  -4.390000e-005   2.865640e-013   0.000000e+000    0.000000e+000
    2  -9.390000e-005   1.417850e-012  -1.377900e-006    0.000000e+000
    3  -1.439000e-004   1.586260e-012  -2.150400e-006    0.000000e+000
    4  -1.939000e-004   1.345670e-012  -1.687870e-006    0.000000e+000
    5  -2.439000e-004   2.103140e-012  -2.669270e-006    0.000000e+000
    6  -2.939000e-004   2.721630e-012  -3.781020e-006    0.000000e+000
    7  -3.439000e-004   3.457770e-012  -4.552170e-006    0.000000e+000
    8  -3.939000e-004   4.804700e-012  -5.481060e-006    0.000000e+000
    9  -4.439000e-004   5.945880e-012  -6.950410e-006    0.000000e+000
   10  -1.308990e-003   2.682550e-004  -2.974330e+001    7.158310e+001
```

Service Load Stresses :
=======================

```
----------------------------------------------------
  Section                   Stresses (ksf)
@ dist(ft)                Top            Bottom
----------------------------------------------------
   60.0     -M          -73.644          -3.771
            +M          -80.598          11.970

  186.0     -M         -153.271         -34.064
            +M         -160.021         -18.784

  358.0     -M         -279.206          26.764
            +M         -286.106          42.383

  358.0     -M         -279.206          26.764
            +M         -286.106          42.383

User defined node :
  272.0     -M          -28.711          69.246
            +M          -38.428          91.243

----------------------------------------------------

Permissible Tensile Stress(ksf) = 3 * sqrt(f'c) =      32.038

Permissible Compressive Stress(ksf) = 0.4 * f'c =    316.800

Section at   272.0ft exceeds the allowable tensile stress
Section at   358.0ft exceeds the allowable tensile stress

[END OF FILE]
```

7.9 SEGMENTAL BOX BRIDGE

Design Conditions

Two spans, continuous: Span 1 =50 ft.; Span 2 =50 ft

Number of segments: Span 1 : 5; Span 2 : 5

Rating to be performed for FDOT204 and HS20 live loads - 2 lanes.

Segment cross-section is as per drawing shown in Figure 7.7 (d). Segment designations are given in Figure 7.8 (a).

Materials

Precast concrete:

Normal weight

f'_c = 5500 psi

Prestressing steel:

Tendon Type 1: 9 - 0.6 in. diameter strands.

Tendon Type 2: 12 - 0.6 in. diameter strands.

Tendon Type 3: 1 in. diameter threaded bar.

All strands 270 ksi stress - relieved with 60% effective prestress.

Prestressing Steel Details

Prestressing is the same as in span 1 in the drawing shown in Figures 7.7(e). Prestressing details at typical sections are given in the table below:

Section from left support (ft)	No. of tendons	Prestressing steel type	Depth at which steel provided from compression flange (ft)
20	14	1	1.541
	6	1	6.920
	2	3	6.920
50	16	1	6.828
80	12	2	1.541
	10	1	6.920
	2	3	6.920

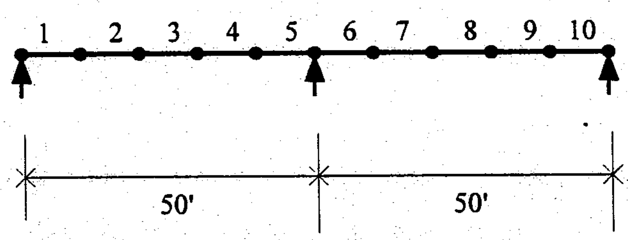


Figure 7.8 (a) Segment designations

Cantilever Construction Details

Construction sequence is specified in Figure 7.8(b). The construction stages are tabulated below:

Day of segment erection	Erected segments (Suffix L: erected to the left of support R: erected to the right of `support C: closure segment)
1	5L 6R
3	4L 7R
5	3L 8R
7	2L 9R
9	1C 10C

Prestressing steel for cantilever construction:

Segments 1 through 10 : Area of prestressing steel =7.74 in^2 provided @ 2ft. depth from top flange.

Continuity Tendon Details

Spans are made continuous as soon as they are completed. All continuity tendons have a straight profile with uniform eccentricity.

Span #	Construction stage in which spans made continuous	No. of tendons	Prestressing steel type	Depth at which steel provided from top flange (ft)	Starts to the left of segment #	Ends to the right of segment #
1	5	2	1	6.92	2	3
		2	1	6.92	2	5
		4	1	6.92	1	5
2	5	2	1	6.92	8	9
		2	1	6.92	6	9
		4	1	6.92	6	10

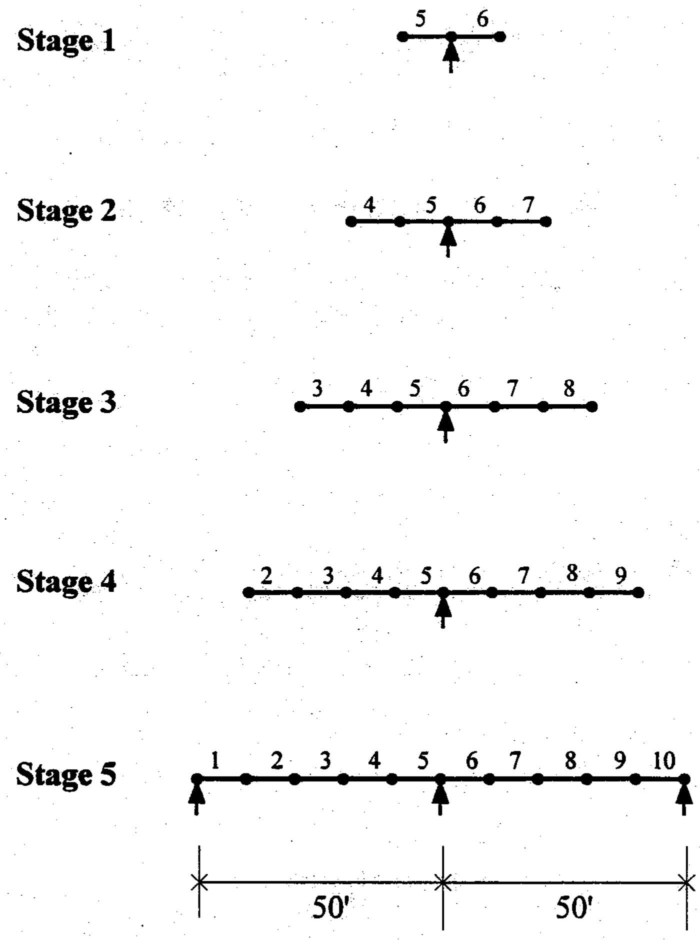


Figure 7.8 (b) Detailed construction sequence for computer analysis

Concrete Factors Required for Time-Dependent Analysis

Ultimate creep	=	3.0
Aging coefficient	=	0.80
Shrinkage	=	-300×10^{-6}
Tensile strength	=	$7.5\sqrt{f'_c}$
Age of the bridge	=	5 years

OUTPUT FILE FOR RATING WITH FDOT204 TRUCK

```
                          FLORIDA DEPARTMENT OF TRANSPORTATION

                    Load Rating and Time-Dependent Stress Computation
                                 for Segmental Box Bridges


RATING SUMMARY:
===============

Rating vehicle = FDOT204
Load and resistance factors: Live load factor,             LLF = 1.20
                             Dead load factor,             DLF = 1.60
                             Impact factor,                I   = 1.30
                             Capacity reduction factor,    PHI = 0.85

Number of spans in the bridge = 2
Number of lanes on the bridge = 2

Rating factor computation based on :
------------------------------------
(a) Operating rating = (PHI*MN - DLF*MD)/(I*LLF*ML)
(b) Inventory rating = (PHI*MN - DLF*MD)/(5/3)*(I*LLF*ML)

        where   MN: moment capacity
                ML: live load moment
                MD: dead load moment

+M : rating for maximum positive moment (near midspan).
-M : rating for maximum negative moment (over support).
 All distances are measured from the extreme left support to the front
axle of the truck.
 L : truck travelling in the left direction.
 R : truck travelling in the right direction.
```

Span#		Max.ML (kip-ft)	@dist (ft)	truck@ (ft)	Max.MD (kip-ft)	Mom.Capacity (kip-ft)	Oper.RF	Inv.RF
1	+M	2326.20	20	62L	1857.96	27185.33	5.5	4.06
	-M	-1618.80	50	77R	-3096.60	54769.11	16.47	9.88
2	+M	2326.20	80	38R	1857.96	42436.12	9.12	5.47
	-M	-1618.80	50	77R	-3096.60	54769.11	16.47	9.88

Live Load Stresses :

Span #	Section @ dist(ft)		Stresses (ksf) Top	Bottom
1	50.0	-M	4.061	-9.192
		+M	0.000	0.000
	20.0	-M	1.310	-2.966
		+M	-5.835	13.209
2	50.0	-M	4.061	-9.192
		+M	0.000	0.000
	80.0	-M	1.310	-2.966
		+M	-5.835	13.209

Stresses due to time-dependent forces and continuity of tendons:

[Tensile stresses are positive; Compressive stresses are negative]

SECTION # : 1

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-1.622000e-005	8.748990e-013	-1.727510e-006	1.206480e-006
2	-3.244000e-005	1.245310e-012	-2.540550e-006	1.251090e-006
3	-4.866000e-005	1.622980e-012	-2.937840e-006	1.674150e-006
4	-6.488000e-005	1.398640e-012	-2.773500e-006	1.374040e-006
5	1.845760e-004	-2.555050e-004	2.829140e+001	-6.808890e+001

SECTION # : 2

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-8.370970e-005	1.256580e-005	-2.944980e+001	1.030360e+001
2	-1.812270e-004	2.303510e-005	-5.394290e+001	8.677980e+000
3	-2.665690e-004	2.595420e-005	-7.347940e+001	-4.876720e+000

```
    4  -3.369130e-004  2.037100e-005   -8.805920e+001   -3.036050e+001
    5  -1.328880e-003  3.481970e-004   -1.243590e+002   5.700100e+001
```

SECTION # : 3

```
STAGE #     Strain          Curvature          Stress(Top)       Stress(Bottom)
    1  -8.370970e-005  1.256580e-005   -2.944980e+001   1.030360e+001
    2  -1.812270e-004  2.303510e-005   -5.394290e+001   8.677980e+000
    3  -2.665690e-004  2.595420e-005   -7.347930e+001   -4.876840e+000
    4  -3.369120e-004  2.037050e-005   -8.805890e+001   -3.036130e+001
    5  -1.328890e-003  3.482000e-004   -1.243590e+002   5.700100e+001
```

SECTION # : 4

```
STAGE #     Strain          Curvature          Stress(Top)       Stress(Bottom)
    1  -1.622000e-005  8.748990e-013   -1.727510e-006   1.206480e-006
    2  -3.244000e-005  1.245310e-012   -2.540550e-006   1.251090e-006
    3  -4.866000e-005  1.622980e-012   -2.937840e-006   1.674150e-006
    4  -6.488000e-005  1.398640e-012   -2.773500e-006   1.374040e-006
    5  -3.591800e-004  -5.414370e-011  4.131110e-006    -1.408570e-005
```

Service Load Stresses :

```
---------------------------------------------------------
  Section                        Stresses (ksf)
@ dist(ft)                    Top              Bottom
---------------------------------------------------------
     50.0 -M               -122.933            53.774
          +M               -124.359            57.001

     50.0 -M               -122.933            53.774
          +M               -124.359            57.001
---------------------------------------------------------
```

Permissible Tensile Stress(ksf) = 3 * sqrt(f'c) = 32.038

Permissible Compressive Stress(ksf) = 0.4 * f'c = 316.800

Section at 50.0ft exceeds the allowable tensile stress
Section at 50.0ft exceeds the allowable tensile stress
Section at 50.0ft exceeds the allowable tensile stress
Section at 50.0ft exceeds the allowable tensile stress

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OUTPUT FILE FOR RATING WITH HS20 TRUCK

FLORIDA DEPARTMENT OF TRANSPORTATION

Load Rating and Time-Dependent Stress Computation for Segmental Box Bridges

RATING SUMMARY:

```
Rating vehicle = HS20
Load and resistance factors: Live load factor,            LLF = 1.20
                             Dead load factor,            DLF = 1.60
                             Impact factor,               I   = 1.30
                             Capacity reduction factor,   PHI = 0.85

Number of spans in the bridge = 2
Number of lanes on the bridge = 2

Rating factor computation based on :
------------------------------------
(a) Operating rating = (PHI*MN - DLF*MD)/(I*LLF*ML)
(b) Inventory rating = (PHI*MN - DLF*MD)/(5/3)*(I*LLF*ML)

        where   MN: moment capacity
                ML: live load moment
                MD: dead load moment

+M : rating for maximum positive moment (near midspan).
-M : rating for maximum negative moment (over support).
 All distances are measured from the extreme left support to the front
axle of the truck.
 L : truck travelling in the left direction.
 R : truck travelling in the right direction.
```

Span#		Max.ML (kip-ft)	@dist (ft)	truck@ (ft)	Max.MD (kip-ft)	Mom.Capacity (kip-ft)	Oper.RF	Inv.RF
1	+M	1007.80	20	6L	1857.96	27185.33	12.81	7.68
	-M	-568.40	50	90R	-3096.60	54769.11	46.91	28.15
2	+M	1007.80	80	94R	1857.96	42436.12	21.05	12.63
	-M	-568.40	50	90R	-3096.60	54769.11	46.91	28.15

Live Load Stresses :

Span #	Section @ dist(ft)		Stresses (ksf) Top	Bottom
1	50.0	-M	1.426	-3.227
		+M	0.000	0.000
	20.0	-M	0.570	-1.291
		+M	-2.528	5.723
2	50.0	-M	1.426	-3.227
		+M	0.000	0.000
	80.0	-M	0.570	-1.291
		+M	-2.528	5.723

Stresses due to time-dependent forces and continuity of tendons:

[Tensile stresses are positive; Compressive stresses are negative]

SECTION # : 1

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-1.622000e-005	8.748990e-013	-1.727510e-006	1.206480e-006
2	-3.244000e-005	1.245310e-012	-2.540550e-006	1.251090e-006
3	-4.866000e-005	1.622980e-012	-2.937840e-006	1.674150e-006
4	-6.488000e-005	1.398640e-012	-2.773500e-006	1.374040e-006
5	1.845760e-004	-2.555050e-004	2.829140e+001	-6.808890e+001

SECTION # : 2

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-8.370970e-005	1.256580e-005	-2.944980e+001	1.030360e+001
2	-1.812270e-004	2.303510e-005	-5.394290e+001	8.677980e+000
3	-2.665690e-004	2.595420e-005	-7.347940e+001	-4.876720e+000
4	-3.369130e-004	2.037100e-005	-8.805920e+001	-3.036050e+001
5	-1.328880e-003	3.481970e-004	-1.243590e+002	5.700100e+001

SECTION # : 3

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-8.370970e-005	1.256580e-005	-2.944980e+001	1.030360e+001
2	-1.812270e-004	2.303510e-005	-5.394290e+001	8.677980e+000
3	-2.665690e-004	2.595420e-005	-7.347930e+001	-4.876840e+000
4	-3.369120e-004	2.037050e-005	-8.805890e+001	-3.036130e+001
5	-1.328890e-003	3.482000e-004	-1.243590e+002	5.700100e+001

SECTION # : 4

STAGE #	Strain	Curvature	Stress(Top)	Stress(Bottom)
1	-1.622000e-005	8.748990e-013	-1.727510e-006	1.206480e-006
2	-3.244000e-005	1.245310e-012	-2.540550e-006	1.251090e-006
3	-4.866000e-005	1.622980e-012	-2.937840e-006	1.674150e-006
4	-6.488000e-005	1.398640e-012	-2.773500e-006	1.374040e-006
5	-3.591800e-004	-5.414370e-011	4.131110e-006	-1.408570e-005

Service Load Stresses :

Section @ dist(ft)		Stresses (ksf) Top	Bottom
50.0	-M	-122.933	53.774
	+M	-124.359	57.001
50.0	-M	-122.933	53.774
	+M	-124.359	57.001

Permissible Tensile Stress(ksf) = 3 * sqrt(f'c) = 32.038

Permissible Compressive Stress(ksf) = 0.4 * f'c = 316.800

Section at 50.0ft exceeds the allowable tensile stress
Section at 50.0ft exceeds the allowable tensile stress
Section at 50.0ft exceeds the allowable tensile stress
Section at 50.0ft exceeds the allowable tensile stress

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CHAPTER 8

CONCLUSIONS

8.1 CONCLUSIONS

The expert system REX developed in this project provides a prototype model for bridge rating. The development of REX system has been made in two phases. During the first phase, the system REX-1 was developed to include solid slab, voided slab AASHTO girder and slab and T-beam bridges. The segmental box bridge rating and time-dependent stresses were included in the system REX-2 during the second phase development. The-system is designed to be user-friendly and requires minimal computer knowledge it is entirely menu driven and easily workable. It enables the novice to analyze and evaluate the load carrying capacity of a highway bridge successfully. The tedious and mistake prone task of bridge idealization and calculation of the corresponding section properties has been automated. Mundane tasks such as the processing of large outputs and calculation of the rating factors are now performed by the computer.

The database containing a wide array of data pertaining to standard bridge cross sections, such as AASHTO girders, voided slab units, etc., can be updated with additional cross sections. The knowledge base can be readily accessed and modified as bridge codes and expertise change and as more bridge types are added to the system. A rule-based module interprets the user input and computes the reliability-based load factors. These factors are intended to represent conditions - existing based on field data obtained from a variety of locations using weigh-in-motion-and other data gathering methods. Furthermore, utilizing the grillage analogy based on space frame idealization eliminated the need for distribution factors in determining the live load effect.

Illustrative examples for typical bridge types are shown demonstrating the use of the expert system REX.

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