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Design Manual for Strengthening of Continuous-Span Composite Bridges

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ABSTRACT

The need for upgrading a large number of understrength bridges in the United States has been well documented in the literature. This manual presents two methods for strengthening continuous-span composite bridges: post-tensioning of the positive moment regions of the bridge stringers and the addition of superimposed trusses at the piers. The use of these two systems is an efficient method of reducing flexural overstresses in undercapacity bridges. Before strengthening a given bridge however, other deficiencies (inadequate shear connection, fatigue problems, extensive corrosion) should be addressed.

Since continuous-span composite bridges are indeterminant structures, there is longitudinal and transverse distribution of the strengthening axial forces and moments. This manual basically provides the engineer with a procedure for determining the distribution of strengthening forces and moments throughout the bridge. As a result of the longitudinal and transverse force distribution, the design methdology presented in this manual for continuous-span composite bridges is extremely complex. To simplify the procedure, a spreadsheet has been developed for use by practicing engineers. This design aid greatly simplifies the design of a strengthening system for a given bridge in that it eliminates numerous tedious hand calculations, computes the required force and moment fractions, and performs the necessary iterations for determining the required strengthening forces. The force and moment distribution fraction formulas developed in this manual are primarily for the Iowa DOT V12 and V14 three-span four-stringer bridges. These formulas may be used on other bridges if they are within the limits stated in this manual. Use of the distribution fraction formulas for bridges not within the stated limits is not recommended.

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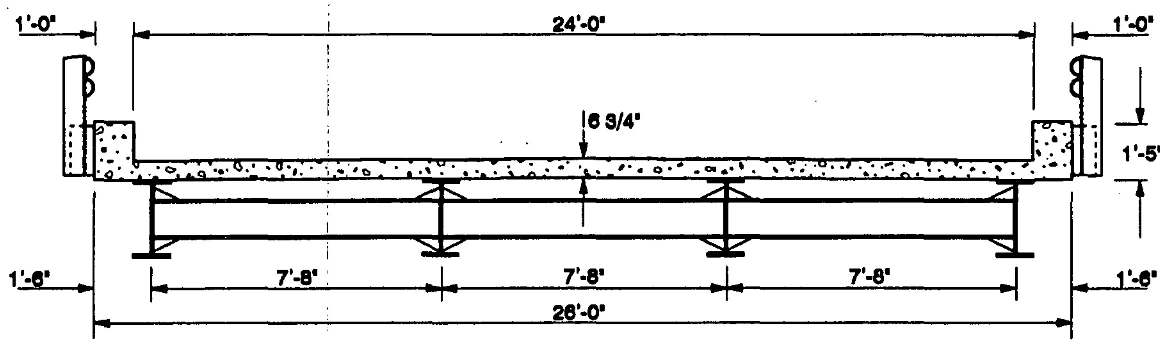
1. INTRODUCTION

1.1. Background

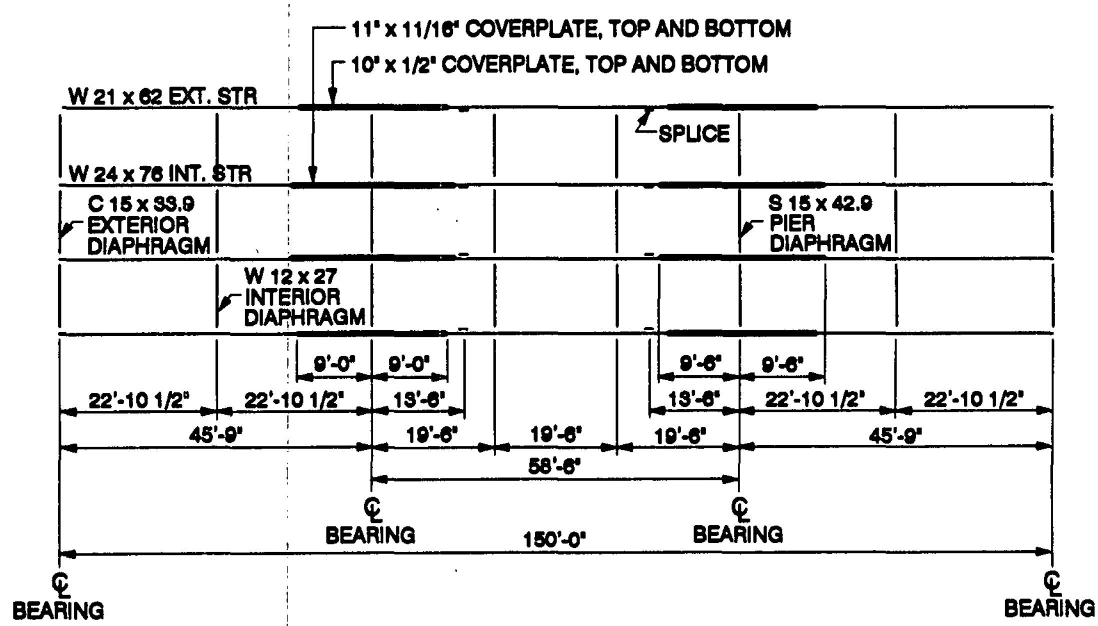
Based on current bridge rating standards, a considerable number of continuous-span composite bridges in the state of Iowa are classified as deficient and in need of rehabilitation or replacement. The change in the AASHO Specifications concerning the wheel-load-distribution fractions in 1957 [1], has increased the wheel-load-distribution fractions for exterior stringers. In 1980, the Iowa state legislature passed legislation which significantly increased the legal loads in the state. This increase in legal loads widened the gap between the rated strength of the older composite bridges with small exterior stringers and current rating standards. To help alleviate these problems, strengthening can often be used as a cost-effective alternative to replacement or posting.

Most Iowa bridges designed prior to 1957 are understrength due to excessive flexural stresses in the steel stringers. However, shear connectors and other parts of the bridge may also be inadequate. In the flexurally overstressed bridges, the exterior stringers are smaller than the interior stringers and thus the overstress is larger in the exterior stringers. Details of a typical Iowa continuous-span composite bridge are shown in Fig. 1.1. For bridges with flexural overstresses, it is logical to strengthen the overstressed stringers to avoid embargoes or costly early replacement of the bridges.

Post-tensioning is an accepted strengthening method for composite bridges in California [2]. The authors have post-tensioned and monitored two single-span composite bridges as described in Refs. 3 and 4. Numerous single-span composite bridges have been strengthened in Iowa and several other states utilizing the design methodology [5] that was developed for these bridges.



a. BRIDGE SECTION



b. BRIDGE FRAMING PLAN

Fig. 1.1. General layout of a typical Iowa continuous-span composite bridge.

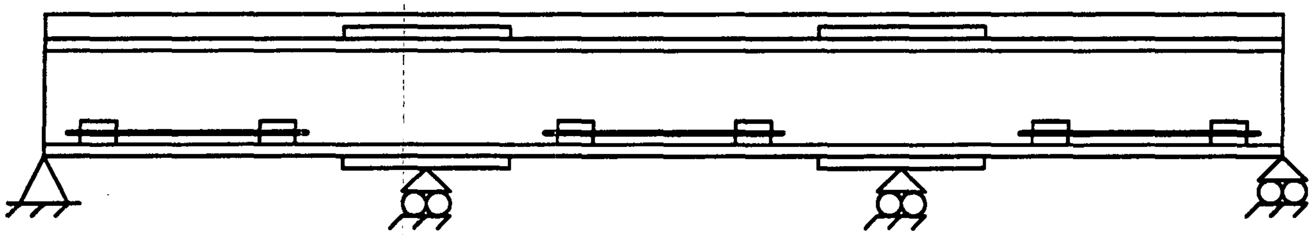
Other applications of post-tensioning as a strengthening method also exist as noted in Ref. 6.

1.2. Bridge strengthening system

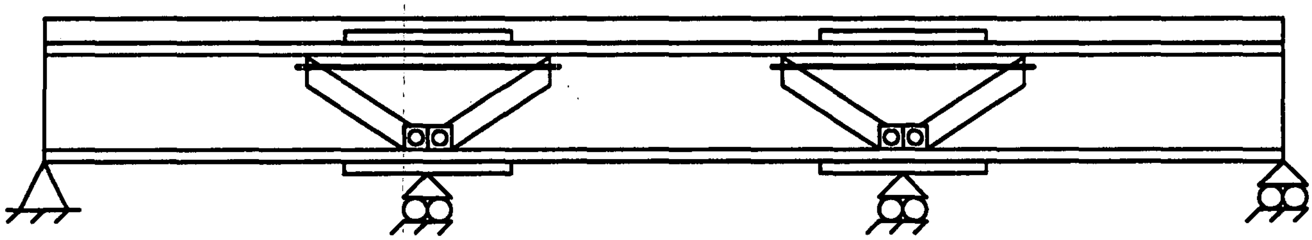
In this manual, two methods for strengthening continuous-span composite bridges are described. The first method involves post-tensioning the positive moment regions of the bridge stringers. In the second method, superimposed trusses are provided at the piers of the exterior stringers to supplement the post-tensioning system. In some cases, it is possible to strengthen the bridge without the addition of the superimposed trusses. A general layout of the strengthening system is illustrated in Fig. 1.2.

The post-tensioning system is composed of high-strength steel tendons on both sides of the stringer web. Tendons are connected to the stringers utilizing brackets that are connected to the stringers using high strength bolts. The use of bolts avoids the problems associated with field welding that are magnified when the bridge's steel welding characteristics are unknown. In most instances, tendons are positioned above the bottom flanges of the stringers to protect the system from being struck by high loads when the bridge is over a roadway or by floating debris when the bridge is over a flooded stream.

The superimposed truss strengthening system is composed of two steel tubes (the inclined members of the trusses) connected to the stringer web and bottom flange at the pier through brackets. One truss is provided on each side of the web of the exterior stringers. The top ends of the tubes of these trusses bear against the top flange of the stringer through a roller bearing. A high strength steel tendon is used to connect the top ends of the tubes to form a truss. By applying tension to the truss tendon, the top ends of the tubes bear against the stringer at the bearing



a. POST-TENSIONING



b. SUPERIMPOSED TRUSSES

Fig. 1.2. Strengthening metods.

locations. Depending upon the force applied to the tendons in the trusses, it is possible to reduce dead load stresses in the stringers. However, in most cases the trusses are simply used to reduce live load stresses.

The senior authors have strengthened and field-tested one continuous-span bridge in Pocahontas County, Iowa by post-tensioning the positive moment regions of all stringers [7]. This bridge was tested two consecutive summers to obtain data on the loss of prestress with time. Recently, a similar bridge in Cerro Gordo County, Iowa was strengthened and tested employing a strengthening system consisting of post-tensioning the positive moment regions of all stringers and superimposed trusses on the exterior stringers [8].

It is recommended to only post-tension the positive moment regions of the stringers whenever possible, due to lower cost and ease of installation. However, in some instances such post-tensioning does not reduce the overstresses at the piers the desired amount. In such cases, it is necessary to use superimposed trusses in combination with post-tensioning the positive moment regions.

Since the exterior stringers are smaller than the interior stringers, they usually have higher overstresses in the negative moment regions at the piers. Thus, superimposed trusses are employed on exterior stringers only. As the result of lateral distribution, the superimposed trusses reduce negative moment region overstresses in the interior stringers also. Although they were not employed on the Cerro Gordo County bridge [8], in the authors' opinion it would be extremely difficult to install superimposed trusses on interior stringers.

Depending upon the magnitude of post-tensioning forces employed, there may be stresses of sufficient magnitude to induce cracking in the curbs and bridge deck. The possibility of cracks occuring increases when the post-tensioning forces are high. The use of superimposed trusses reduces the possibility of cracking since smaller post-tensioning forces are required. In this case, the change in the overall stress profile along the stringer is relatively small and therefore there is less potential for cracking.

1.3. LOTUS spreadsheet

A LOTUS 1-2-3 spreadsheet was developed to assist the engineer with designing the strengthening system. The spreadsheet calculates the required strengthening forces and provides the designer with the final stress envelopes of the bridge stringers. The use and organization of the spreadsheet are presented in detail in Chp. 5.

1.4. Manual organization

The following sections of this manual address the different steps required to compute the strengthening forces. A description of the actual design methodology is presented in Chp. 2. In Chp. 3, details are provided on the design procedure as well as some practical recommendations for the design of a strengthening system for a given bridge. An approximate procedure for computing the ultimate strength of a strengthened, continuous-span, composite bridge stringer is described in Chp. 4. Chapter 5 of this manual provides an example to illustrate the use of the spreadsheet in designing a strengthening system for a 150 ft long, standard Iowa DOT V12, four-stringer, three-span, composite bridge [9].

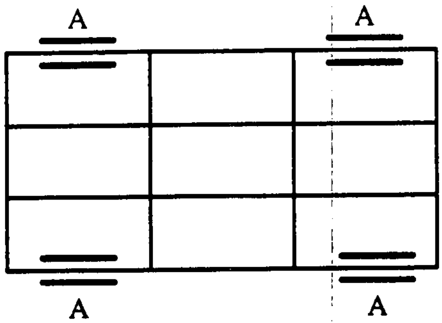
2. DESIGN METHODOLOGY

Due to the lateral stiffness of the bridge deck and diaphragms, the post-tensioning forces applied to each stringer and the truss forces applied to the exterior stringers are partially distributed to other stringers. Also, as a result of longitudinal distribution, post-tensioning one span induces moments in the other spans. Therefore, a method for calculating how these forces are distributed among the bridge stringers is needed so that the engineer can determine the magnitude of forces required to strengthen a given bridge.

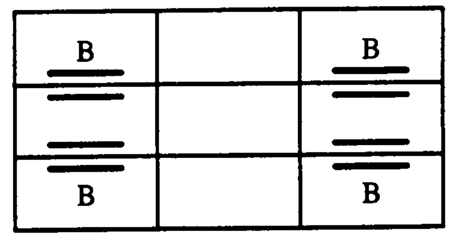
The use of a finite element model for the analysis of bridges under the effect of the forces from a strengthening system requires access to a large computer, a finite element solution package, and preprocessing and postprocessing programs. In order to simplify the design process for a typical continuous-span, composite bridge, the authors developed a simplified design methodology for use by the practicing engineer. The development of the design methodology is briefly explained in this chapter and is described in detail in Chp. 4 of Ref. 8.

2.1. Basic assumptions and idealizations

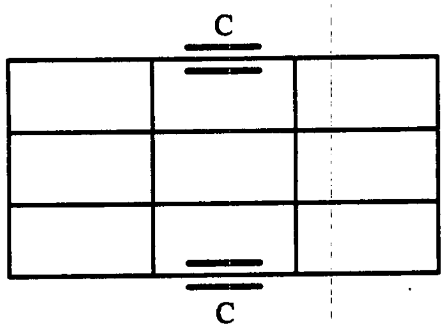
This design methodology is based on dividing the strengthening system into a number of separate schemes. In each scheme, the post-tensioning forces (or superimposed trusses) were applied so that symmetrical force application was maintained. When designing a strengthening system, the designer can add a number of these schemes together to obtain the desired stress reduction at the various locations on the bridge. The possible strengthening schemes [A] through [E] are shown in Fig. 2.1. Reference will be made to these schemes throughout the manual.



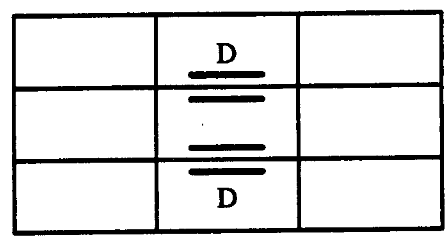
a. STRENGTHENING SCHEME [A]:
POST-TENSIONING END SPANS
OF THE EXTERIOR STRINGERS



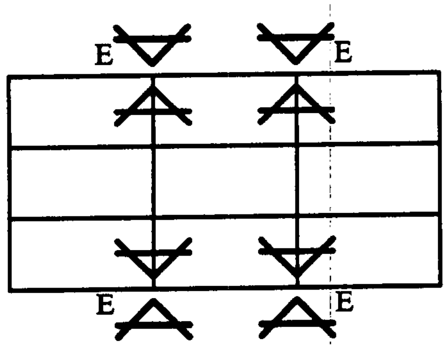
b. STRENGTHENING SCHEME [B]:
POST-TENSIONING END SPANS
OF THE INTERIOR STRINGERS



c. STRENGTHENING SCHEME [C]:
POST-TENSIONING CENTER SPANS
OF THE EXTERIOR STRINGERS



d. STRENGTHENING SCHEME [D]:
POST-TENSIONING CENTER SPANS
OF THE INTERIOR STRINGERS



e. STRENGTHENING SCHEME [E]:
SUPERIMPOSED TRUSSES AT THE PIERS
OF THE EXTERIOR STRINGERS

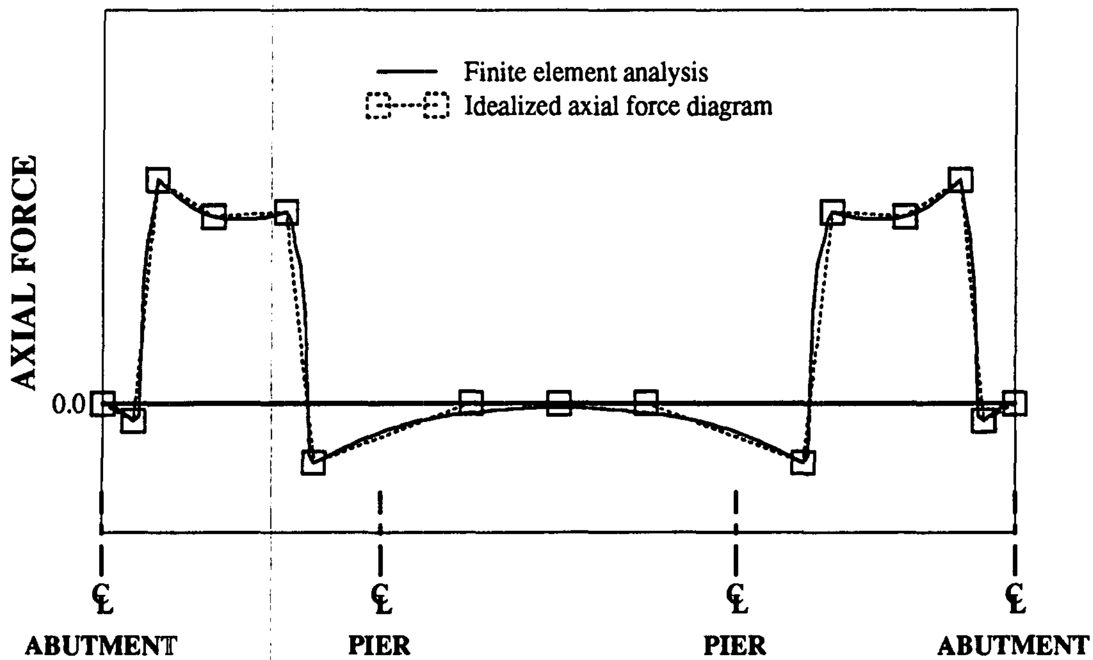
Fig. 2.1. Possible schemes for the strengthening system.

The first step in developing a simplified design methodology was to idealize the axial force and moment diagrams (resulting from each strengthening scheme) into a number of straight line segments as shown in Fig. 2.2. The straight line segments are defined by a number of critical points on the actual force and moment diagrams (obtained from finite element analysis of the bridge). The idealized diagrams represent the actual forces and moments on the stringers fairly accurately.

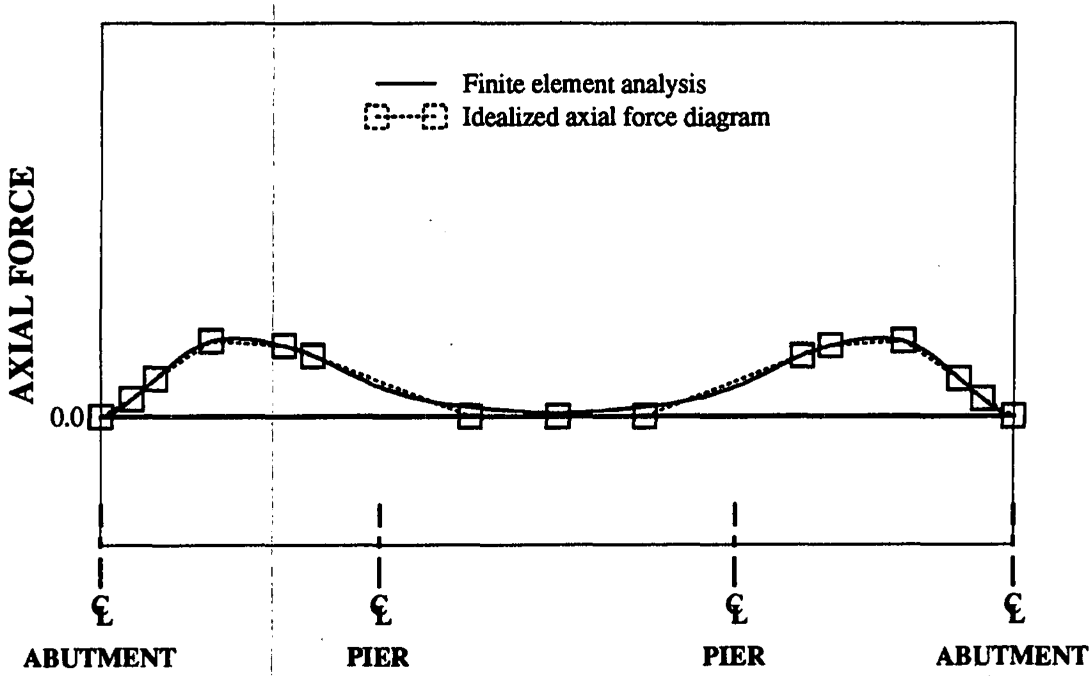
The next step in the distribution analysis was to relate the axial force (or moment) on the stringers at each of the critical points to the axial force (or moment) on the total bridge at that location. Figure 2.3 illustrates the axial force and moment diagrams for the total bridge section as well as for the individual stringers. The force (or moment) fraction at each location is defined as the ratio of the force (or moment) on the composite section of the exterior stringer to the force (or moment) on the total composite bridge section at that location. The development of formulas for the force and moment fractions at the different locations is described in Sec. 2.2; the actual formulas for the various force and moment fractions are given in Appendix A.

To determine if it is necessary to analyze the entire bridge using finite elements to obtain the moments in the total composite bridge, the moment diagrams obtained by such a finite element analysis were compared to those obtained by analyzing the bridge as continuous beams with variable moments of inertia. As shown in Fig. 2.4, the difference in the moments determined using the two methods of analysis was very small.

The design methodology therefore allows the user to obtain the force and moment diagrams on the bridge stringers by solving the bridge as a continuous beam with variable moments of inertia

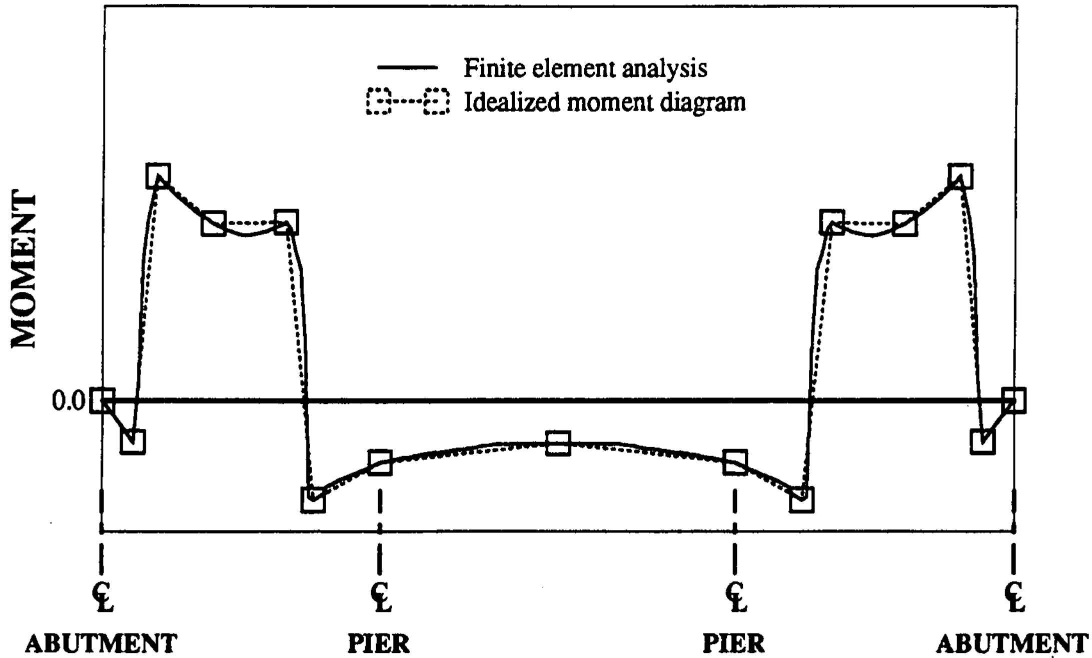


a. AXIAL FORCE ON EXTERIOR STRINGER

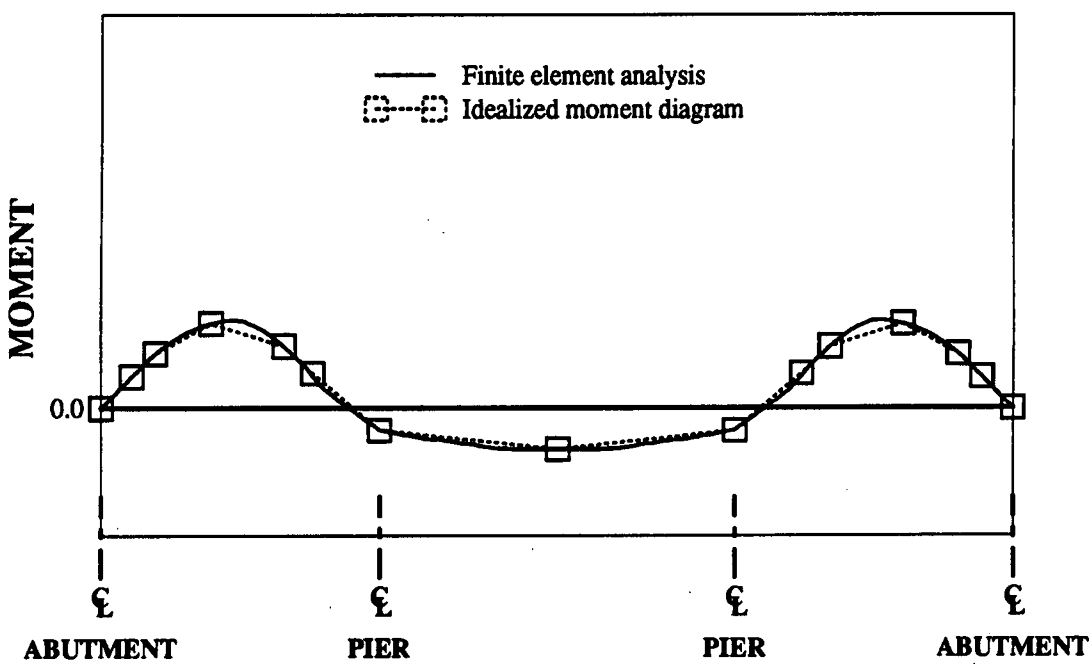


b. AXIAL FORCE ON INTERIOR STRINGER

Fig. 2.2. Idealization of axial force and moment diagrams on the stringers due to the strengthening system: Strengthening scheme [A].



c. MOMENT ON EXTERIOR STRINGER



d. MOMENT ON INTERIOR STRINGER

Fig. 2.2. Continued.

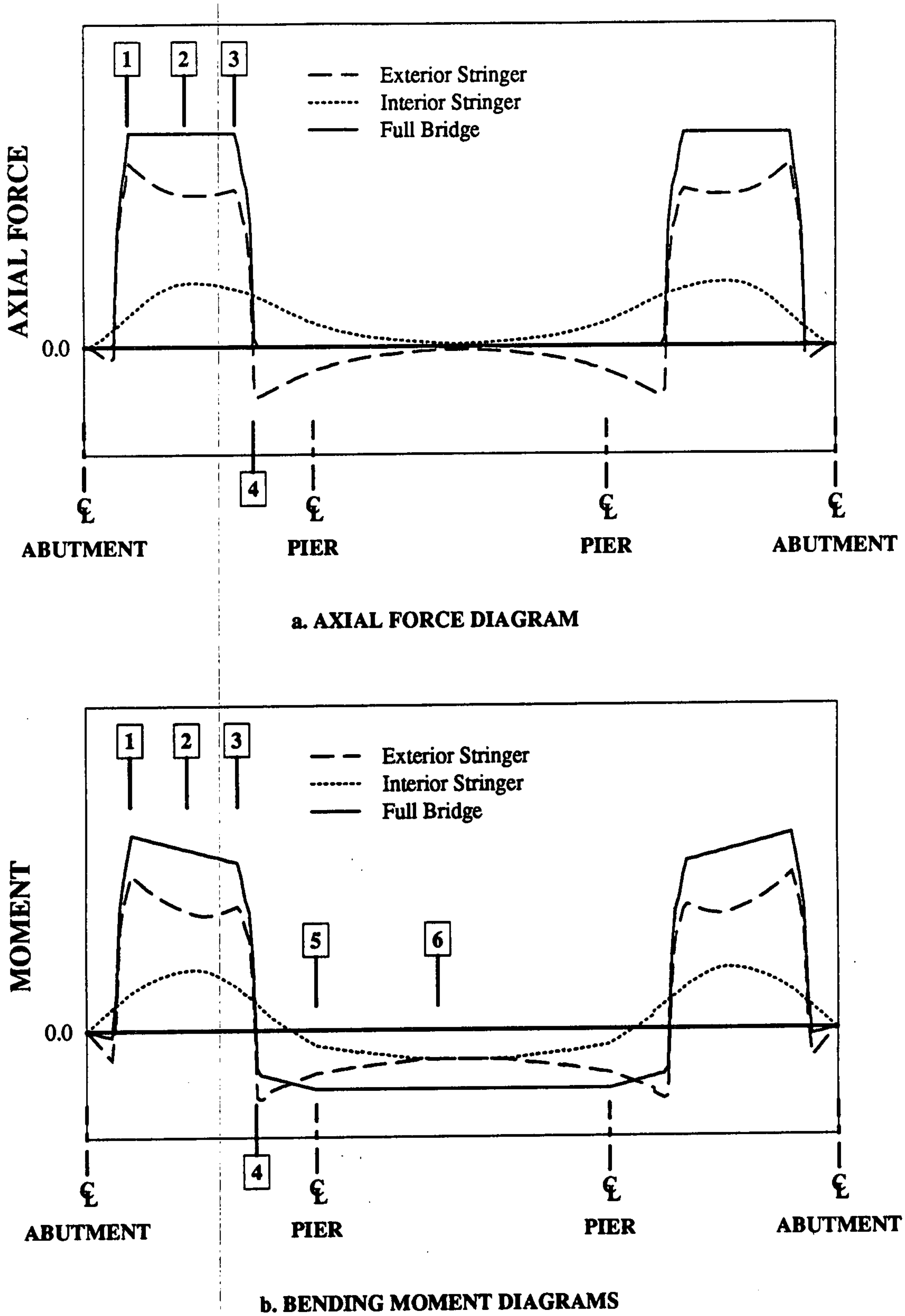


Fig.2.3. Location of distribution fractions: Strengthening scheme [A].

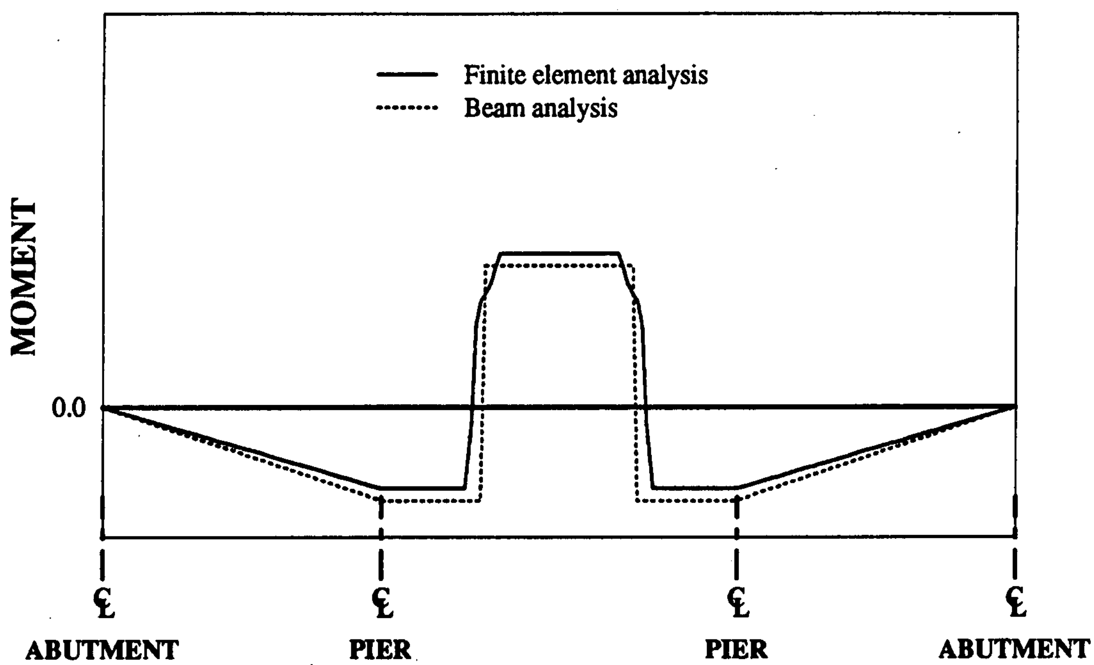


Fig.2.4. Total moments on the bridge section:
Strengthening scheme [C].

equivalent to those of the total composite bridge section. The force and moment fractions are computed at the different critical locations using the regression formulas developed in Sec. 2.2 and given in Appendix A. By applying these fractions to the forces and moments obtained from the continuous beam analysis, one may obtain the axial forces and moments at the critical locations. Connecting these values using straight line segments produces 'approximate' axial force and moment diagrams along the stringers (See Fig. 2.2).

2.2. Development of force and moment distribution fractions

For computing the force and moment distribution fractions and for the analysis of continuous-span composite bridges, a model was developed using the finite element analysis program, "ANSYS". The model was verified using results from the testing of a bridge model in the laboratory [10] and from the field-testing of an actual continuous-span bridge [7]. Details of the finite element model and the verification of its results are described in Sec. 2.1. of Ref. 11.

The finite element model was used for the analysis of the standard Iowa DOT bridges of the V12 and V14 series [9,12]. The models were solved with the individual stringer spans strengthened separately, with various angles of skew, and with variable ratios of tendon lengths to span lengths. Similar runs were performed for the superimposed trusses. The variety and number of bridges analyzed is given in Table 2.1. The theoretical results were used to compute force and moment distribution fractions at a number of critical sections along the stringers. The locations of the critical sections for the various strengthening schemes are shown in Figs. A.1 through A.9 of Appendix A.

An analysis was performed using the statistical analysis program, "SAS", to determine the parameters which have the most

Table 2.1. Bridges included in regression analysis for distribution fractions.

Iowa DOT Series (Date)	Number of Beams/ No. of lanes	Design Live Load	Total bridge Lengths, ft	Skew	No. of strengthening schemes	No. of runs/scheme on each bridge	Total No. of runs
V12 (1957)	4/2	H-15	125, 150 175, 200 250, 300	0°, 15°, 30°, 45°	5	5	600
V14 (1960)	4/2	H-20	125, 150 175, 200 225, 250	0°, 15°, 30°, 45°	5	5	600

significant effect on the force and moment distribution fractions. From this analysis, it was determined that the three most significant variables are the deck thickness to stringer spacing ratio, the total bridge length to stringer spacing ratio, and the ratio of the post-tensioned portion of the span to the individual span length. These variables are shown in Fig. 2.5.

Simple regression formulas for the force and moment fractions were developed using SAS. The formulas, as previously noted, are given in Appendix A together with limits for the distribution fractions. These limits were developed to avoid the possibility of obtaining unrealistically high or low values for the fractions when using parameter values that are significantly different from those of the standard V12 and V14 bridges. The coefficients of determination, R^2, given for the formulas indicate their relative reliability. The error range values are also given for each formula. Note that in the majority of cases the error is less than 5%. The range of error is generally less in the moment fractions than in the force fractions. Minimal error is introduced in the final stringer stresses computed using this design methodology as moment fraction have a greater effect on the final stress.

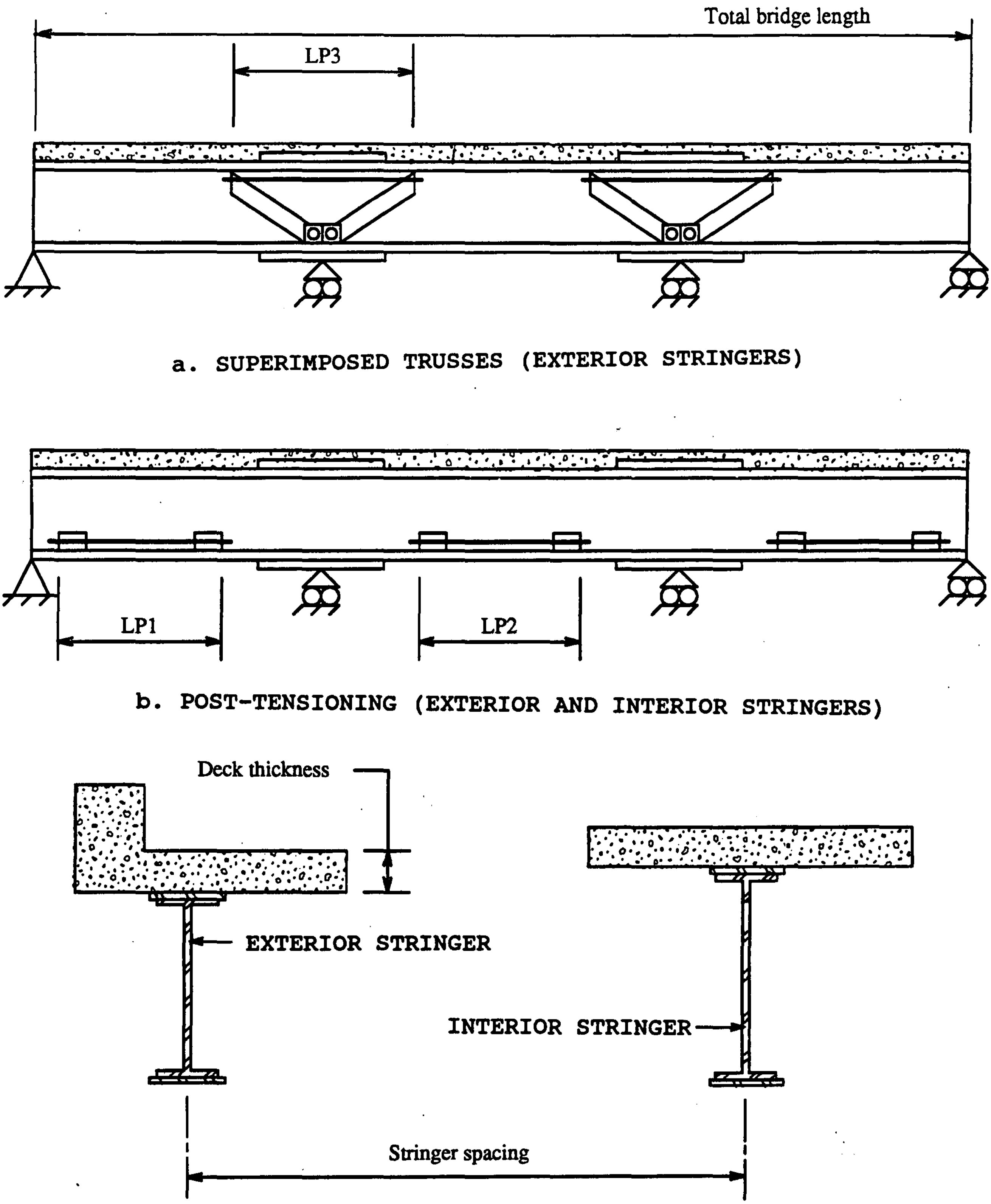


Fig. 2.5. Regression formula variables.

3. SERVICE LOAD DESIGN METHOD

3.1. Section properties

3.1.1. Section properties for stress computation

The analysis of the bridge stringers subjected to dead and live loads is completed according to the AASHTO Standard Specifications for Highway Bridges [13]. The assumptions considered here are:

- Bridge stringers are considered individually.
- Since Iowa composite bridges were constructed without shoring, the dead load stresses are computed based on the "bare" steel section (W-shape or W-shape and coverplates).
- Stresses due to live loads plus impact are computed using the composite section properties of the stringers in the positive moment regions (inducing compression in the concrete slab and curb) and using the "bare" steel section properties in the negative moment regions.
- For long-term dead loads (future wearing surface, dead loads applied after the concrete deck has cured, etc.), the ratio of the modulus of elasticity of steel to that of concrete (n) is increased by a factor of three to account for creep [13].

To obtain the final stress envelopes, the moments induced by the strengthening system (i.e., post-tensioning and superimposed trusses) are added to those induced by the maximum positive and maximum negative live load moment envelopes (including impact). The final stresses (including strengthening) are computed based on the assumptions previously outlined using the final moments together with the axial forces induced by the strengthening system.

3.1.2. Section properties for analysis

As explained in Chp. 2, the design procedure involves the computation of moments on the total bridge; moment fractions are used to determine the distribution of these moments to the bridge stringers. The neutral axis of the bridge varies depending on whether the exterior and/or interior stringers are coverplated. This variation depends on the size or absence of integral curbs, the relative size and bearing elevations of the stringers, and the amount or absence of deck crown. To simplify the design procedure, a "standard" position for the neutral axis was chosen for use in computing moments. The position chosen is the location of the neutral axis of the composite uncoverplated bridge section. The moment fraction formulas developed are based on this "standard" position of the neutral axis. Therefore, when computing stresses in the stringers, the moments computed should be modified to account for the difference between the "standard" neutral axis on which the computed moments were based and the neutral axis location of the individual stringers at specific sections. This adjustment is automatic in the spreadsheet.

3.2. Recommended design procedure

This section describes the various steps required in the design of a strengthening system for a typical continuous-span, composite bridge. A few of the steps outlined must be completed by the user; however the majority of the steps are completed by the spreadsheet. To determine the configuration of the strengthening system and the tendon forces, the following procedure is suggested:

1. Load the spreadsheet "STRCONBR.WK1" into LOTUS 1-2-3, and become familiar with the different sections of the spreadsheet. All spreadsheet sections have a "HELP" area provided for guidance.
2. Determine section properties of the exterior and interior stringers for the following sections:
   - Steel beam
   - Steel beam with coverplates

- Composite stringer (steel beam + deck)
- Composite stringer with coverplates (steel beam + coverplates + deck)

Also determine the location of the "standard" neutral axis,i.e., the neutral axis location of the composite bridge without coverplates.

3. Determine all loads and load fractions for exterior and interior stringers for:
   - Dead load
   - Long-term dead load
   - Live load and impact
4. Compute the moments induced in the exterior and interior stringer due to:
   - Dead load
   - Long-term dead load
   - Live load and impact
5. Compute the stresses in the exterior and interior stringers at numerous sections along the length of the bridge due to:
   - Dead load
   - Long-term dead load
   - Live load and impact
6. Make an initial assumption of the strengthening scheme (See Sec. 3.3.1), the tendon lengths and bracket locations (See Sec. 3.3.2). Use these values to compute the initial force and moment fractions.
7. Compute the overstresses at the critical section locations to be removed by strengthening.
8. Determine the post-tensioning forces and the vertical truss force which produce the desired stress reduction at the critical sections.
9. Check the final stresses in the exterior and interior stringers at various sections along the length of the bridge; one should especially check the stresses at the

coverplate cutoff points, bracket locations, and truss bearing points.

10. Increase the strengthening design forces to account for time-losses and errors due to approximations in the design methodology.

The design example in Chp. 5 of this manual illustrates the computation details for each of these steps. Sections 5.1. through 5.10. of Chp. 5 correspond to the ten steps outlined above.

3.3. Recommendations for design

The following guidelines may be helpful in obtaining an efficient practical design for the strengthening system. In the following sections, information is provided on selecting the strengthening scheme, bracket locations, and tendon and truss design considerations.

3.3.1. Selection of the strengthening scheme

- Due to the extra cost and installation time required when superimposed trusses are used, it is recommended to use only post-tensioning whenever possible.

- A recommended design procedure is to use the post-tensioning forces to compensate for the overstresses in the positive moment regions. This will also reduce some of the overstress in the pier negative moment regions. If the remaining overstress in the negative moment regions is small, the post-tensioning forces can be increased to compensate for this overstress. If the negative moment overstress is not eliminated using this procedure, superimposed trusses should be used to obtain the desired stress reduction in the negative moment regions.

- One may increase the post-tensioning forces significantly beyond what is required to compensate for the overstress in the positive moment regions. Although the stresses along the stringers may still be within the allowable stress limits, large post-tensioning forces may cause excessive cracking in the deck and curbs. Such cracking can be avoided by using superimposed trusses (which are very efficient in reducing overstresses at the piers) coupled with the post-tensioning of positive moment regions.

3.3.2. Selection of the bracket locations

- The initial positions of the brackets may be determined by using the following guidelines:
    - Length of post-tensioned portion of end-span = 0.60 x Length of end-span.
    - Length of post-tensioned portion of center-span = 0.50 x Length of center-span.
    - Length of truss tendon = 0.50 x Length of end-span.
    - Distance of first bracket from abutment = 0.12 x Length of end-span.
    - Bracket length = 1.50 ft.

  These values can be used in the preliminary stages of calculating the required strengthening forces and modified later within the allowable limits (given in Appendix A) to obtain a better design.

- Numerous practical considerations should be taken into account when one positions the brackets. For example, adequate clearance should be provided for the post-tensioning hydraulic cylinder as well as the jacking chair. The tendon extension beyond the end of the bracket, and tendon elongation during the stressing must also be considered. Special consideration must be given to the splice locations to ensure that they do not interfere with the stressing.

- It is often difficult to give adequate clearance between the bracket locations and the stringer splice location in the center span since reducing the length of the center span tendons to avoid this interference may not allow the achievement of the desired stress reduction. In such situations, larger brackets may be used to increase the distance between the tendon and the bottom flange and the web. By increasing the clearances between the tendon and the stringer flange and web, one will be able to use the chair and hydraulic cylinder above the splice plates. Another option would be to use special jacking chairs which clear the splice area. When there is sufficient clearance under the bridge, one could position brackets (and thus the tendons) under the bottom flange. The center span of the bridge in Ref. 7 was strengthened with post-tensioning under the bottom flange in the center span. See additional comments which follow on this under the flange location.

- It is not recommended to place the brackets outside the splice locations in the center span, as this would subject the splice to post-tensioning forces.

- For skewed bridges (45 degrees or less), the bracket locations on the stringers can be determined as in the case of right-angle bridges.

- Placing the tendon and the brackets under the stringer creates a large eccentricity, and therefore smaller tendon forces are required. However, this arrangement reduces clearance under the bridge. Therefore, it is recommended to position the brackets above the lower flanges of the stringers. This location allows the brackets to be bolted to both the stringer flange and web and thus requires a smaller bracket. This location also "protects" the strengthening system from unexpected overheight vehicles (when the bridge is over a road) and floating debris (when the bridge is over a flooded stream).

3.3.3. Design considerations for the post-tensioning tendons and superimposed trusses

- The designer should allow for decreases in the tendon forces with time. Therefore, stresses should be checked for both initial and final forces. Some of the most common causes for losses are:
  a. Steel relaxation.
  b. Temperature differential between the tendons and the bridge.
  c. Reduction of end-restraint present at the time of post-tensioning.
  d. Removal of the deck and curbs for replacement. This causes a significant decrease in the tendon forces. It is therefore recommended to temporarily remove post-tensioning during deck and curb repairs.

- The post-tensioning tendons used in the strengthening system should be protected from the elements. Epoxy coating is one method of obtaining this protection. If epoxy-coated Dywidag threadbars are used [14], special nuts should be ordered if the tendons are coated over their entire length. The epoxy coating should be omitted at the ends of the tendons if only ordinary nuts are available.

- The designer should make a careful study of the tendon locations since in some bridges diaphragms and/or other construction details may interfere with the tendons.

- In choosing the bearing points of the superimposed trusses, the angle between the truss tube members and the stringer should not be too small. It is recommended that the inclination of the truss tube be not less than 1 in 15.

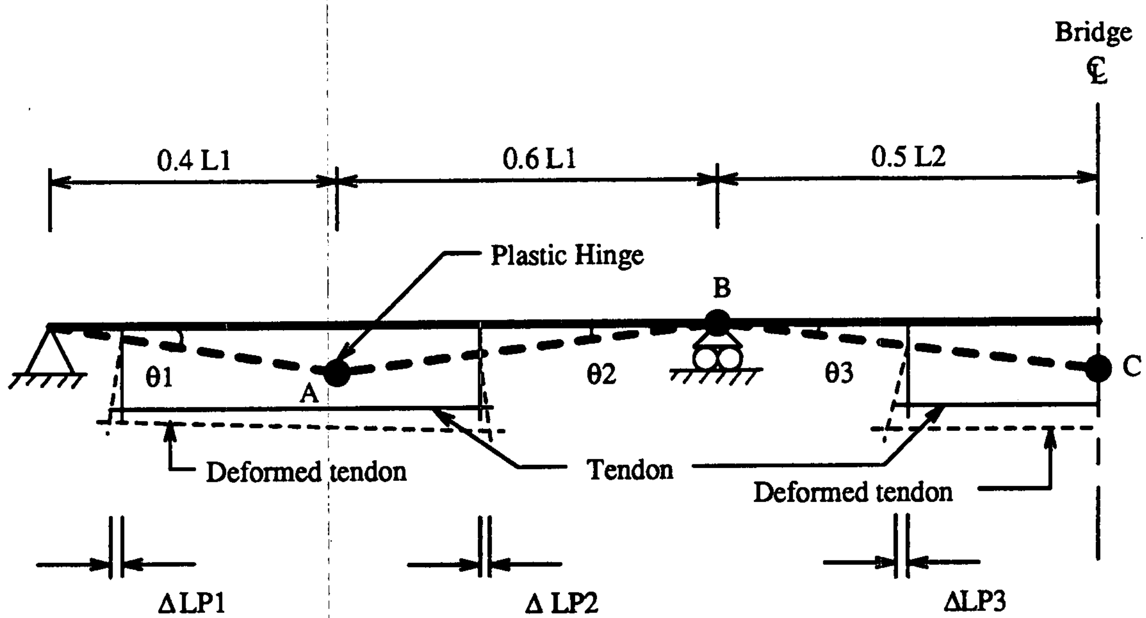
4. ULTIMATE STRENGTH

The design methodology outlined in the previous chapters is based on the working stress design method. The distribution fraction formulas developed were obtained from the results of the elastic analysis of several composite bridges. These distribution fractions obviously can not be used to predict the behavior of the bridge at ultimate load.

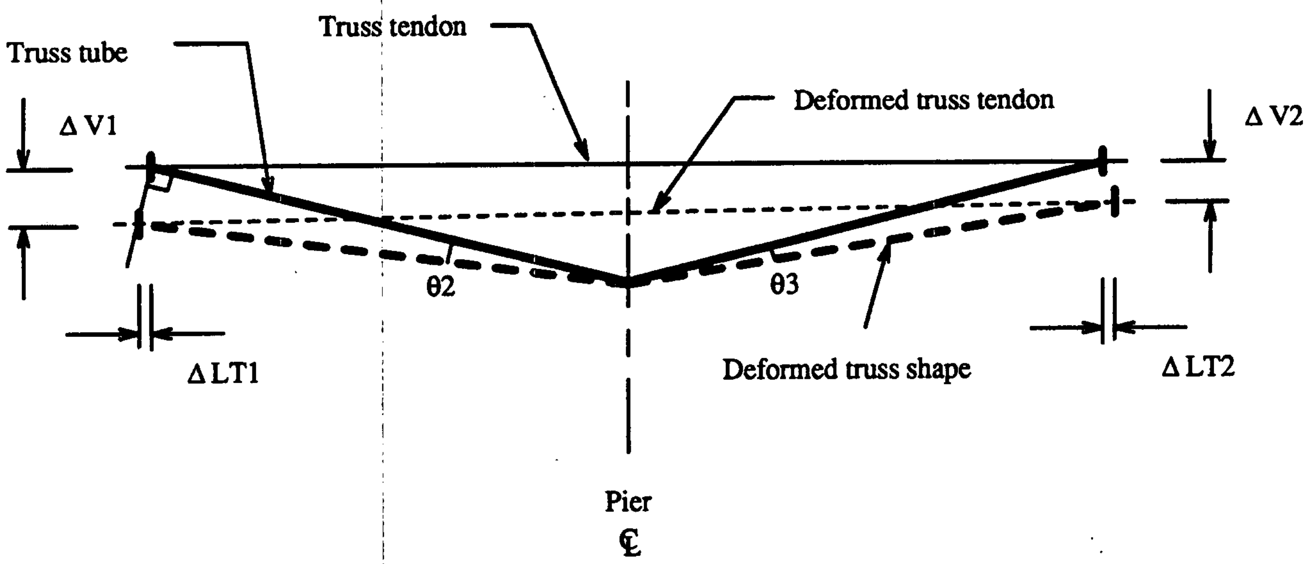
Several laboratory tests have been conducted to investigate the behavior of post-tensioned bridge stringers at failure. A review of this work, conducted in the ISU Structural Research Laboratory, is described in Sec. 5.4 of Ref. 4. A system consisting of superimposed trusses on a composite beam, supported to simulate the negative moment region in a continuous beam, was also loaded to failure in the ISU Structural Research Laboratory. The results of this test (in which the beam failed before the superimposed trusses) is presented in Ref. 15.

In this chapter, a procedure is suggested for predicting the ultimate strength of bridge stringers strengthened by post-tensioning and/or superimposed trusses. Using a theoretical analysis, it was determined that increasing the vertical loads on the bridge caused a significantly larger percentage increase in the stresses in bridge stringers, than in the post-tensioning tendons or superimposed trusses. This is mainly due to the relatively small stiffnesses of the post-tensioning tendons and the trusses compared to the stiffness of the stringers. It is therefore assumed that failure would occur due to the formation of plastic hinges in the bridge stringers, rather than due to the collapse of the strengthening system.

The assumed pattern of failure is shown in Fig. 4.1a. The following principles and assumptions are recommended for use in



a. FAILURE PATTERN



b. DEFORMATION OF SUPERIMPOSED TRUSS

Fig. 4.1. Idealization of bridge stringer at ultimate load.

predicting the approximate flexural strength of the bridge stringers:

1. The failure pattern shown in Fig. 4.1a may be used. Plastic hinges are assumed to form at three locations:
   - At the maximum positive moment location in the end span (assumed to be at a distance of 40% of the span length from the support).
   - At the maximum positive moment location in the center span (assumed to be at midspan).
   - At the maximum negative moment location (i.e., at the centerline of the pier).
2. The deflection of the positive moment locations at which the plastic hinges occur may be assumed to be (L/80), where L is the span length, L1 or L2.
3. The effective flange width can be determined according to the AASHTO rules for load factor design [13, Sec. 10.38].
4. The compressive force in the slab can be determined according to AASHTO rules, which account for slab reinforcing (unlike service load design), relative capacity of concrete slab vs. steel beam, and partial or full shear connection [13, Sec. 10.50].
5. The tendon strain can be obtained from the idealized stringer configuration shown in Fig. 4.1a as follows:

   End-span tendon elongation = $\Delta LP1 + \Delta LP2$

   Center-span tendon elongation = $2 \times \Delta LP3$

   In the idealized stringer, the tendon is permitted to rise and the change in elevation is accounted for in the computation. If the tendons are restricted from rising, the configuration in Fig. 4.1a must be modified to correctly represent the actual condition.
6. The superimposed truss tendon strain can be obtained from the idealized truss configuration shown in Fig. 4.1b as follows:

   $\Delta LT1 = \Delta V1 \times \tan(\theta 2)$

   $\Delta LT2 = \Delta V2 \times \tan(\theta 3)$

   Truss tendon elongation = $\Delta LT1 + \Delta LT2$.

7. Tendon force can be computed using an idealized stress-strain curve for the tendon steel.
8. The increase in the truss tendon force can be used to compute the increase in the truss vertical forces which act on exterior stringers of the bridge.
9. Shear connector capacities can be computed from the formulas given in Sec. 10.38 of Ref. 13. For angle-plus-bar shear connectors, the capacity can be based on a modified channel formula as noted in Ref. 3.
10. The distribution of forces in the bridge stringers at failure has not been addresses in this study. It is left for the designer either to obtain these distribution fractions by performing a nonlinear finite element analysis, or to use engineering judgement to make reasonable assumptions for the distribution fractions.

With reference to Fig. 4.1, the recommended procedure for computation of the flexural strength of a post-tensioned composite stringer (with or without superimposed trusses) is as follows:

1. Assume plastic hinges at the positions shown in Fig. 4.1a.
2. Assume the deflection at hinges A and C to be L/80, where L is the length of the span in which the hinge is located.
3. Compute the angles $\theta 1$, $\theta 2$, and $\theta 3$.
4. Compute the maximum compressive force according to AASHTO rules considering deck reinforcing, concrete deck vs. steel stringer capacity, tendon yield strength and shear connection.
5. Using the geometry of Fig. 4.1a, compute $\Delta LP1$, $\Delta LP2$, and $\Delta LP3$. Calculate the elongation of post-tensioning tendons.
6. Using the geometry of Fig. 4.1b, compute $\Delta LT1$, and $\Delta LT2$. Calculate the elongation of the superimposed truss tendons.
7. Compute the increase in tendon forces using the stress-strain diagrams for the tendon steel. Compute the new tendon forces.
8. Compute the vertical truss forces acting on the stringers based on the new tendon force and the angle of inclination of the truss tubes.

9. Compute the elevations of the compressive and tensile force resultants, accounting for the rise in the tendon.
10. Compute the flexural strength as the product of the maximum compressive force and the distance between compressive and tensile force resultants.

The simple analytical model covered in this chapter gives an approximation of the strength of individual, strengthened composite stringers. At this time, however, the authors have no specific experimental or analytical distribution factors by which to apply the individual stringer model to a strengthened bridge. Without experimental or analytical data for determining distribution at ultimate load, the distribution is left to the judgment of the designer.

5. DESIGN EXAMPLE

In this section, the procedure for designing a strengthening system for a typical steel-stringer, composite, concrete-deck, continuous-span bridge is illustrated using the procedure presented in Chapter 3. The example is divided into ten sections - Secs. 5.1 through 5.10 which correspond to the ten steps outlined in Sec. 3.3. The illustrative example utilizes the spreadsheet (STRCONBR.WK1) developed as part of this research project.

The example is prepared assuming the user to be interacting simultaneously with the spreadsheet. The example is organized in steps each of which is denoted with the symbol: ◘; brief descriptions of the various steps are typed in CAPS. These steps include both computations to be performed by the user outside the spreadsheet, and commands to be executed on the spreadsheet. Each step is followed by an explanation and the required computations.

The design process described in this example is composed of two parts. The first part is the computation of the stresses along the lengths of the bridge stringers due to vertical loading and is described in Secs. 5.2 through 5.5, while the second part comprises the design of the strengthening system which is described in Secs. 5.6 through 5.10. If the stringer stresses due to vertical loading are available from the Iowa DOT rating files for the bridge, the user has the option to skip Secs. 5.2 through 5.5 and continue with the balance of the design procedure. The example as well as the spreadsheet are prepared to allow the user to skip these sections.

The bridge used in this example is a two-lane, three-spans,four-stringer, standard Iowa DOT V12 bridge with a total length of 150 ft. This bridge is strengthened to meet current Iowa legal load standards.

The bridge consists of four steel stringers acting compositely with the concrete deck. Coverplates are added to the steel stringers at the piers. In the transverse direction, steel diaphragms are provided at the abutments, piers, and several intermediate locations. A general layout of the bridge is shown in Fig. 1.1.

In order to simplify computations, the transverse section of the bridge has been idealized as shown in Fig. 5.1. The curb cross-section is idealized as a rectangle, the deck is assumed to be horizontal at each of the steel stringers, and the 1/2 in. wearing surface has been removed. Since the actual thickness of the deck varies slightly across the bridge width, an average value of 6.6 in. has been used.

5.1. Using the spreadsheet

The spreadsheet is composed of four parts containing a number of tables and macros (i.e., a subroutine within the spreadsheet). Part I of the spreadsheet computes the section properties of the bridge stringers and the total bridge section. In Part II, the different bridge parameters are input and used to compute the force and moment fractions. In Part III of the spreadsheet, the strengthening system design forces are computed, and in Part IV, the check of final stresses on the bridge stringers is completed.

A HELP section is provided in the spreadsheet, providing directions and explanations on the use of the various tables and macros. It is recommended that initially the user read and study the notes given in the HELP section of the spreadsheet before starting to work on each table or macro.

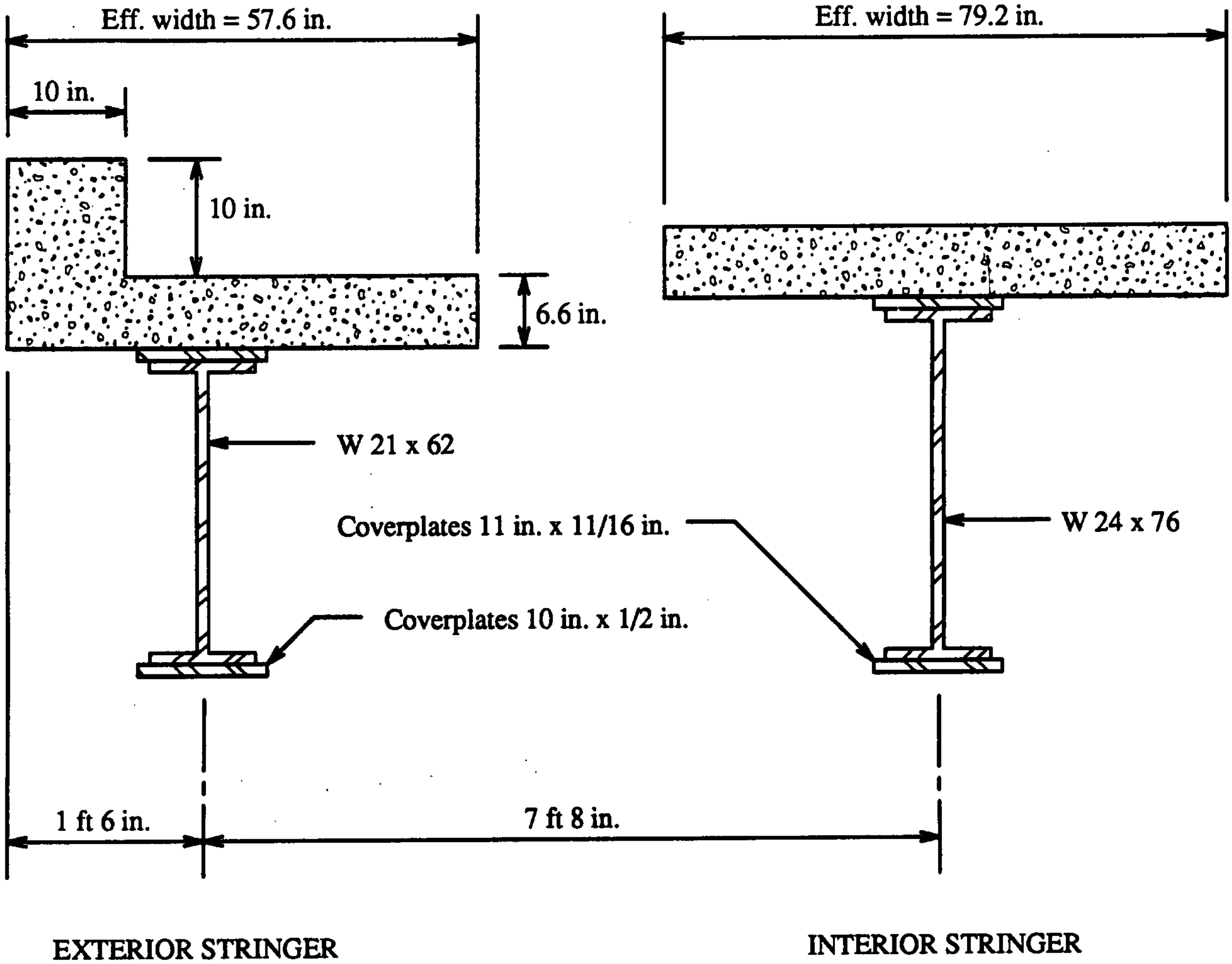


Fig. 5.1. Idealized transverse section of composite bridge.

5.1.1. Retrieving the spreadsheet into LOTUS 1-2-3

Two spreadsheet files (on a 3.5 in. floppy disk) are provided with this manual. The user should start with the spreadsheet file "START.WK1", which is used to initialize the worksheet settings so that the design worksheet "STRCONBR.WK1" can be retrieved. The following steps describe the use of the spreadsheet:

- **TURN ON THE COMPUTER AND START LOTUS 1-2-3**

- **RETRIEVE "START.WK1" INTO LOTUS 1-2-3**

To do this, use "/ FILE RETRIEVE A:\START.WK1 " . Some versions of LOTUS have an UNDO option. This option takes a considerable amount of memory. Due to the large size of the spreadsheet, there may be insufficient memory to retrieve the spreadsheet "STRCONBR.WK1", if the UNDO option is ON. The "START.WK1" spreadsheet provides a macro ALT-A to turn the UNDO option OFF.

- **IF THE SIGNAL UNDO SHOWS AT THE BOTTOM OF THE SCREEN, PRESS ALT-A**

- **RETRIEVE "STRCONBR.WK1" INTO LOTUS**

To do this, use " / FILE RETRIEVE A:\STRCONBR.WK1 ".

5.1.2. Getting acquainted with the spreadsheet

- **USE THE PAGE UP AND PAGE DOWN KEYS TO MOVE UP AND DOWN THE SPREADSHEET**

Most of the time throughout the design, the user will only need to view columns [A through H] of the spreadsheet. However, some tables occupy more than these columns. In these cases, a

"Table cont." sign is given to direct the user to the balance of the table.

■ **PRESS ALT-H**

This moves the cursor from the user interactive area [Columns A through H] into the HELP area [Columns I through P] which is normally hidden from view.

■ **PRESS ALT-B**

This returns the cursor to the user interactive area.

Throughout the spreadsheet, the values to be input by the user are designated as input cells, which appear with a different color on the screen. The user is allowed to input values only into these "input cells". When inputting data, the user can activate the INPUT mode in LOTUS using a macro ALT-P.

■ **PRESS ALT-P**

This allows the cursor to move only to cells designated as "input cells". When inputting data, the user can activate this macro to avoid overwriting cells not designated as "input cells". However, in the INPUT mode, the user can not move freely through the spreadsheet to view the various instructions and the HELP area. To do this, the user needs to leave the INPUT mode.

■ **PRESS ESC**

The INPUT mode is off, and the user is able once again to go through the rest of the spreadsheet and the HELP area.

In this example, printouts from the spreadsheet are shown in each step to allow the user to check the results from the computer screen. All spreadsheet tables in this example are shaded to be easily distinguished from other tables used in the example, and the "input cells" within these tables are underlined.

5.2. Computation of section properties:

5.2.1. Section properties of the exterior stringers

The following steps should be performed to compute the section properties of the exterior stringers of the bridge:

■ COMPUTE THE EFFECTIVE FLANGE WIDTH FOR THE EXTERIOR STRINGERS

The composite action between the concrete deck and the steel stringer requires the determination of an effective flange width of the deck. Since the deck extends a distance of 18 in. beyond the centerline of the exterior steel stringer, the exterior stringer is assumed to have a flange on both sides. Based on Sec. 10.38 of Ref. 13, the flange width should be taken as the smallest of the following:

a. Cantilever deck length + span length / 8 (not to exceed span length / 4) = 18 + 45.75 x 12 / 8 = 86.625 in. < 137.25 in.

   The end-span length has been used since it is more conservative to use the smaller length.

b. Cantilever deck length + stringer spacing / 2 (not to exceed stringer spacing) = 18 + 92 / 2 = 64 in. < 92 in.

c. Cantilever deck length + 6 x deck thickness (not to exceed 12 x deck thickness) = 18 + 6 x 6.6 = 57.6 in. < 79.2 in.

   Therefore, the effective flange width is 57.6 in.

■ COMPUTE THE MODULAR RATIO (n)

The modular ratio, n, is the ratio of the modulus of elasticity of the steel to that of the concrete. According to Sec. 10.38 of Ref. 13, the modular ratio, n, corresponding to f_c' = 3000 psi is 9.

■ INPUT THE BASIC DIMENSIONS OF THE EXTERIOR STRINGERS INTO TABLE I.1 OF THE SPREADSHEET

The following is a list of these input values:

W-shape properties:	Height = 21 in.
(W21x62)	Area = 18.30 in^2
	Moment of inertia = 1330.0 in^4
Coverplate dimensions:	Width = 10 in.
	Thickness = 0.5 in.
Deck dimensions:	Effective flange width = 57.6 in.
	Thickness = 6.6 in.
Curb dimensions:	Width = 10 in.
	Height = 10 in.
Modular ratio:	n = 9

The remaining values in Table I.1 are computed automatically after the input of these values.

TABLE I.1.

Section Properties for Exterior Stringer:

	Width (in.)	Height (in.)	Area (in.^2)	Inertia (in.^4)	Neutral axis elev. (in.)	Y from bot.fiber to Neut. axis(in.)	I at NA of beam X-sec. (in.^4)
W-shape	---	21.00	18.30	1330.00	10.50	10.50	1330.00
Cover PL	10.00	0.50	10.00	1155.83	21.25		
Deck	57.60	6.60	42.24	153.33	24.30		
Curb	10.00	10.00	11.11	92.59	32.60		
W-shape+CPs			28.30		10.50	11.00	2485.83
W-shape+deck			71.65		22.06	22.06	5467.71
Full comp. sec.			81.65		20.65	21.15	7796.73

n = Young's modulus of steel / Young's modulus of concrete = 9.00

<u>Definition of terms in Table I.1:</u>

Cover PL:	Cover plates; the steel W-shape has two flange coverplates - one on the top and one on the bottom - in the negative moment regions at the piers. The coverplate width and height input is for one coverplate; the area and inertia are computed for both coverplates.
W-shape + CPs:	Steel section composed of W-shape and coverplates.
W-shape + deck:	Composite section in noncoverplated regions.
Full comp. sec.:	Composite section including W-shape, coverplates and concrete deck.
N-A elevation:	Measured from the extreme bottom fiber of the exterior stringer W-shape (or coverplates).
Y from bottomr fibers to N-A:	The distance from the extreme bottom fiber of the section W-shape (or coverplates) to the section neutral axis (to be used later in computing bottom fiber stresses).
I @ N-a of stringer X-sec:	Moment of inertia of the section about its neutral axis.

<u>5.2.2. Section properties of the interior stringers</u>

The following steps should be performed to compute the section properties of the interior stringer of the bridge:

▪ COMPUTE THE EFFECTIVE FLANGE WIDTH FOR THE INTERIOR STRINGERS

Based on Sec. 10.38 of Ref. 13, the flange width should be taken as the smallest of the following:

a. Span length / 4 = 45.75 x 12 / 4 = 137.25 in.
b. Stringer spacing = 92 in.
c. 12 x deck thickness = 12 x 6.6 = 79.2 in.

Therefore, the effective flange width of the interior stringers is 79.2 in.

■ **INPUT THE BASIC DIMENSIONS OF THE INTERIOR STRINGER INTO TABLE. I.2 OF THE SPREADSHEET.**

The following is a list of these input values:
Elevation difference between the top of the interior and exterior W-shapes = 2.75 in. (Since the exterior and interior stringers are of different sizes, have coverplates with different thicknesses, and bear at the same elevation - this results in an elevation difference between the stringer tops. This elevation difference provides a crown in the bridge deck).

W-shape properties:	Height	= 24 in.
(W24x76)	Area	= 22.40 in^2
	Moment of inertia	= 2100.00 in^4
Coverplate dimensions:	Width	= 11 in.
	Thickness	= 11/16 in.
Deck dimensions:	Effective flange width	= 79.2 in.
	Thickness	= 6.6 in.

The remaining values in Table I.2 are computed automatically after the input of these values. The table has the following form:

TABLE I.2.

Section Properties for Interior Stringer:

Elevation of int. W-shape top - Elevation of ext. W-shape top = 2.75 in.

	Width (in.)	Height (in.)	Area (in.^2)	Inertia (in.^4)	Neutral axis elev. (in.) &w	Y from bot.fiber to Neut. axis(in.)	I at NA of beam X-sec. (in.^4)
W-shape	---	24.00	22.40	2100.00	11.75	12.00	2100.00
Cover PL	11.00	0.69	15.13	2305.16	24.09		
Deck	79.20	6.60	58.08	210.83	27.05		
W-shape+CPs			37.53		11.75	12.69	4405.16
W-shape+deck			80.48		22.79	23.04	6094.99
Full comp. sec.			95.61		21.04	21.29	9952.41

5.2.3. Section properties of the entire bridge cross-section

■ **PROCEED TO TABLE I.3.**

No additional input by the user is needed for Table I.3. Due to symmetry, only half of the bridge cross-section needs to be considered. For simplicity, the section properties for half the bridge section are computed by combining those of the two stringers (Note that portions of the deck not included in the effective flange widths of the stringers are excluded). The neutral axis elevation for the half-bridge section is computed and all moments of inertia given in the table are computed with respect to this location. Table I.3 is as shown below:

TABLE I.3.

Half-bridge section Properties:	Area [A] (in.^2)	Elev. of C.G. [z] (in.)	A*z (in.^3)	Inertias about bridge NA (in.^4) Exterior Strigner	Interior Stringer	Total Bridge
W-shapes+deck	152.13	22.45	3415.07	5478.37	6104.48	11582.85
Full comp. sec.	177.26	20.86	3697.79	7800.50	9955.63	17756.13

<u>Definition of terms in Table I.3:</u>

Half-bridge section:	A section composed of the exterior and interior stringers including only the portions of the deck included in the effective flange areas of both sections.
W-shapes + deck:	Section composed of both W-shapes together with their effective deck areas and the curb.
Full comp. sec.:	Section composed of both W-shapes together with their coverplates, effective deck areas and the curb.
A*z:	The sum of the products of the area of each stringer section and its neutral axis elevation (measured from the extreme bottom fiber of the exterior stringer W-shape). These values are used to compute the overall neutral axis of the bridge.
Elev. of C.G.:	The neutral axis elevation of the entire bridge cross-section measured from the extreme bottom fiber of the exterior stringer W-shape.
Inertias about N-A:	The moments of inertia of the individual stringers and of the half-bridge cross-section about the neutral axis of the bridge.

■ **PRESS ALT-A**

This macro copies the section properties from all three tables in Part I of the spreadsheet to Parts II, III and IV.

5.3. Computation of vertical loads on the bridge stringers

The computation of vertical loads on the bridge stringers is performed in accordance with the AASHTO specifications [13].

5.3.1. Dead loads

■ **COMPUTE DEAD LOADS ON EXTERIOR STRINGERS**

Steel W-shape:	W21x62	= 62 plf
Coverplates:	2 x 10 x 0.5 x (2x18/150)	
	x (490 pcf / 144 in^2)	= 8 plf
(2 coverplates, each 18 ft long, averaged over the total bridge length)		
R.C. deck:	(18 + 92/2) x 6.6	
	x (150 pcf / 144 in^2)	= 440 plf
R.C. curb:	10 x 10 x (150 pcf / 144 in^2)	= 104 plf
Steel diaphragms:	(assumed average)	= 10 plf
Steel rail:	(assumed average)	= 48 plf
Total dead load on exterior stringer		= 672 plf

■ **COMPUTE DEAD LOADS ON INTERIOR STRINGERS**

Steel W-shape:	W24x76	= 76 plf
Coverplates:	2 x 11 x 11/16 x (2x19/150)	
	x (490 pcf / 144 in^2)	= 13 plf
(2 coverplates, each 19 ft long, averaged over the total bridge length)		
R.C. deck:	92 x 6.6 x (150 pcf / 144 in^2)	= 633 plf
Steel diaphragms:	(assumed average)	= 20 plf
Total Dead load on interior stringer		= 742 plf

5.3.2. Long-term dead loads

■ **COMPUTE THE LONG-TERM DEAD LOADS FOR EACH STRINGER**

The long-term dead loads are assumed to be distributed equally to each stringer, as permitted in Sec. 3.23 of Ref. 13. Therefore, the long-term dead load per stringer can be computed as:

Strengthening steel tendons and brackets (estimated average)	= 8 plf
Future wearing surface 19 psf x (2x18+3x92)/12 /4 (average wt. is assumed to be 19 psf)	= 124 psf
Long-term dead load per stringer	= 132 psf

5.3.3. Live loads

- **DETERMINE THE LIVE LOADS, IMPACT FRACTION, AND THE WHEEL LOAD FRACTIONS ON THE EXTERIOR AND INTERIOR STRINGERS**

The six Iowa legal trucks shown in Appendix C were used for the calculation of the maximum positive and negative moments induced in each stringer. The impact factor used was computed using the impact formula given in Sec. 3.8 of Ref. 13.

$$I = \frac{50}{L + 125} \leq 0.30$$

where L is the length of the span that is loaded to produce the maximum stress in the bridge, in ft.

The wheel load fractions on the stringers were computed according to Sec. 3.8. of Ref. 13. In this example, the wheel load fraction on the exterior stringer is the greater of:

a. Reaction from the truck wheels, assuming the truck to be 2 ft from the curb
   = (1 x 6.33 + 1 x 0.33) / 7.667 = 0.87

b. S / (4 + 0.25 S), where S is the stringer spacing
   = 7.667 / (4.0 + 0.25 x 7.667) = 1.30

Therefore, the wheel load fraction is 1.30 for the exterior stringers.

The wheel load fraction on the interior stringer is the greater of:

a. Reaction from the truck wheels, assuming one of the truck wheels to be above the interior stringer

$$= 1 + 1.667 / 7.667 \qquad = 1.22$$

b. S / 5.5 $= 7.667 / 5.5 \qquad = 1.39$

Therefore, the wheel load fraction is 1.39 for the exterior stringers

5.4. Computation of maximum moments due to vertical loads

■ COMPUTE THE MAXIMUM POSITIVE AND NEGATIVE MOMENTS ON THE BRIDGE STRINGERS DUE TO VERTICAL LOADS

The user would normally need a computer program to determine the maximum positive and negative moment envelopes on the stringers. The authors have developed a computer program for analyzing the bridge stringers due to vertical loads. The program analyzes each stringer separately as a continuous beam with variable moments of inertia using the three-moments equation. This program is used to perform all moment and stress computations in this section and the next section (i.e., Secs. 5.4 and 5.5). To shorten this example, details of this program are not included. The user has the option to develop their own program for computing moment envelopes on the bridge or to use the moment envelopes in the Iowa DOT rating files if available.

The limits of the regions where changes in section properties occur are determined by the locations of the coverplate cutoff points. To ensure that the coverplates have sufficient length to allow for the transfer of force from the W-shape to the coverplates, a theoretical cutoff point is assumed for each coverplate; this is obtained by subtracting a distance of $1^1/_2$ times the plate width from the actual coverplate length at each end (Ref.

13, Sec. 10.13.4). The actual coverplate lengths are given in Fig. 1.1.

Theoretical length of exterior stringer coverplates

$= 18 - 2 \times 1.5 \times 10/12 = 15.50$ ft

Theoretical length of interior stringer coverplates

$= 19 - 2 \times 1.5 \times 11/12 = 16.25$ ft

The boundaries for the change in section properties - measured from the abutment centerline - are computed as follows:

For the exterior stringer, the coverplates start at:

$45.75 - 15.50/2 = 38.00$ ft

and end at:

$45.75 + 15.50/2 = 53.50$ ft

For the interior stringer, the coverplates start at:

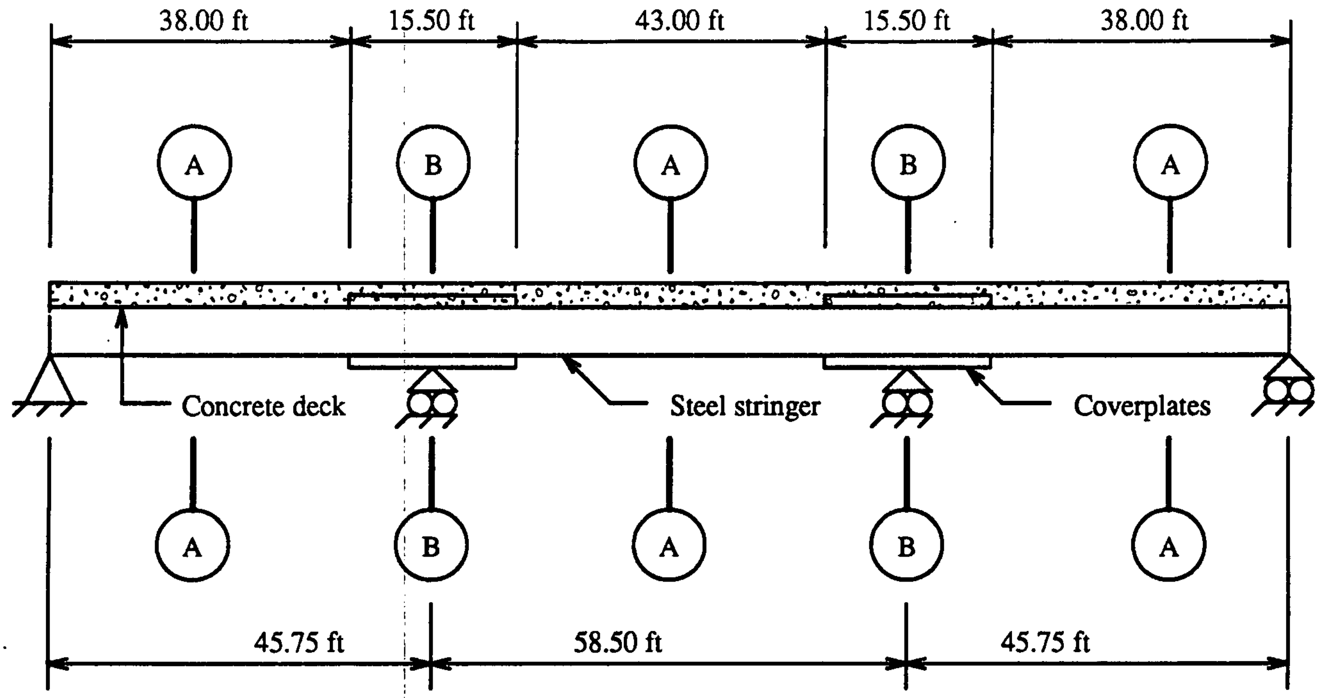
$45.75 - 16.25/2 = 37.62$ ft

and end at:

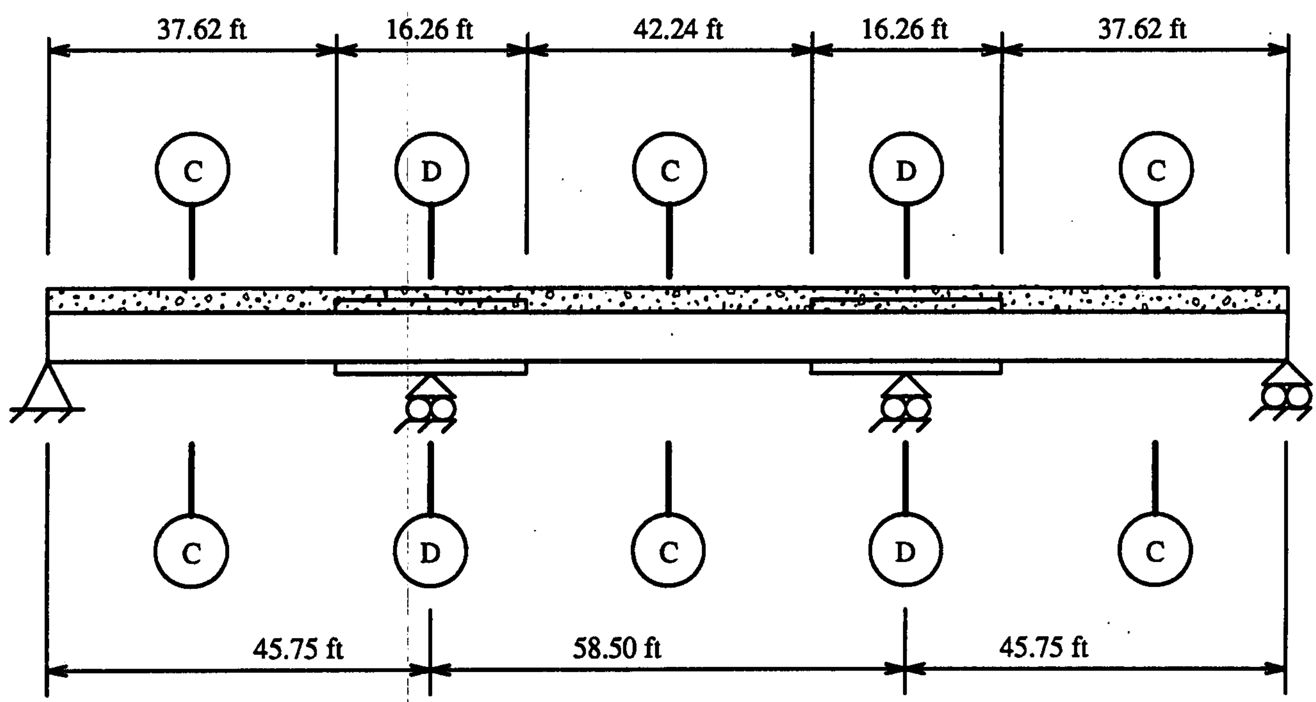
$45.75 + 16.25/2 = 53.88$ ft

The section properties used for the analysis of the stringers for vertical loads were obtained from Tables I.1 and I.2 of the spreadsheet. The locations of the various section properties used are shown in Fig. 5.2 and the values of the section properties are given in Table 5.1; this structural modeling was obtained as follows:

- For analysis of the stringers due to dead loads, and due to the maximum negative live load, the steel section properties were used throughout the stringer lengths.
- For analysis of the stringers due to the maximum positive live load, the composite section properties were used throughout the stringer lengths.
- For the superimposed dead loads, the factor, n, was taken to be equal to $3 \times 9 = 27$. To obtain the section properties for this case, the user can change the value of the factor, n, from 9 to 27 in Table I.1. The value of (n=9) should be input again into Table I.1 after obtaining the required section properties since this value is used later in the



a. EXTERIOR STRINGER



b. INTERIOR STRINGER

Fig. 5.2. Locations of various moments of inertia along stringers.

Table 5.1 Section properties used for analysis and stress computations in stringers due to vertical loads.

Loading	Stringer	Section*	Area (in.^{2})	Inertia (in.^{4})	Y_{bot} (in.)
Analysis for dead load and for maximum negative moments due to long-term dead load, and live load + impact	Exterior	A-A	18.30	1330.00	10.50
		B-B	28.30	2485.83	11.00
	Interior	C-C	22.40	2100.00	12.00
		D-D	37.53	4405.16	12.69
Analysis for maximum positive moments due to long-term dead load	Exterior	A-A	36.08	3788.82	18.15
		B-B	46.08	5403.27	16.99
	Interior	C-C	41.76	4601.23	19.01
		D-D	56.89	7564.03	17.21
Analysis for maximum positive moments due to live load + impact	Exterior	A-A	71.65	5467.71	22.06
		B-B	81.65	7796.73	21.15
	Interior	C-C	80.48	6094.99	23.04
		D-D	95.61	9952.41	21.29

* See Fig. 5.2.

spreadsheet to compute section properties for computing stresses induced by the strengthening system.

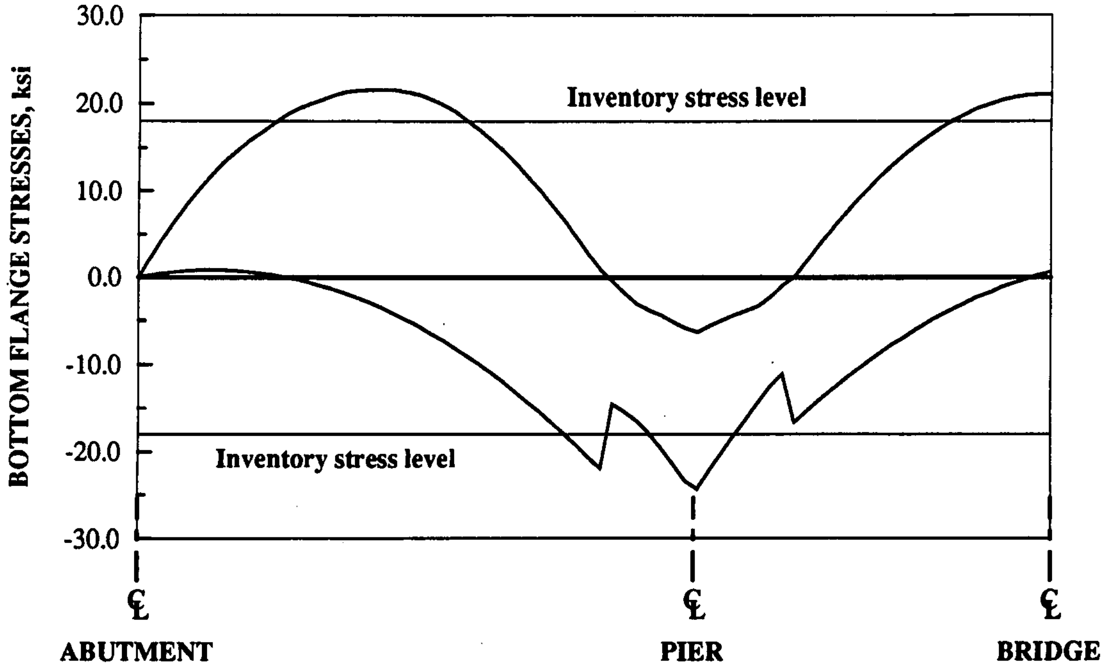
The moments due to dead loads, and superimposed dead loads, were computed along the lengths of both stringers at sections spaced one ft apart.

To compute the maximum and minimum live load moment envelopes along the stringers, the load fractions and the impact factor were applied to the Iowa legal truck loads. Each truck was positioned at numerous locations along the stringer length, and the maximum and minimum live load moments were computed at sections spaced one ft apart.

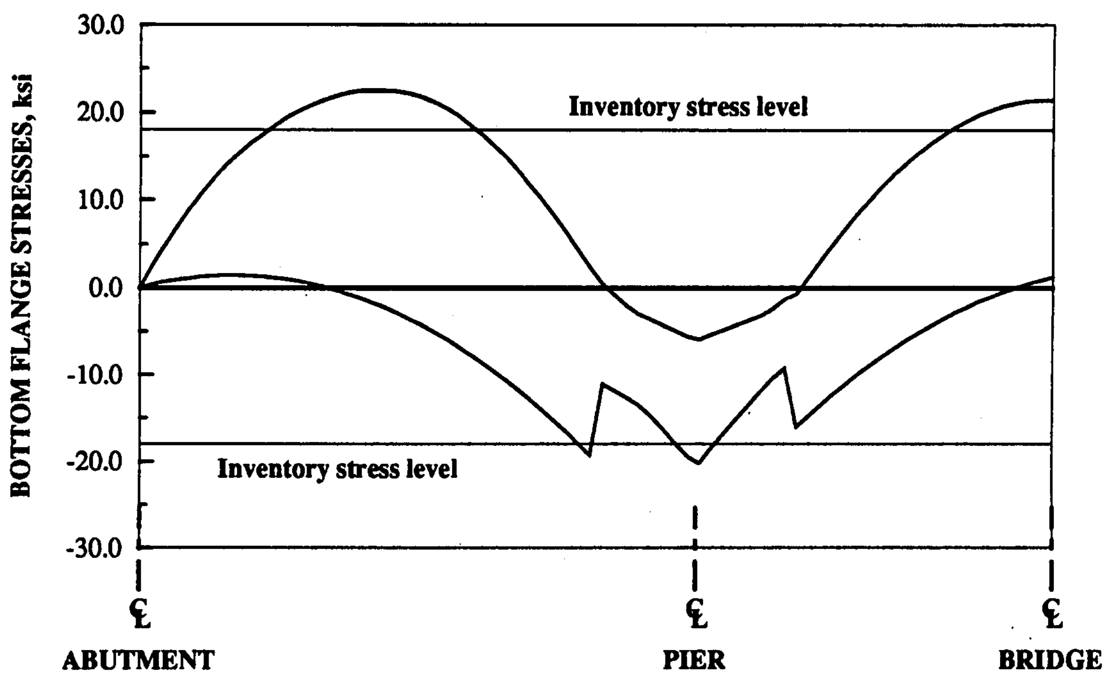
5.5. Computation of stresses on the bridge stringers due to vertical loads

▫ COMPUTE BOTTOM FLANGE STRESSES ALONG THE LENGTH OF THE STRINGERS DUE TO VERTICAL LOADS

The moment envelopes computed in Sec. 5.4 have been used to compute the stresses induced by the vertical loads in the bridge stringers at sections spaced one ft apart. The section properties used for computing stresses are the same as those used for the analysis of the stringers due to vertical loads, and are given in Table 5.1. The stresses were computed separately for dead loads, superimposed dead loads, and live loads, and are added to give the final stress envelopes shown in Fig. 5.3.



a. EXTERIOR STRINGER



b. INTERIOR STRINGER

Fig. 5.3. Stress envelopes due to vertical loads.

- **CREATE A FILE "STRESS.VRT" CONTAINING THE STRESS ENVELOPE VALUES DUE TO VERTICAL LOADS AT A NUMBER OF SECTIONS ALONG THE LENGTH OF THE STRINGERS.**

The user needs to prepare this file for later use (see Sec. 5.9.1). This file will be imported into the spreadsheet Table IV.3 to be added to the stresses due to the strengthening system for determining the stress envelopes after strengthening. The file should be composed of four columns containing the following data:

- Stress envelope for the maximum tensile stresses in the extreme bottom fibers of the exterior stringers.
- Stress envelope for the maximum compressive stresses in the extreme bottom fibers of the exterior stringers.
- Stress envelope for the maximum tensile stresses in the extreme bottom fibers of the interior stringers.
- Stress envelope for the maximum compressive stresses in the extreme bottom fibers of the interior stringers.

It should be noted that the top flange steel stresses and the concrete stresses are not input into the spreadsheet since the bottom flange stresses are usually more critical. The check of stringer top flange stresses and the concrete deck stresses is given in Secs. 5.9.2 and 5.9.3.

The length of the file created should not exceed 80 rows in order to fit into Table IV.3. In this example, the length of the file was 75 rows. A printout of the file is given in Appendix B.

5.6. Input of bridge parameters and computation of force and moment fractions

In this section, the user inputs values into all the designated "input cells" of Table II.1 of the spreadsheet. Preliminary estimates need to be made for some of these values as they will be unknown at this time; these values may be revised at a later stage in the calculations to obtain a better design.

■ MAKE A PRELIMINARY ESTIMATE OF THE TENDON LENGTHS AND POSITIONS, AND THE BRACKET LOCATIONS

In Sec. 3.3.2, recommended values are provided to assist the engineer in making reasonable assumptions for the lengths and the positions of the post-tensioning tendons, and the superimposed trusses.

Length of end-span tendon	= 0.60 x 45.75	= 28.00 ft
Length of center-span tendon	= 0.50 x 58.50	= 30.00 ft
Length of truss tendon	= 2 x 0.24 x 45.75	= 22.00 ft
Distance of first bracket from centerline of end abutment	= 0.12 x 45.75	= 5.50 ft
Bracket length		= 1.50 ft

■ INPUT THE ESTIMATED VALUES TOGETHER WITH THE BASIC BRIDGE PARAMETERS INTO TABLE II.1 OF THE SPREADSHEET.

The following is a list of these input values:

Stringer spacing = 92 in.
Deck thickness = 6.6 in.
End-span length = 45.75 ft
Center-span length = 58.50 ft
Inertia of half-bridge section:

- Considering only steel W-shape and reinforced concrete deck
- Considering full composite section including W-shape, coverplates and reinforced concrete deck

Note, these two values have been automatically copied from Table I.3. However, the user has the option of overriding these values and inputting other computed values. This option is needed if the user did not use Tables I.1, I.2, and I.3 to compute the section properties, and is using section properties computed by other means.

Tendon lengths:	for end-span	= 28.00 ft
	for center-span	= 30.00 ft
	for truss	= 22.00 ft

Note, tendon lengths are measured from the outside edges of the brackets. i.e., the bracket lengths are included.

Coverplate lengths:	for exterior stringer	= 18.0 ft
(see Fig. 1.1)	for interior stringer	= 19.0 ft
First bracket location:		= 5.50 ft from abutment centerline
Bracket length:		= 1.50 ft for all stringer spans

The first and second brackets are in the end span while the third bracket is in the center span; locations of the second and third brackets are automatically computed based on the specified tendon lengths and first bracket location. The bracket locations are the same for all exterior and interior stringers.

Values in Table II.1 are used by the spreadsheet to compute the force and moment fractions described in Sec. 3.1. Although the user does not need to review these computations, they can be seen in the spreadsheet area [R1..Z75].

5.7. Computation of overstresses to be removed by strengthening

The maximum tensile and compressive stresses in the extreme bottom fiber of the W-shape (or coverplate) of the exterior and interior stringers due to dead, live and impact loads were computed in Sec. 5.4. Since the bottom flange of the steel section experiences the largest stringer stresses, actual and allowable stresses are computed for the bottom fibers of the steel sections of both stringers. The strengthening system is initially designed to reduce the actual stresses to the allowable limits in the bottom fibers at the most critical sections along the stringers. The stresses in the top of the steel section and in the concrete deck are checked after determining the final design forces since they are usually less critical. Modification may be made in the strengthening system if the top flange steel stresses or concrete deck stresses exceed the allowable limits. It should be noted however that the top flange stresses and concrete deck stresses are seldom critical.

Table II.1 of the spreadsheet has the following form:

TABLE II.1.

Input of bridge parameters :

Stringer spacing	=	92.00	in.
Deck thickness	=	6.60	in.
Length of end span	=	45.75	ft
Length of center span	=	58.50	ft
Total bridge length	=	150.00	ft
%w			
Inertia of bridge section:			
Steel beam + R.C. deck	=	11582.85	in.^4
Full composite section	=	17756.13	in.^4
Length of end-span cable	=	28.00	ft
Length of center-span cable	=	30.00	ft
length of truss cable	=	22.00	ft
coverplate length: ext. stringer	=	18.00	ft
int. stringer	=	19.00	ft
First bracket location	=	5.50	ft
Second bracket location	=	33.50	ft
Third bracket location	=	60.00	ft
Bracket length	=	1.50	ft

5.7.1. Allowable stresses

◘ COMPUTE THE ALLOWABLE STEEL TENSION STRESSES

The allowable stresses in the bottom flange of the steel section are given in Sec. 10.32 of Ref. 13. In positive moment locations, the bottom flange is in tension, and the allowable stress (assuming F_y = 33 ksi) is given by:

$F_t = 0.55\ F_y = 0.55 \times 33 = 18$ ksi (to the nearest ksi)

■ COMPUTE THE ALLOWABLE COMPRESSIVE STRESS IN THE BOTTOM FLANGE OF THE EXTERIOR STRINGERS

In the negative moment regions on both sides of the piers, the bottom flange is in compression. According to Sec. 10.32 of Ref. 13, the allowable compressive stress in the bottom flange of the exterior stringers is computed as follows:

The unsupported length of the flange is the minimum of :

a. Distance between diaphragms
(in end span) = 45.75/2 = 22.88 ft
(in center-span) = 58.50/3 = 19.50 ft

b. Distance from support to dead load inflection point
= 13.50 ft

Therefore, the unsupported length of the flange is 13.50 ft. The radius of gyration, r′, of the bottom flange is computed as follows:

$$(r')^2 = \frac{I_{bottom\ flange}}{A_{bottom\ flange}} = \frac{0.5x10^3+0.615x8.24^3}{0.5x10+0.615x8.24} = 6.99\ in^2$$

The allowable compression stress is given by:

$$F_b = 0.55\ F_y\left[1 - \frac{\left(\frac{l}{r'}\right)^2 F_y}{4\ \pi^2\ E}\right]$$

$$F_b = 0.55\ x\ 33\ x\left[1 - \frac{\frac{(13.5\ x\ 12)^2}{6.99}\ x\ 33}{4\ \pi^2\ x\ 29000}\right] = 16.17\ ksi$$

According to Note (a) of Table 10.32.1.A of Ref. 13, the allowable compression stress at the pier may be increased by 20%, but should not exceed 0.55 F_y. In this case,

F_b = 1.20 x 16.17 = 19.40 ksi > 18 ksi

Hence, the allowable compressive stress is F_b = 18 ksi. (to the nearst ksi)

■ COMPUTE THE ALLOWABLE COMPRESSIVE STRESS IN THE BOTTOM FLANGE OF THE INTERIOR STRINGER

Since the bottom flange of the interior stringer is larger than that of the exterior stringer, its radius of gyration is larger and consequently its allowable compressive stress is also 18 ksi.

5.7.2. Stresses due to vertical loads at the critical sections

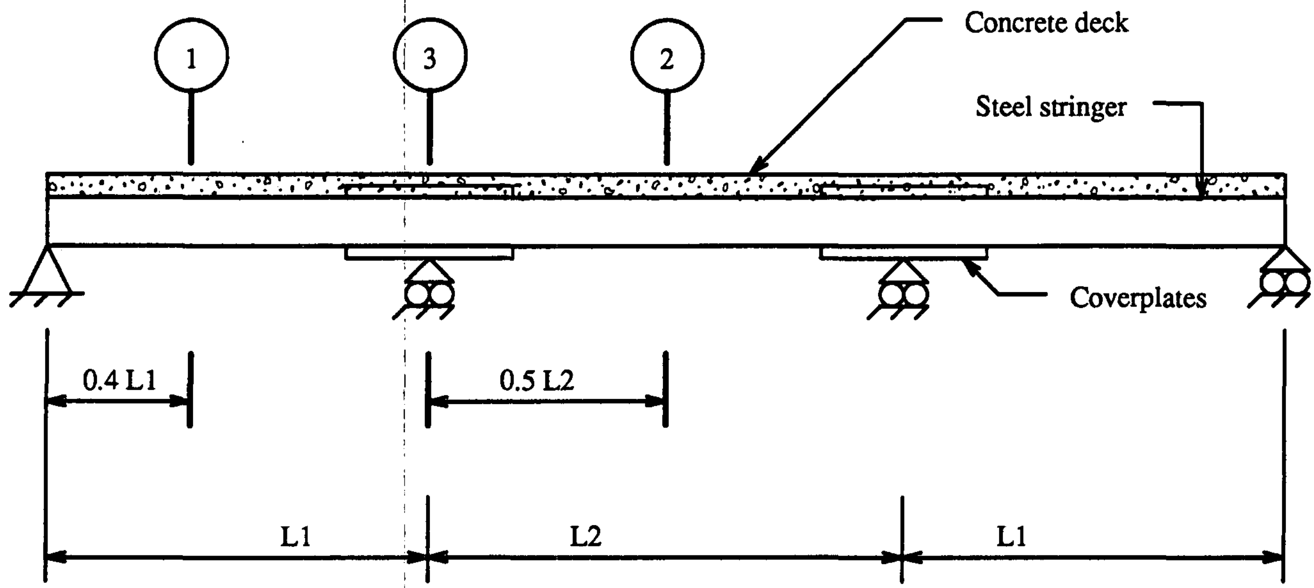
■ DETERMINE BOTTOM FLANGE STRESSES AT THE CRITICAL SECTIONS OF THE EXTERIOR AND INTERIOR STRINGERS RESULTING FROM VERTICAL LOADS

Three critical stress locations in each stringer are shown in Fig. 5.4. The first section is in the end span at the maximum tensile stress location. This maximum stress location obviously varies depending on the bridge parameters and loads. To simplify the design procedure, the critical section has been assumed to be at a distance of 40% of the span length from the end support. The second section is at the middle of the center span, and the third is at the maximum negative moment location, i.e., at the pier.

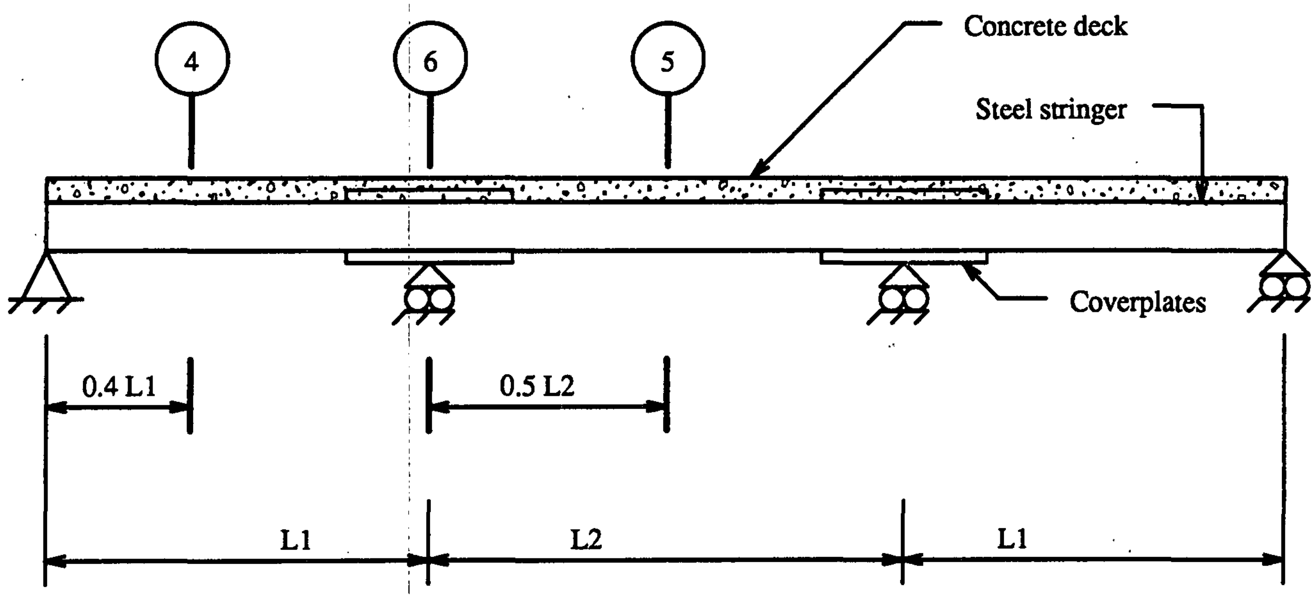
Table II.2 of the spreadsheet lists a numbering scheme for the critical sections [1] through [6], as shown in Fig. 5.4. Reference will be made to these sections throughout the example using this numbering scheme. The stresses in the bottom flange - or coverplates - at these sections due to vertical loads are obtained from Fig. 5.3, and are as follows:

Vertical load stress at Sec. [1] = + 21.56 ksi
at Sec. [2] = + 21.02 ksi
at Sec. [3] = - 24.36 ksi
at Sec. [4] = + 22.48 ksi
at Sec. [5] = + 21.42 ksi
at Sec. [6] = - 20.23 ksi

Note, the negative sign indicates a compression stress in the bottom flange.



a. EXTERIOR STRINGER



b. INTERIOR STRINGER

Fig. 5.4. Critical stress locations.

5.7.3. Computation of overstresses at the critical sections

- **COMPUTE OVERSTRESSES IN THE BOTTOM FLANGES OF THE EXTERIOR AND INTERIOR STRINGERS AT THE CRITICAL SECTIONS**

The overstresses at the critical sections need to be computed by the user. The overstresses are computed as the difference between the stresses due to vertical loads and the allowable stresses at the sections .

Overstress at Sec. [1] = + 21.56 - 18 = + 3.56 ksi
at Sec. [2] = + 21.02 - 18 = + 3.02 ksi
at Sec. [3] = - 24.36 + 18 = - 6.36 ksi
at Sec. [4] = + 22.48 - 18 = + 4.48 ksi
at Sec. [5] = + 21.42 - 18 = + 3.42 ksi
at Sec. [6] = - 20.23 + 18 = - 2.23 ksi

As previously noted, the negative sign indicates a compression stress in the bottom flange.

- **COMPUTE THE DISTANCE FROM THE EXTREME BOTTOM FLANGE FIBER OF THE W-SHAPE TO THE CENTER OF THE TENDONS AT THE CRITICAL SECTIONS**

The engineer needs to make an estimate of the tendon elevations above the bottom flanges of the exterior and interior stringers based on the size of available hydraulic cylinders and jacking chairs. These values will be input into Table II.2 of the spreadsheet together with the overstresses at the critical sections.

As previously noted in Sec. 3.2.2, it is recommended to position the tendons above the bottom flanges of the stringers. In this example, the tendon elevation was estimated based on the diameter of the available hollow-core hydraulic cylinders. In most instances, it is necessary to use a 120 kip capacity hollow-core hydraulic cylinder. Hollow-core cylinders of this capacity frequently have a diameter of $6^1/_4$ in. [16]. Assuming an $^1/_8$ in.

clearance, the tendons can be placed so that the centerline of the tendons are $3^1/_4$ in. above the bottom flanges, and $3^1/_4$ in. away from the stringer web. It is desirable to minimize the tendon elevation above the bottom flange to increase the moment arm of the post-tensioning forces about the bridge neutral axis. Therefore, if less post-tensioning force is required, smaller hydraulic cylinders (capacity and diameter) can be used and the $3^1/_4$ in. elevation can be reduced.

The elevation of the tendons above the extreme bottom fiber of the W-shape is equal to the tendon elevation above the top of the bottom flange plus the flange thickness =

3.25 + 0.615 = 3.87 in.   for exterior stringers

3.25 + 0.685 = 3.94 in.   for interior stringers

▪ INPUT DATA INTO THE DESIGNATED "INPUT CELLS" OF TABLE II.2.

The following is a list of values that need to be input by the user:

- The data input in the first three columns of the table are the cross-sectional area, the moment of inertia, and the distance from the extreme bottom fiber of the W-shape (or coverplate) to the neutral axis of the section, respectively. These values were automatically entered into the table when the user pressed ALT-A, while working on Part I of the spreadsheet. The user needs to make sure that the values in these three columns are the section properties used in computing the vertical load stresses at these sections. If the user did not use Tables I.1 and I.2 of the spreadsheet to compute the section properties of the stringers, the section property values in Table II.2 should be overridden with the values used.
- In the fourth column of the table entitled "Bottom flange overstress", the values +3.56, +3.02, -6.36, +4.48, +3.42,

-2.23 ksi are input for the overstresses in Secs. [1] through [6], respectively.

- In the last column of the table, the tendon elevation values are input. A value of 3.87 in. is input into the cells corresponding to Secs. [1] and [2], and 3.94 in. is input for Secs. [4] and [5].

Table II.2 of the spreadsheet now takes the following form:

TABLE II.2.

Table Cont. ------>

Overstresses:	Sec.	X-sec. Area (in.^2)	X-sec. Inertia (in.^4)	Y of bot. flange from NA (in.)	Bottom flange overstress (ksi)	Tendon Elev. (in.)
Exterior Stringer:						
@ 40 % of end span	[1]	71.65	5467.71	22.06	3.56	3.87
@ middle of center span	[2]	71.65	5467.71	22.06	3.02	3.87
@ pier	[3]	28.30	2485.83	11.00	-6.36	---
Interior Stringer:						
@ 40 % of end span	[4]	80.48	6094.99	23.04	4.48	3.94
@ middle of center span	[5]	80.48	6094.99	23.04	3.42	3.94
@ pier	[6]	37.53	4405.16	12.69	-2.23	---

Comments on Table II.2:

- The section numbering used here [1] through [6] is the same as that in Fig. 5.4.
- In the column titled "Bottom flange overstress", a tension overstress in the bottom flange should be input as positive, and a compression overstress as negative.
- The tendon elevation is measured from the extreme bottom fiber of the W-shape (or coverplate, depending on the section) to the centerline of the tendon.

■ **PRESS ALT-Q**

Running this macro, the data input into Tables II.1 and II.2 of the spreadsheet are transferred to the rest of the spreadsheet.

5.8. Design of the required strengthening system

5.8.1. Choice of strengthening scheme

■ **ASSUME THE STRENGTHENING SCHEME REQUIRED**

The different locations for post-tensioning and superimposed trusses are shown in Fig. 5.5. The user can select a configuration composed of any combination of the cases [A, B, C, D, and E] for strengthening a given bridge. Considering the locations of the overstresses in this example, a system composed of post-tensioning tendons on all spans of the exterior and interior stringers together with superimposed trusses at the piers of the exterior stringers, as shown in Fig. 5.6 was assumed. This is specified in the spreadsheet as follows:

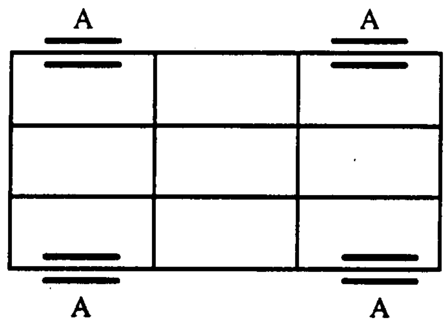
■ **INPUT THE VALUE OF 1 INTO ALL FIVE INPUT CELLS OF TABLE III.1.**

TABLE III.1.

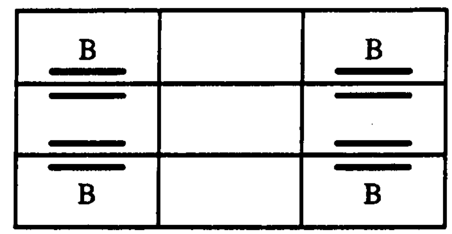
Design of strengthening system:	See Help ------->
	System [1/0]
Post-tensioning end spans of exterior stringers	1
Post-tensioning center spans of exterior stringers	1
Superimposed Trusses at piers of exterior stringer	1
Post-tensioning end spans of interior stringers	1
Post-tensioning center spans of interior stringers	1

Comments on Table III.1:

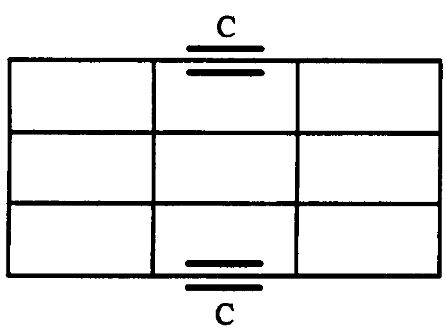
In the system column, 1 = post-tensioning or trusses used in this span



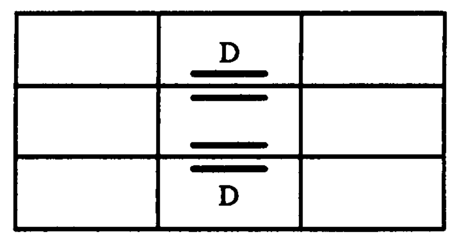
a. STRENGTHENING SCHEME [A]:
POST-TENSIONING END SPANS
OF THE EXTERIOR STRINGERS



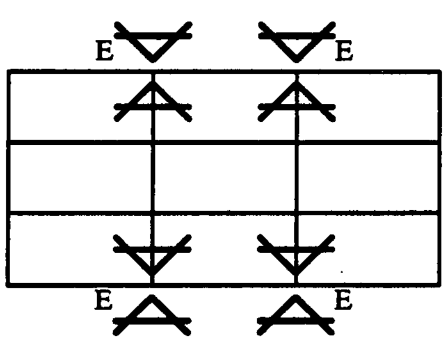
b. STRENGTHENING SCHEME [B]:
POST-TENSIONING END SPANS
OF THE INTERIOR STRINGERS



c. STRENGTHENING SCHEME [C]:
POST-TENSIONING CENTER SPANS
OF THE EXTERIOR STRINGERS



d. STRENGTHENING SCHEME [D]:
POST-TENSIONING CENTER SPANS
OF THE INTERIOR STRINGERS



e. STRENGTHENING SCHEME [E]:
SUPERIMPOSED TRUSSES AT THE PIERS
OF THE EXTERIOR STRINGERS

Fig. 5.5. Various locations of post-tensioning and superimposed trusses.

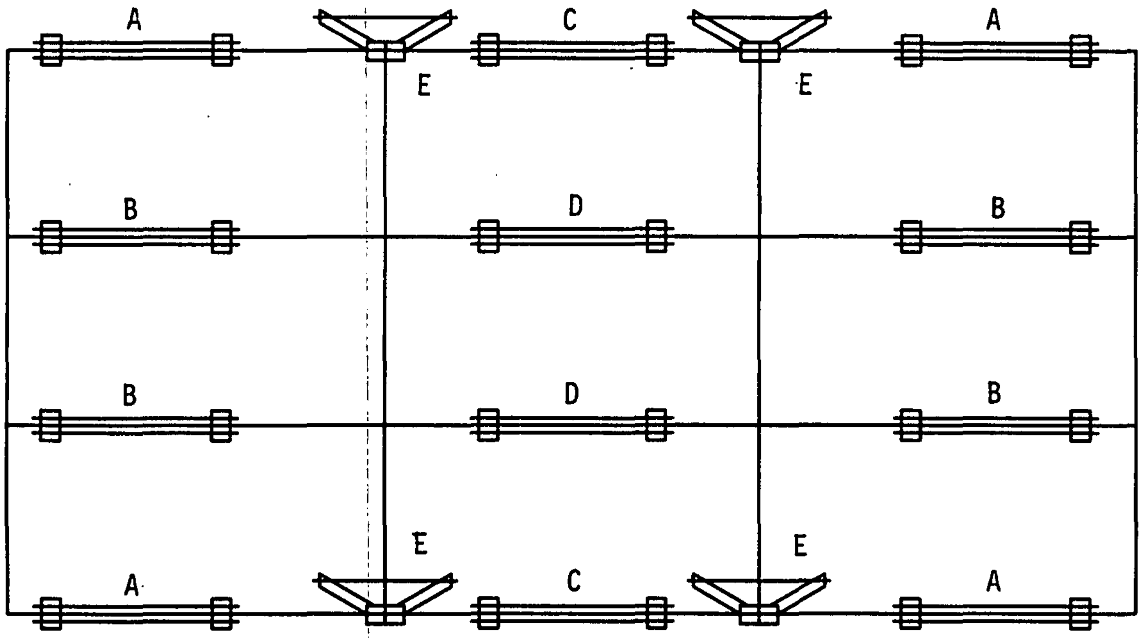


Fig.5.6. Strengthening system selected for use in example problem.

0 = post-tensioning or trusses not used in this span

CHECK PRACTICALITY OF THE ASSUMED SYSTEM AND ITS DIMENSIONS

Practical guidelines for design are given in Sec. 3.2. In this example, it was found that the stringer splices are very close to the bracket locations. Thus, the distance between them is not sufficient for placing the jacking chair and the hydraulic cylinder. To solve this problem, the designer has several options. Reducing the length of the center-span tendon increases the clearance between the splices and the brackets, however, this reduces the effectiveness of the post-tensioning. Another option is to use larger brackets thus increasing the distance between the tendons and the stringer web and flange; this permits the use of the jacking chair and hydraulic cylinder despite the presence of the splice plates. This has the disadvantage of reducing the moment arm of the post-tensioning forces and therefore making them less effective in reducing stresses. A third option is to use special jacking chairs to bypass the splice locations. In this example, it is assumed that special jacking chairs are available and thus the current design will be continued without modification.

5.8.2. Computation of strengthening forces

Tables III.2 and III.3 are for the computation of the strengthening system forces. These include the post-tensioning forces in the different spans of the exterior and interior stringers as well as the vertical truss forces.

Table III.2 is used to initiate the design and to perform the iterations needed to obtain the required forces. Final force values, after noting practical considerations, are input into Table III.3. These force values are automatically transferred to subsequent sections of the spreadsheet.

■ TO START THE DESIGN, PRESS ALT-S

This activates a macro which initializes all force values to zero. However, the cells in the column entitled "Force" are designated as "input cells" which provides the engineer the option of inputting assumed values of the forces rather than zeros.

Table III.2 has the form:

TABLE III.2.

See Help ------>

		Force (kips)	Sec. No.	Stress Reduction Required [Sr] (ksi)	Stress Reduction Achieved [Sa] (ksi)	Diff. [Sa-Sr] (ksi)	Is stress reduction achieved ?
PT EX END	F1 =	0.00	[1]	-3.56	0.00	3.56	NO
PT EX CEN	F2 =	0.00	[2]	-3.02	0.00	3.02	NO
TRUSS EX	F3 =	0.00	[3]	6.36	0.00	-6.36	NO
PT IN END	F4 =	0.00	[4]	-4.48	0.00	4.48	NO
PT IN CEN	F5 =	0.00	[5]	-3.42	0.00	3.42	NO
			[6]	2.23	0.00	-2.23	NO

PT: Post-tensioning EX: Exterior Stringer END: End-spans
TRUSS: Superimposed trusses IN: Interior stringers CEN: Center-spans

Comments on Table III.2:

- Forces in the first column: F1, F2, F4, and F5 are the post-tensioning forces in the tendons. F3 is the vertical force at the truss bearing points.
- The column [Sr] contains the required stress reduction at the six critical sections. These values are automatically copied from Table II.2 of the spreadsheet.
- The column [Sa] contains the actual stress reduction achieved by the forces in the [Force] column. The stress reduction values are computed using the force and moment fractions computed in Sec. 5.5.
- The column [Sa-Sr] gives the difference between the achieved stress reduction and the desired reduction.

- A "NO" in the column [Is stress reduction achieved ?] indicates that the stress reduction is less than that desired at the critical sections. When the desired stress reduction is achieved, it is so designated by the word, "YES".

■ TO ITERATE UNTIL THE DESIRED STRESS REDUCTION IS ATTAINED, PRESS ALT-I

By pressing Alt-I, an iteration is performed changing the forces so that the stress reduction is closer to the required reduction. Table III.2 of the spreadsheet now takes this form:

TABLE III.2.

See Help ------>

		Force (kips)	Sec. No.	Stress Reduction Required [Sr] (ksi)	Stress Reduction Achieved [Sa] (ksi)	Diff. [Sa-Sr] (ksi)	Is stress reduction achieved ?
PT EX END	F1 =	30.66	[1]	-3.56	-2.16	1.40	NO
PT EX CEN	F2 =	36.88	[2]	-3.02	-1.61	1.41	NO
TRUSS EX	F3 =	6.29	[3]	6.36	4.07	-2.29	NO
PT IN END	F4 =	36.51	[4]	-4.48	-2.33	2.15	NO
PT IN CEN	F5 =	39.72	[5]	-3.42	-1.76	1.66	NO
			[6]	2.23	2.11	-0.12	NO

PT: Post-tensioning EX: Exterior Stringer END: End-spans
TRUSS: Superimposed trusses IN: Interior stringers CEN: Center-spans

■ REPEAT THE ITERATION PROCESS BY PRESSING ALT-I

The user should repeat pressing ALT-I until all cells desired in the last column of Table III.2 indicate the desired stress reduction is achieved, i.e., a "YES" in all cells of the last column. If the engineer decides values in the [Sa-Sr] column are sufficiently small, one may proceed with one or more "NO's" in the last column. In this example, a total of 24 iterations were required to achieve the required stress reduction at all six critical sections. Table III.2 now takes this form:

TABLE III.2.

See Help ------>

		Force (kips)	Sec. No.	Stress Reduction Required [Sr] (ksi)	Stress Reduction Achieved [Sa] (ksi)	Diff. [Sa-Sr] (ksi)	Is stress reduction achieved ?
PT EX END	F1 =	41.54	[1]	-3.56	-3.56	-0.00	YES
PT EX CEN	F2 =	67.48	[2]	-3.02	-3.02	-0.00	YES
TRUSS EX	F3 =	8.64	[3]	6.36	6.36	-0.00	YES
PT IN END	F4 =	81.55	[4]	-4.48	-4.48	0.00	YES
PT IN CEN	F5 =	82.22	[5]	-3.42	-3.42	0.00	YES
			[6]	2.23	3.91	1.68	YES

PT: Post-tensioning EX: Exterior Stringer END: End-spans
TRUSS: Superimposed trusses IN: Interior stringers CEN: Center-spans

Note, the stress difference value, $[S_a-S_r]$, at Sec. [6] is 1.68 ksi. This indicates that the achieved stress reduction is more than required.

5.8.3. Final design forces

■ **PRESS ALT-W**

By running this macro, the design forces in the "Force" column in Table III.2 are transferred into the "Force" column of Table III.3, which consequently takes the following form:

TABLE III.3.

Final design: See Help ------>

	Force (kips)	Sec. No.	Stress Reduction Required [Sr] (ksi)	Stress Reduction Achieved [Sa] (ksi)	Diff. [Sa-Sr] (ksi)	Is stress reduction achieved ?
PT EX END F1 =	41.54	[1]	-3.56	-3.56	-0.00	YES
PT EX CEN F2 =	67.48	[2]	-3.02	-3.02	-0.00	YES
TRUSS EX F3 =	8.64	[3]	6.36	6.36	-0.00	YES
PT IN END F4 =	81.55	[4]	-4.48	-4.48	0.00	YES
PT IN CEN F5 =	82.22	[5]	-3.42	-3.42	0.00	YES
		[6]	2.23	3.91	1.68	YES

PT: Post-tensioning EX: Exterior Stringer END: End-spans
TRUSS: Superimposed trusses IN: Interior stringers CEN: Center-spans

■ **REVIEW THE DESIGN FORCE VALUES FOR PRACTICALITY, AND INPUT THE FINAL FORCE VALUES INTO THE "FORCE" COLUMN OF TABLE III.3.**

The user has the option to override the previously determined values to meet practical design considerations. Some of these considerations have been outlined in Sec. 3.2. In this example, the strengthening forces were considered suitable, and were only rounded to the nearest integer value (F1 = 42 kips, F2 = 68 kips, F3 = 9 kips, F4 = 82 kips, F5 = 83 kips). This rounding process resulted in the desired stress reductions not being achieved at some of the critical sections. In such cases, the user should adjust the five forces to restore the "YES" in all cells of the last column. After a few minor changes, Table III.3 takes this form:

TABLE III.3.

Final design: See Help ------>

		Force (kips)	Sec. No.	Stress Reduction Required [Sr] (ksi)	Stress Reduction Achieved [Sa] (ksi)	Diff. [Sa-Sr] (ksi)	Is stress reduction achieved ?
PT EX END	F1 =	41.00	[1]	-3.56	-3.57	-0.01	YES
PT EX CEN	F2 =	67.00	[2]	-3.02	-3.03	-0.01	YES
TRUSS EX	F3 =	9.50	[3]	6.36	6.62	0.26	YES
PT IN END	F4 =	82.00	[4]	-4.48	-4.50	-0.02	YES
PT IN CEN	F5 =	82.00	[5]	-3.42	-3.44	-0.02	YES
			[6]	2.23	3.99	1.76	YES

PT: Post-tensioning EX: Exterior Stringer END: End-spans
TRUSS: Superimposed trusses IN: Interior stringers CEN: Center-spans

■ COMPUTE THE TRUSS TENDON FORCES

The horizontal force in the truss tendons is computed based on the truss angle of inclination and the required truss vertical force (F3 in Table III.3) as follows:

From the truss drawing, assuming the truss members are 6 in. x 6 in. square tubes, the angle between truss tube centerline and the horizontal is determined to be 4.45°. The horizontal tension force = 9.50 / tan(4.45°) = 122 kips. (Note, that this force is to be divided between the two trusses on both sides of the web of the exterior stringer).

■ COMPUTE THE REQUIRED CROSS-SECTIONAL AREA OF THE TENDONS

High-strength steel should be used for the post-tensioning and truss tendons. In strengthening simple-span and continuous-span bridges, the authors have used DYWIDAG threadbars [14]. The ultimate strength of these tendons is 150 ksi.

5.9. Check of stresses

In the previous section, the design forces were determined. These forces achieved the desired stress reduction in the bottom flange of the stringers at the six critical sections. Other critical locations in the stringers, however, must be checked also. Examples of these critical locations are: (1) the coverplate cutoff points, (2) the bracket locations, and (3) the truss bearing points. The stresses in the top flanges or coverplates of the steel stringers and in the concrete deck will be addressed in this section as well.

5.9.1. Stresses in the bottom flange of the steel stringers

Part IV of the spreadsheet computes the bottom flange stresses at various locations along the length of the stringers.

- **CHECK THE VALUES IN TABLE IV.1, AND ADJUST VALUES IN THE "INPUT CELLS" IF NECESSARY**

The values in the "input cells" of Table IV.1 are transferred from Parts I and II of the spreadsheet. The user has the option to override the values in the "input cells" of this table to match those used for computation of stresses due to vertical loads. Table IV.1 appears on the screen as shown on the following page.

It should be noted that in most of the spreadsheet tables, there are cells designated as input cells (shown here underlined). The spreadsheet, in most instances, automatically computes values and inputs them into these cells. However, the user should change these values depending on his/her assumptions. To demonstrate the flexibility of the design spreadsheet, an example in which some of the values in Table IV.1 of the spreadsheet are changed is given here.

TABLE IV.1.

See Help ------>

[A] Section Properties for computation of stresses in the different ranges of the EXTERIOR STRINGER due to maximum POSITIVE MOMENTS:

Range From (ft)	To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	36.75	71.65	5467.71	22.06	22.06	0.39
36.75	54.75	81.65	7796.73	21.15	20.65	1.80
54.75	75.00	71.65	5467.71	22.06	22.06	0.39
75.00						
	---	---	---	---	---	---

[B] Section Properties for computation of stresses in the different ranges of the EXTERIOR STRINGER due to maximum NEGATIVE MOMENTS:

Range From (ft)	To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	36.75	18.30	1330.00	10.50	10.50	11.95
36.75	54.75	28.30	2485.83	11.00	10.50	11.95
54.75	75.00	18.30	1330.00	10.50	10.50	11.95
75.00						
	---	---	---	---	---	---

[C] Section Properties for computation of stresses in the different ranges of the INTERIOR STRINGER due to maximum POSITIVE MOMENTS:

Range From (ft)	To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	36.25	80.48	6094.99	23.04	22.79	-0.34
36.25	55.25	95.61	9952.41	21.29	21.04	1.40
55.25	75.00	80.48	6094.99	23.04	22.79	-0.34
75.00						
	---	---	---	---	---	---

[D] Section Properties for computation of stresses in the different ranges of the INTERIOR STRINGER due to maximum NEGATIVE MOMENTS:

Range From (ft)	To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	36.25	22.40	2100.00	12.00	11.75	10.70
36.25	55.25	37.53	4405.16	12.69	11.75	10.70
55.25	75.00	22.40	2100.00	12.00	11.75	10.70
75.00						
	---	---	---	---	---	---

In Sec. 5.6, the coverplate lengths input into Table II.1 of the spreadsheet are the actual coverplate lengths (i.e., 18.0 ft and 19.0 ft for the exterior and interior stringers, respectively). These lengths were used in the spreadsheet to compute section properties used in the three moment equations. They were also used automatically to create the first two columns of Table IV.1.[A,B,C, and D]. When the stresses due to vertical loads were computed, theoretical coverplate lengths (i.e., 15.50 ft and 16.25 ft for the exterior and interior stringers, respectively) were used (See Sec. 5.4). The user therefore needs to change the limits of the different section properties in Table IV.1 of the spreadsheet (i.e., values in column 2 of the table). By making this modification, the range limits used for computing the stresses induced by the strengthening system match those used for computing the vertical load stresses.

In Sec. 5.4, the limits of the regions of different section properties along the stringers were computed as follows:

On the exterior stringers:

First range:	from	00.00 ft	to	38.00 ft
Second range:	from	38.00 ft	to	53.50 ft
Third range:	from	53.50 ft	to	75.00 ft

On the interior stringers:

First range:	from	00.00 ft	to	37.62 ft
Second range:	from	37.62 ft	to	53.88 ft
Third range:	from	53.88 ft	to	75.00 ft

Since the stresses are computed at intervals of one ft, stresses are computed at one section which is exactly 38.00 ft from the support. When computing stresses due to vertical loads, this section was considered to be in the first range. It is important to adjust the limits of the different ranges in Table IV.1 to ensure that the stresses at this section due to the strengthening system are computed based on the same section properties that were used to compute vertical load stresses. Therefore, a value of 38.02 ft (slightly higher than 38.00 ft) was substituted for 38.00 ft as the limit of the first range.

- **INPUT THE VALUES [38.02, 53.50, AND 75.00] INTO THE FIRST THREE CELLS OF THE SECOND COLUMN OF TABLE IV.1.[A,B] AND INPUT [37.62, 53.88, AND 75.00] INTO THE FIRST THREE CELLS OF THE SECOND COLUMN OF TABLE IV.1.[C,D].**

Table IV.1 now takes the following form:

TABLE IV.1.

See Help ------->

[A] Section Properties for computation of stresses in the different ranges of the EXTERIOR STRINGER due to maximum POSITIVE MOMENTS:

Range From (ft)	Range To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	38.02	71.65	5467.71	22.06	22.06	0.39
38.02	53.50	81.65	7796.73	21.15	20.65	1.80
53.50	75.00	71.65	5467.71	22.06	22.06	0.39
75.00						
	---	---	---	---	---	---

[B] Section Properties for computation of stresses in the different ranges of the EXTERIOR STRINGER due to maximum NEGATIVE MOMENTS:

Range From (ft)	Range To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	38.02	18.30	1330.00	10.50	10.50	11.95
38.02	53.50	28.30	2485.83	11.00	10.50	11.95
53.50	75.00	18.30	1330.00	10.50	10.50	11.95
75.00						
	---	---	---	---	---	---

[C] Section Properties for computation of stresses in the different ranges of the INTERIOR STRINGER due to maximum POSITIVE MOMENTS:

Range From (ft)	Range To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	37.62	80.48	6094.99	23.04	22.79	-0.34
37.62	53.88	95.61	9952.41	21.29	21.04	1.40
53.88	75.00	80.48	6094.99	23.04	22.79	-0.34
75.00						
	---	---	---	---	---	---

[D] Section Properties for computation of stresses in the different ranges of the INTERIOR STRINGER due to maximum NEGATIVE MOMENTS:

Range From (ft)	Range To (ft)	Area (in.^2)	Inertia (in.^4)	Dist. of bottom flange to NA(in.)	Stringer NA elev. (in.)	Elev. diff. (stringer NA -bridge NA) (in.)
0.00	37.62	22.40	2100.00	12.00	11.75	10.70
37.62	53.88	37.53	4405.16	12.69	11.75	10.70
53.88	75.00	22.40	2100.00	12.00	11.75	10.70
75.00						
	---	---	---	---	---	---

▪ DETERMINE THE NUMBER OF DIVISIONS ALONG THE STRINGER LENGTHS AT WHICH STRESSES ARE TO BE COMPUTED FOR PLOTTING.

The sections used for stress computation in the spreadsheet should be the same as those used in the computation of the vertical load stresses. This is particularly important since the stresses will be added to give the final stress diagrams along the stringers in Table IV.3. Therefore, the spacing used here is the same as that which was used in the vertical load stress computations (i.e., one ft).

Half-bridge length = 150/2 = 75.00 ft
Number of divisions = 75.00 / 1.00 = 75 divisions

▪ INPUT THE NUMBER OF DIVISIONS INTO THE SPREADSHEET

In this example, it was determined that 75 divisions would be used. The maximum number of divisions permitted in the spreadsheet is 80.

▪ PRESS ALT-E

This macro uses the number of divisions specified to create the first column of Table IV.2. The user can override these values to input other values for the location of the sections at which stresses are to be computed (unequal spacing of the sections is allowed). These sections positions do not have to be equally spaced, but should match those used for computation of vertical load stresses.

▪ PRESS ALT-Y

This macro uses the section properties in Table IV.1 to create a table containing the section properties for each section along the stringer length. It is usually unnecessary for the user to review this table, however, the table is given in spreadsheet area [S490..AI580].

■ PRESS ALT-R

This macro uses the final design force values in Table III.3, together with the force and moment fractions computed for the bridge, to compute the axial force and moment values due to the strengthening system at the stringer sections previously identified. The stress values are placed in columns [2 through 5] of Table IV.2. A portion of Table IV.2 is shown here for illustration, and a full printout of the table is given in Appendix B.

TABLE IV.2.

Axial forces and bending moments due to the strengthening system:

Distance (ft)	Axial Force (kips)		Bending Moment at standard neutral axis (in.k)	
	Exterior Stringer	Interior Stringer	Exterior Stringer	Interior Stringer
0.00	0.00	0.00	0.00	0.00
1.00	0.52	-0.52	-2.79	-32.70
2.00	1.04	-1.04	-5.59	-65.41
3.00	1.56	-1.56	-8.38	-98.11
4.00	2.07	-2.07	-11.18	-130.81
5.00	2.59	-2.59	-13.97	-163.52
..				
..				
..				
70.00	67.23	81.77	543.78	617.39
71.00	67.26	81.74	538.77	622.40
72.00	67.28	81.72	533.77	627.41
73.00	67.31	81.69	528.76	632.41
74.00	67.33	81.67	523.75	637.42
75.00	67.36	81.64	518.75	642.42

■ **IMPORT FILE "STRESS.VRT" INTO THE SPREADSHEET TABLE IV.3.**

The file "STRESS.VRT" contains the stresses due to the applied vertical loads as explained in Sec. 5.4. Since the file will be imported into columns [B through E] of Table IV.3 of the spreadsheet, it is important to check that the number of rows in the file does not exceed 80. Also, one should check that the computed stresses are placed in the file in the correct order as was explained in Sec. 5.4.

To import the file, move the cursor to the cell in the first row and the second column of numbers of Table IV.3. Use " / FILE IMPORT NUMBERS A:\STRESS.VRT ", and press RETURN. The file is imported into columns [B through E] of Table IV.3. The table now takes this form:

TABLE IV.3.

Table Cont. ------>

Distance (ft)	Bottom flange stress envelopes due to vertical loads (dead + live + impact) (ksi)				Bottom flange stress envelopes due to vertical loads and the strengthening system (ksi)			
	Exterior Stringer		Interior Stringer		Exterior Stringer		Interior Stringer	
	Maximum Tension	Maximum Compres.	Maximum Tension	Maximum Compres.	Maximum Tension	Maximum Compres.	Maximum Tension	Maximum Compres
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	2.39	0.25	2.50	0.35	2.39	0.29	2.63	0.53
2.00	4.59	0.45	4.82	0.65	4.60	0.54	5.08	1.00
3.00	6.65	0.61	6.98	0.90	6.67	0.74	7.37	1.43
4.00	8.55	0.73	8.97	1.10	8.57	0.90	9.50	1.82
5.00	10.30	0.80	10.80	1.26	10.32	1.01	11.45	2.15
..								
..								
71.00	20.38	-1.18	20.75	-0.45	17.37	-2.77	17.28	-2.66
72.00	20.70	-0.68	21.09	0.03	17.71	-2.22	17.59	-2.21
73.00	20.90	-0.21	21.31	0.47	17.93	-1.72	17.80	-1.80
74.00	21.00	0.20	21.42	0.85	18.06	-1.26	17.89	-1.44
75.00	21.00	0.58	21.42	1.19	18.07	-0.85	17.87	-1.13
MAX.	21.56		22.48		18.15		18.03	
MIN.		-24.36		-20.23		-17.67		-16.35

See Help ------>

■ CHECK THE MAXIMUM STRESSES IN THE LAST TWO ROWS OF TABLE IV.3.

The last two rows of Table IV.3 entitled "MAX & MIN" give the maximum positive and negative stresses in the bottom flanges of the stringers, respectively. The values in the last four columns of these rows indicate the maximum and minimum stresses after strengthening and should not exceed the allowable stress limits.

In this example, the maximum tension stress on the interior stringer was found to be 18.03 ksi on the exterior stringer and 18.15 ksi on the interior stringer, which are slightly larger than the allowable stress limit of 18 ksi. The reason for this is that in this design procedure, the maximum stress section was assumed to be at a distance of 40% of the end-span length from the support. Checking the stress values in Table IV.3, the actual maximum stress section is shifted slightly towards the midspan. To account for this slight overstress, one possibility is to increase the overstress value at sec. [4] and repeat the spreadsheet design steps starting from Table II.2.

Overstress at sec. [1] = 3.56 + (18.03 - 18.0) = 3.59 ksi.

Overstress at sec. [4] = 4.48 + (18.15 - 18.0) = 4.63 ksi.

Details of the repeated design steps are not shown here.

■ GRAPHS OF THE FINAL STRESSES ON THE EXTERIOR AND INTERIOR STRINGERS

Reviewing the graphs of the final stresses is particularly important due to the several locations along the stringers at which the stresses could exceed the allowable limits.

To view the graphs use " / GRAPH NAME USE ", use the arrow keys to choose the desired graph, and press RETURN. After viewing, the user can leave the graphics screen by pressing RETURN. Four named graphs are available for the engineer to review:

EXTINITL: Exterior stringer stress envelopes before strengthening: See Fig. 5.3a.

INTINITL: Interior stringer stress envelopes before strengthening: See Fig. 5.3b.

EXTFINAL: Exterior stringer stress envelopes after strengthening: See Fig. 5.7a

INTFINAL: Interior stringer stress envelopes after strengthening: See Fig. 5.7b

5.9.2. Stresses in the top flanges of the steel stringers

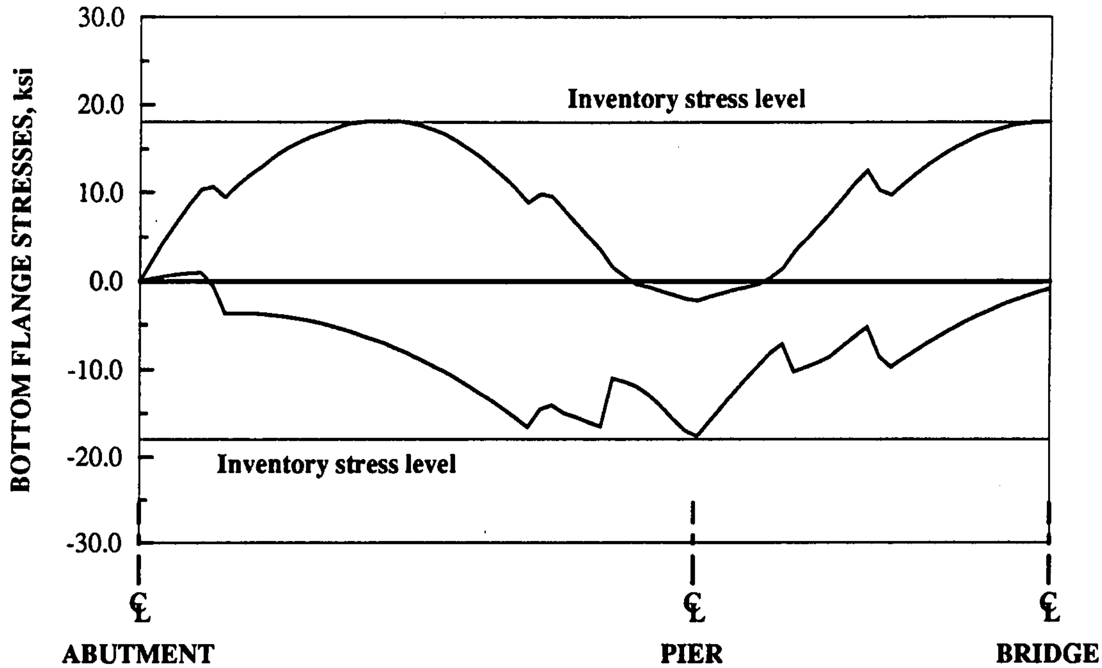
■ **CHECK THE STRESSES IN THE STRINGER TOP FLANGES**

In positive moment regions, the stresses in the top fibers of the steel stringers are relatively small. In this example, the maximum stresses in the top fibers before strengthening are equal to:

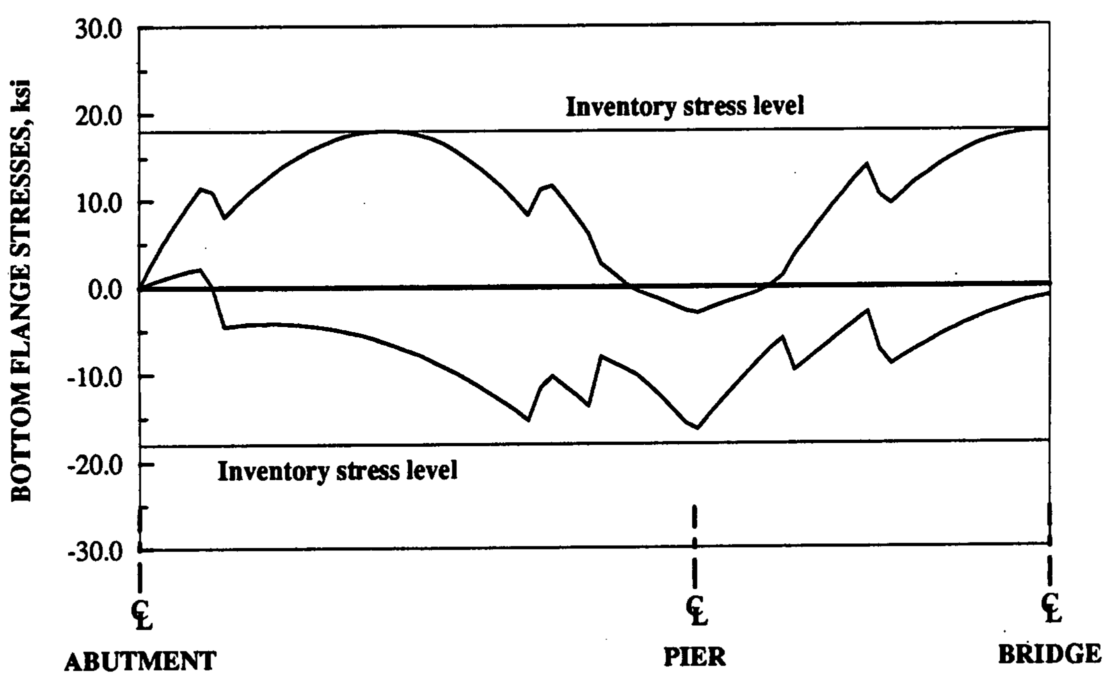
- 5.17 ksi at Sec. [1]
- 6.93 ksi at Sec. [4]

Since the stresses are below the allowable stress level, and the effect of the strengthening system is to produce a reduction in stresses at these sections, there is no need to check the stresses after strengthening.

In the negative moment regions, all stresses are computed based on the "bare" steel sections. Due to the symmetry of the section and the top and bottom coverplates, the stresses in the top flange are equal to those in the bottom flange. Also, since the axial forces resulting from the post-tensioning system are small at the piers, the stress reduction is achieved solely by the moments imposed by the strengthening system. Therefore, the stress reduction is the same at the top and bottom fibers, and there is no need for an additional stress check.



a. EXTERIOR STRINGER



b. INTERIOR STRINGER

Fig. 5.7. Stress envelopes due to vertical loads and strengthening system.

5.9.3. Stresses in the concrete deck

■ **CHECK THE STRESSES IN THE CONCRETE DECK**

The allowable compression stress in the concrete is given by:

$$f^{c}_{all} = 0.4\ f'_{c} = 0.4 \times 3.00 = 1.2 \text{ ksi comp.}$$

In this example, the maximum compression stresses in the concrete deck are equal to:

0.44 ksi comp. < 1.20 ksi comp. at Sec. [1]

0.59 ksi comp. < 1.20 ksi comp. at Sec. [4]

The effect of the strengthening system is to reduce the concrete stresses at these sections. However, one must check to determine if there are excessive tension stresses at these sections which would cause excessive deck cracking.

5.10. Accounting for post-tensioning losses and approximations in the design methodology

As explained in Sec. 4.2 of Ref. 8, several assumptions have been made in developing the design methodology which may result in some small errors in the computed strengthening forces. In addition, the post-tensioning losses which occur in the tendons with time need to be taken into account.

In the force and moment fraction formulas, the error range varies from one formula to another, which makes it difficult to account for the errors using the error ranges given in Appendix A. An easier approach to account for the errors and losses is outlined in Sec. 4.2 of Ref. 8. The approach is based on increasing the design force values by 8% and checking the stringer stresses for the design forces with and without the increase.

■ INCREASE ALL DESIGN FORCE VALUES BY 8%

F1 = 41.00 x 1.08 = 44.28 kips
F2 = 67.00 x 1.08 = 72.36 kips
F3 = 9.50 x 1.08 = 10.26 kips
F4 = 82.00 x 1.08 = 88.56 kips
F5 = 82.00 x 1.08 = 88.56 kips

■ CHECK STRINGER STRESSES FOR THE REVISED DESIGN FORCES

Although the revised Table III.3 with F1= 44.28 kips, F2= 72.36 kips, etc. has not been included, all stresses were within allowable limits. The user should input the new design force values into the "Force" column in Table III.3 and repeat the stress check procedure.

6. SUMMARY

Two methods of strengthening continuous-span composite bridges have been described in this manual. The first is the post-tensioning of the positive moment regions of the bridge stringers, the second is the addition of superimposed trusses to the exterior stringers at the piers.

The use of post-tensioning and superimposed trusses is an efficient method of correcting flexural overstresses in under capacity bridges. However, if the bridge has other deficiencies such as inadequate shear connection, fatigue problems, or extensive corrosion, correction or elimination of these problems must be considered in the decision to strengthen or replace a given bridge.

Transverse and longitudinal distribution of axial forces and moments induced by the strengthening system occur since the bridge is an indeterminant structural unit. The force and moment distribution fraction formulas developed in this manual (valid for standard Iowa DOT V12 and V14, three-span, four-stringer bridges) provide the practicing engineer with a tool for determining the distribution of forces and moments induced by the strengthening system throughout the bridge. These formulas are valid within the limits of the variables stated in this manual. Use of the distribution fraction formulas beyond these limits is not recommended.

Post-tensioning (and the superimposed trusses) will reduce elastic, flexural-tension stresses in bridge stringers, will induce a small amount of camber, and will increase the strength of the bridge. Post-tensioning of the positive moment regions and the application of superimposed trusses both increase the redundancy of the original structure and thus both increase the strength. Post-tensioning of the positive moment regions does not, however, significantly reduce live load deflection. Superimposed trusses as a result of providing an additional "load path" slightly reduce live load deflections. Neither post-tensioning the positive moment regions nor the superimposed trusses significantly affect truck live load distribution. If qualified contractors install the strengthening system and perform the actual post-tensioning with care, relatively little short term loss of post-tensioning will occur.

For long-term preservation of the strengthening system, components (such as the tendons, brackets, truss tubes, etc.) must be protected against corrosion. It also should be noted that removal of portions of the bridge deck or integral curbs after strengthening will cause losses in the tendon forces. Also, reduction of the cross-section (removal of a portion of the deck or integral curbs) while the bridge is post-tensioned will result in undesired and possibly damaging large upward deflections of the bridge. Thus, in most instances, it is advisable to completely remove or significantly reduce the post-tensioning forces before removing portions of deck and/or integral curbs.

The design methodology for strengthening continuous-span bridges is extremely complex due to the fact that both transverse and longitudinal distribution of the strengthening forces must be taken into account. To simplify the procedure, a spreadsheet has been developed for use by practicing engineers. This design aid greatly simplifies the design of a strengthening system for a given bridge in that it eliminates numerous tedious hand calculations, computes the different force and moment fractions, and performs the necessary iterations for determining the required strengthening forces.

7. ACKNOWLEDGMENTS

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- Dirk Jablonski (County Engineer, Cerro Gorrdo County)
- Robert D. Reinhart (County Engineer, Pocahontas County)
- Douglas L. Wood (Structures Laboratory Supervisor, ISU)

Special thanks are accorded to the several undergraduate students in Civil Engineering and graduate students in Structural Engineering at ISU for their assistance in various phases of the project. Former graduate students, Sam M. Planck and Thomas E. Bosch, are acknowledged for having made significant contributions to this investigation.

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APPENDIX A

FORMULAS FOR FORCE AND MOMENT FRACTIONS

Definition of terms

R^2 = Coefficient of Determination.

ERROR = Predicted value (using formula)

– Actual value (from finite element analysis).

Strengthening schemes:

Case A : Post-tensioning of all end-span exterior stringers.

Case B : Post-tensioning of all end-span interior stringers.

Case C : Post-tensioning of all center-span exterior stringers.

Case D : Post-tensioning of all center-span interior stringers.

Case E : Superimposed trusses on exterior stringers at all pier locations.

For cases A, B, and E:

$$\mathrm{FF_i} = \text{Force Fraction at Sec (i)} = \frac{\text{Axial force in exterior stringer at Sec (i)}}{\text{Total axial force on the bridge at Sec (i)}}$$

$$\mathrm{MF_i} = \text{Moment Fraction at Sec (i)} = \frac{\text{Moment in exterior stringer at Sec (i)}}{\text{Total moment on the bridge at Sec (i)}}$$

For cases C and D:

$$\mathrm{FF_i} = \text{Force Fraction at Sec (i)} = \frac{\text{Axial force in interior stringer at Sec (i)}}{\text{Total axial force on the bridge at Sec (i)}}$$

$$\mathrm{MF_i} = \text{Moment Fraction at Sec (i)} = \frac{\text{Moment in interior stringer at Sec (i)}}{\text{Total moment on the bridge at Sec (i)}}$$

Definition of parameters

$$X_L = 0.0167 \times \frac{\text{TOTAL BRIDGE LENGTH}}{\text{STRINGER SPACING}} + 0.3$$

$0.50 < X_L < 1.00$

$$X_S = 9.0 \times \frac{\text{DECK THICKNESS}}{\text{STRINGER SPACING}}$$

$0.50 < X_S < 1.00$

$$X_{P1} = 1.5 \times \frac{\text{LENGTH OF POST – TENSIONED PORTION OF END SPAN}}{\text{LENGTH OF END SPAN}}$$

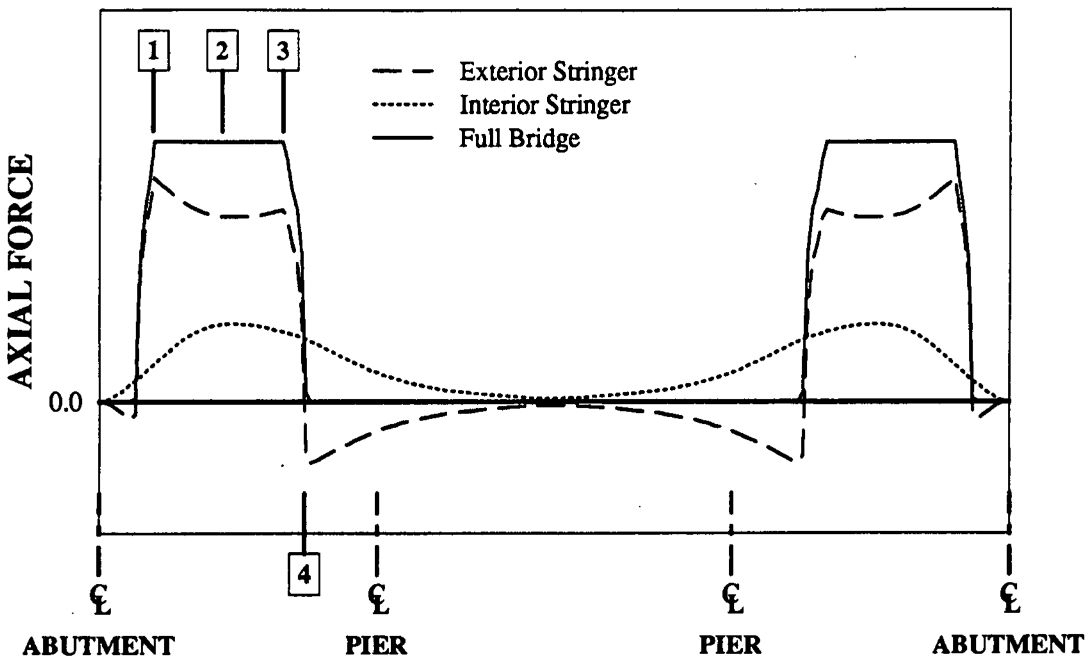
$0.60 < X_{P1} < 1.00$

$$X_{P2} = 1.5 \times \frac{\text{LENGTH OF POST – TENSIONED PORTION OF CENTER SPAN}}{\text{LENGTH OF CENTER SPAN}}$$

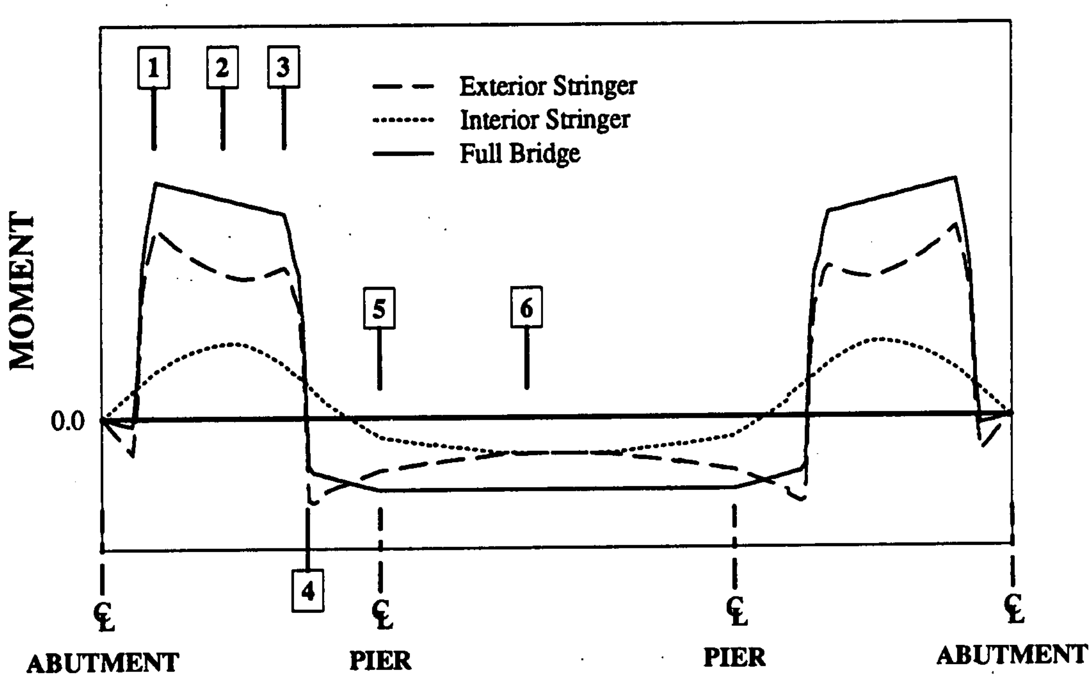
$0.60 < X_{P2} < 1.00$

$$X_{P3} = 1.5 \times \frac{\text{LENGTH OF SUPERIMPOSED TRUSS TENDON}}{\text{LENGTH OF END SPAN}}$$

$0.60 < X_{P3} < 1.00$



a. AXIAL FORCE DIAGRAM



b. MOMENT DIAGRAM

Fig. A-1. Locations of distribution fractions for strengthening scheme [A].

Table. A.1. Force Fractions for strengthening scheme [A].

$$FF_1 = 0.1659 + \frac{0.4171}{X_S} + \frac{0.0490}{X_L} - 0.1035\,X_{P1}$$

$0.76 < FF_1 < 0.92$; $R^2 = 0.98$; $-0.010 < ERROR < +0.015$

$$FF_2 = -\,0.1460 + \frac{0.6331}{X_S} + \frac{0.0465}{X_L} - 0.2650\,X_{P1}$$

$0.62 < FF_2 < 0.84$; $R^2 = 0.97$; $-0.020 < ERROR < +0.020$

$$FF_3 = -\,0.1928 + \frac{0.4057}{X_S} + \frac{0.0234}{X_L} + \frac{0.2099}{X_{P1}}$$

$0.66 < FF_3 < 0.82$; $R^2 = 0.97$; $-0.015 < ERROR < +0.015$

$$FF_4 = -\,0.1254 + 0.4852\,X_S - 0.0181\,X_L + \frac{0.0377}{X_L} + 0.0763\,X_{P1} - \frac{0.0417}{X_L\,X_{P1}}$$

$0.17 < FF_4 < 0.25$; $R^2 = 0.96$; $-0.008 < ERROR < +0.010$

Table. A.2. Moment Fractions for strengthening scheme [A].

$$MF_1 = 1.4444 - 1.0496\ X_S - 0.1532\ X_L + \frac{0.0724}{X_{P1}}$$

$0.68 < MF_1 < 0.86$; $R^2 = 0.98$; $-0.010 < ERROR < +0.013$

$$MF_2 = 1.6750 - 1.4748\ X_S + \frac{0.0782}{X_L} - \frac{0.2663}{X_{P1}}$$

$0.53 < MF_2 < 0.82$; $R^2 = 0.99$; $-0.015 < ERROR < +0.020$

$$MF_3 = 0.0084 + \frac{0.3657}{X_S} + \frac{0.0525}{X_L} + 0.0503\ X_{P1}$$

$0.66 < MF_3 < 0.82$; $R^2 = 0.98$; $-0.015 < ERROR < +0.020$

$$MF_4 = -5.8310 + 0.8482\ X_S - 0.6426\ X_L + \frac{0.6780}{X_L} + 1.7923\ X_{P1} + \frac{4.7586}{X_{P1}} + 0.5884\ X_L\ X_{P1} - \frac{0.6578}{X_L\ X_{P1}}$$

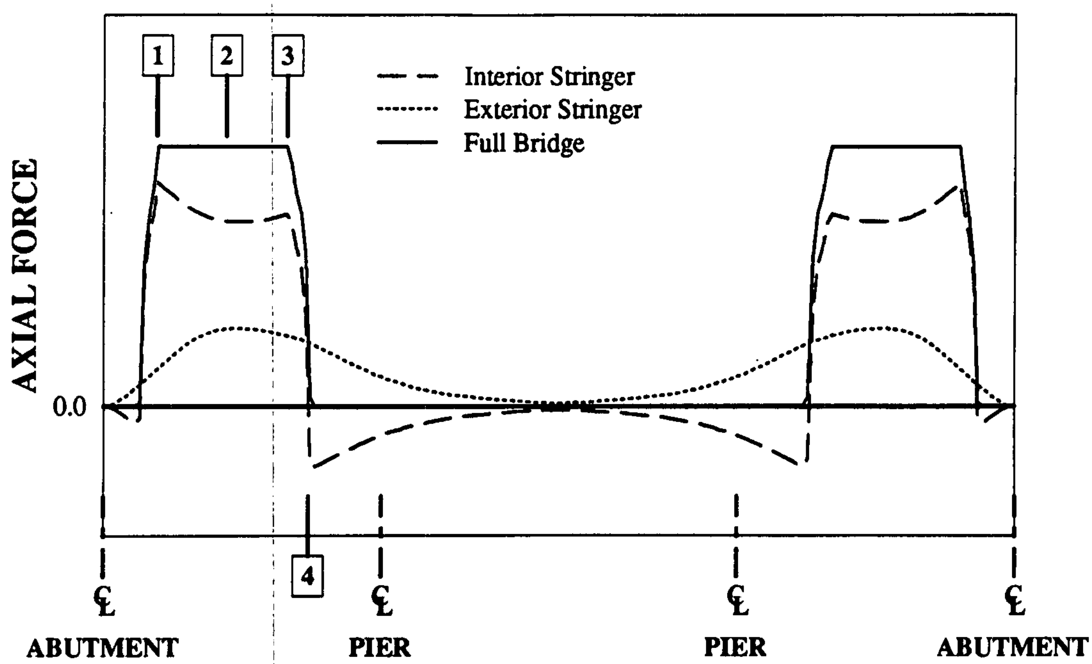
$1.20 < MF_4 < 2.00$; $R^2 = 0.99$; $-0.030 < ERROR < +0.040$

$$MF_5 = +2.8190 - 2.3043\ X_S - 0.2371\ X_L + \frac{0.1034}{X_L} - \frac{0.6381}{X_{P1}}$$

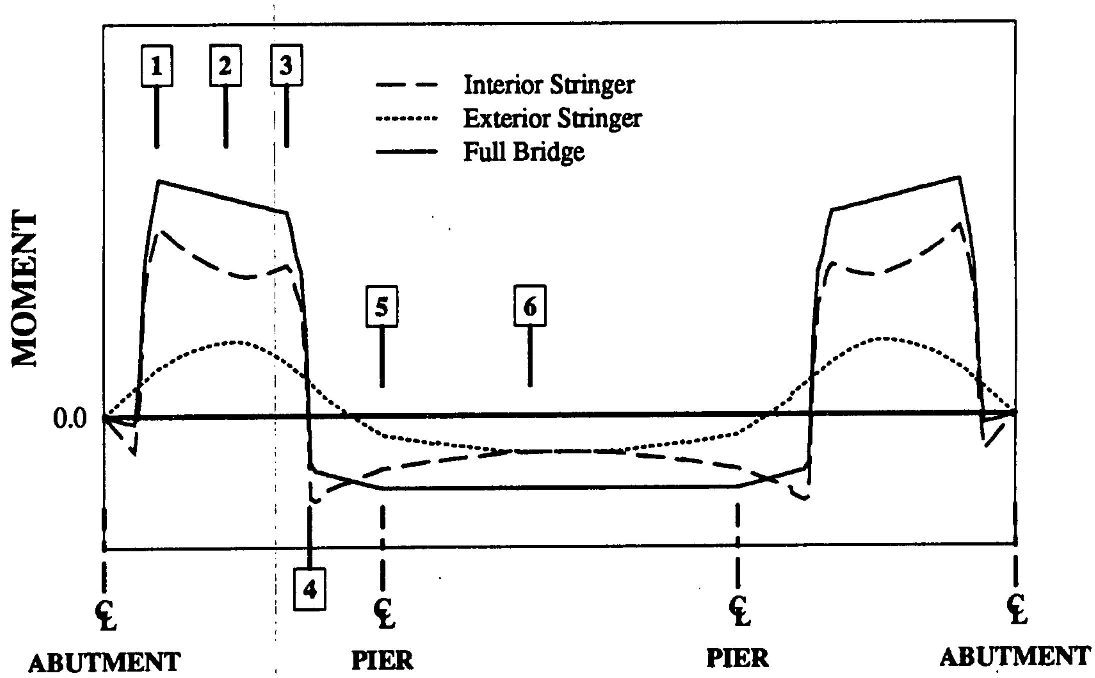
$0.35 < MF_5 < 1.00$; $R^2 = 0.98$; $-0.040 < ERROR < 0.060$

$$MF_6 = +0.8804 - 0.8078\ X_S + 0.0570\ X_L + \frac{0.0547}{X_L}$$

$0.47 < MF_6 < 0.57$; $R^2 = 0.96$; $-0.015 < ERROR < +0.025$



a. AXIAL FORCE DIAGRAM



b. BENDING MOMENT DIAGRAM

Fig. A-2. Locations of distribution fractions for strengthening scheme [B].

Table. A.3. Force Fractions for strengthening scheme [B].

$$FF_1 = 1.4847 - 1.1178\ X_S + 0.1157\ X_L + \frac{0.0419}{X_L} - 0.0576\ X_{P1}$$

$$- 0.0464\ X_L\ X_{P1}$$

$0.81 < FF_1 < 0.92$; $R^2 = 0.96$; $-0.015 < ERROR < +0.015$

$$FF_2 = 1.7760 - 1.6438\ X_S + 0.1516\ X_L + \frac{0.0617}{X_L} - 0.2043\ X_{P1}$$

$0.70 < FF_2 < 0.86$; $R^2 = 0.96$; $-0.020 < ERROR < +0.015$

$$FF_3 = 1.4215 - 1.0827\ X_S - 0.0356\ X_L + \frac{0.0395}{X_L} - 0.2193\ X_{P1}$$

$$+ \frac{0.0828}{X_{P1}} + 0.1636\ X_L\ X_{P1}$$

$0.72 < FF_3 < 0.86$; $R^2 = 0.96$; $-0.015 < ERROR < +0.015$

$$FF_4 = -0.2683 + 0.5053\ X_S + 0.0411\ X_L - \frac{0.0219}{X_L} + 0.2395\ X_{P1}$$

$$- 0.1342\ X_L\ X_{P1}$$

$0.13 < FF4 < 0.21$; $R^2 = 0.97$; $-0.006 < ERROR < +0.008$

Table. A.4. Moment Fractions for strengthening scheme [B].

$$MF_1 = 1.1697 - 0.9576\, X_S + \frac{0.0405}{X_L} + \frac{0.1008}{X_{P1}} + 0.0849\, X_L\, X_{P1}$$

$0.77 < MF_1 < 0.87$; $R^2 = 0.96$; $-0.020 < \text{ERROR} < +0.010$

$$MF_2 = 1.0494 - 1.3421\, X_S + \frac{0.0652}{X_L} + \frac{0.2531}{X_{P1}} + 0.1488\, X_L\, X_{P1}$$

$0.62 < MF_2 < 0.80$; $R^2 = 0.96$; $-0.030 < \text{ERROR} < +0.015$

$$MF_3 = 1.4142 - 0.9255\, X_S - 0.3347\, X_L + 0.2518\, X_L^2 + 0.0305\, X_{P1}$$

$0.72 < MF_3 < 0.80$; $R^2 = 0.93$; $-0.015 < \text{ERROR} < +0.015$

$$MF_4 = -4.6041 + 1.1642\, X_S - 1.9754\, X_L + \frac{0.6102}{X_L} + 0.8588\, X_{P1} + \frac{4.3578}{X_{P1}} + 1.7884\, X_L\, X_{P1} - \frac{0.5963}{X_L\, X_{P1}}$$

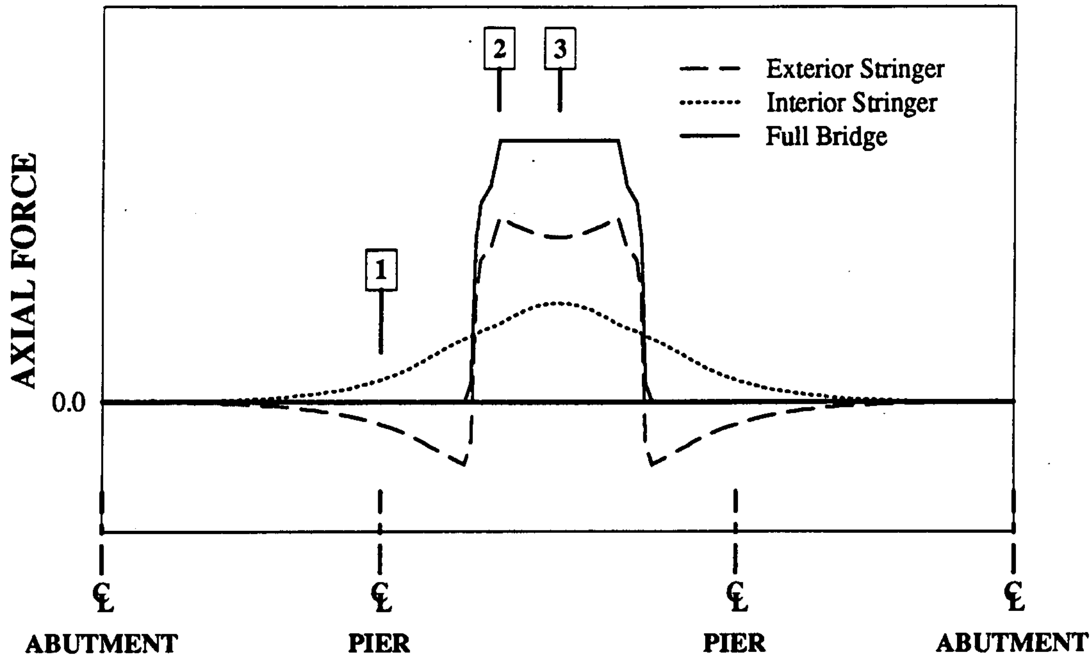
$1.20 < MF_4 < 1.85$; $R^2 = 0.99$; $-0.030 < \text{ERROR} < +0.030$

$$MF_5 = 0.9533 - 1.8118\, X_S + \frac{0.1361}{X_L} + 0.7762\, X_{P1}$$

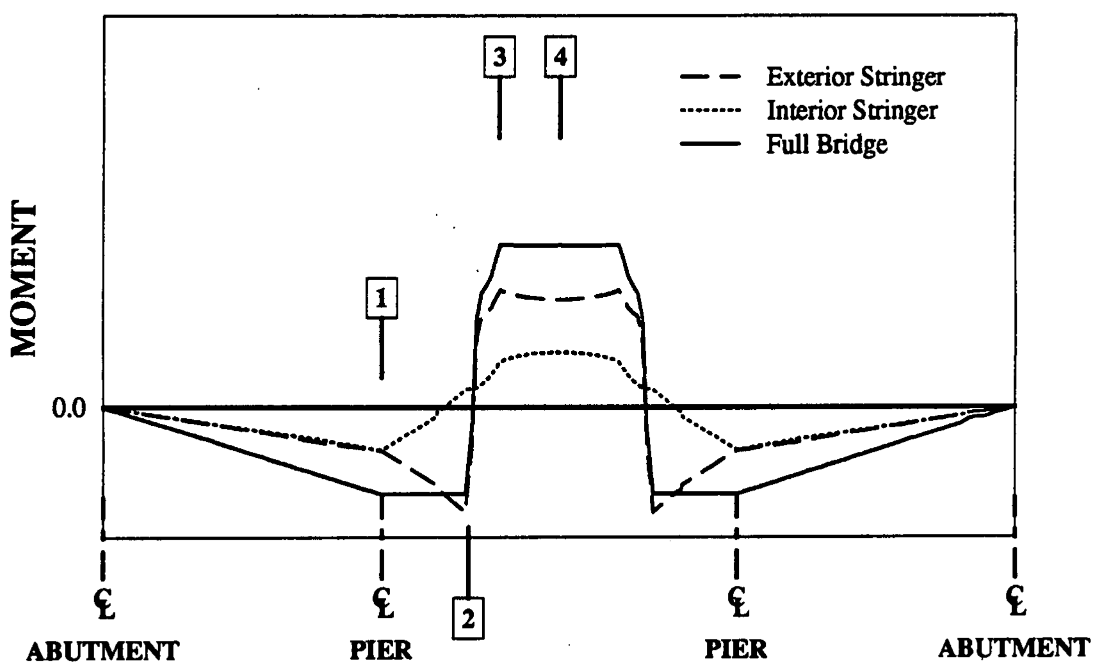
$0.50 < MF_5 < 1.05$; $R^2 = 0.98$; $-0.040 < \text{ERROR} < +0.030$

$$MF_6 = 0.9568 - 0.9214\, X_S + 0.1971\, X_L + \frac{0.0268}{X_L}$$

$0.50 < MF_6 < 0.59$; $R^2 = 0.95$; $-0.020 < \text{ERROR} < +0.010$



a. AXIAL FORCE DIAGRAM



b. MOMENT DIAGRAM

Fig. A-3. Locations of distribution fractions for strengthening scheme [C].

Table. A.5. Force Fractions for strengthening scheme [C].

$$FF_1 = 0.1305 + 0.2323\ X_S + \frac{0.0104}{X_L} + 0.0363\ X_L\ X_{P2} - \frac{0.0527}{X_{P2}}$$

$0.21 < FF_1 < 0.27$; $R^2 = 0.84$; $-0.015 < \text{ERROR} < +0.020$

$$FF_2 = 1.1259 - 0.7558\ X_S - \frac{0.0042}{X_L} - 0.0719\ X_L\ X_{P2} + \frac{0.0604}{X_{P2}}$$

$0.63 < FF_2 < 0.75$; $R^2 = 0.93$; $-0.020 < \text{ERROR} < +0.015$

$$FF_3 = 1.4098 - 1.2269\ X_S + \frac{0.0744}{X_L} - 0.2491\ X_{P2} + \frac{0.1110}{X_{P2}} - \frac{0.0464}{X_L\ X_{P2}}$$

$0.51 < FF_3 < 0.73$; $R^2 = 0.93$; $-0.030 < \text{ERROR} < +0.030$

Table. A.6. Moment Fractions for strengthening scheme [C].

$$MF_1 = 0.9832 - 1.7646\ X_S + 0.5882\ X_{P2} + \frac{0.0831}{X_L\ X_{P2}}$$

$0.32 < MF_1 < 0.74$; $R^2 = 0.99$; $-0.025 < ERROR < +0.010$

$$MF_2 = 0.7190 - 0.6419\ X_L + \frac{0.4874}{X_L} - 1.0113\ X_{P2} + \frac{0.7383}{X_{P2}} + 0.9387 X_L\ X_{P2} - \frac{0.3317}{X_L\ X_{P2}}$$

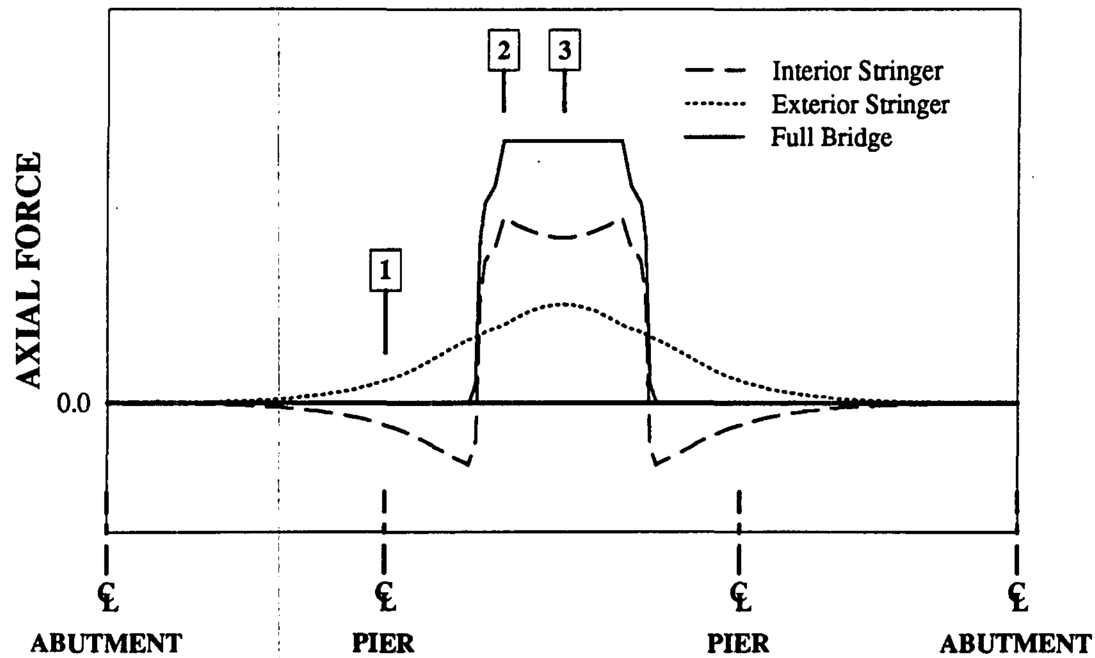
$0.90 < MF_2 < 1.25$; $R^2 = 0.93$; $-0.060 < ERROR < +0.060$

$$MF_3 = 0.1070 - 1.060\ X_S - 0.6953\ X_L + \frac{0.2683}{X_L} + 0.2219\ X_{P2} + \frac{0.7311}{X_{P2}} + 0.9839\ X_L\ X_{P2} - \frac{0.1566}{X_L\ X_{P2}}$$

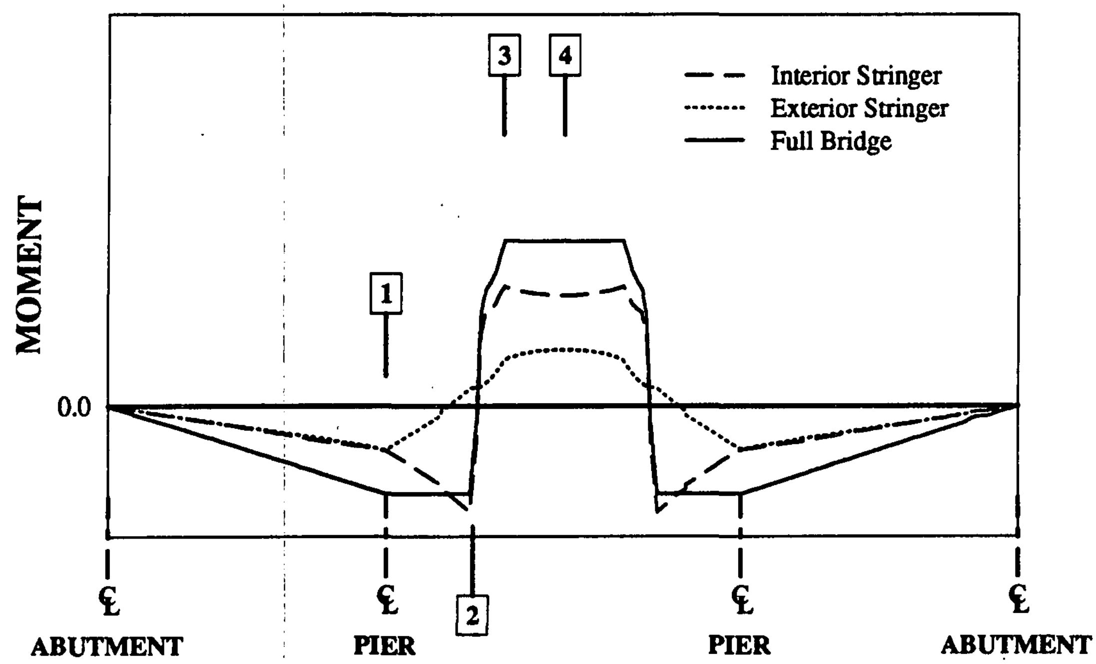
$0.65 < MF_3 < 0.83$; $R^2 = 0.98$; $-0.020 < ERROR < +0.015$

$$MF_4 = 1.7184 - 1.5195\ X_S - 0.3942\ X_L + \frac{0.2319}{X_L} - 0.6210\ X_{P2} + \frac{0.2605}{X_{P2}} + 0.4269\ X_L\ X_{P2} - \frac{0.1500}{X_L\ X_{P2}}$$

$0.50 < MF_4 < 0.77$; $R^2 = 0.98$; $-0.020 < ERROR < +0.025$



a. AXIAL FORCE DIAGRAM



b. MOMENT DIAGRAM

Fig. A-4. Locations of distribution fractions for strengthening scheme [D].

Table. A.7. Force Fractions for strengthening scheme [D].

$$FF_1 = -0.0081 + 0.3222\, X_S - 0.0240\, X_L + 0.0639\, X_{P2} - \frac{0.0238}{X_{P2}}$$

$0.16 < FF_1 < 0.23$; $R^2 = 0.88$; $-0.010 < \text{ERROR} < +0.020$

$$FF_2 = 1.3411 - 0.8362\, X_S + 0.0653\, X_L - 0.1033\, X_{P2} - 0.0589\, X_L\, X_{P2}$$

$0.71 < FF_2 < 0.80$; $R^2 = 0.91$; $-0.015 < \text{ERROR} < +0.015$

$$FF_3 = 1.6851 - 1.3404\, X_S + 0.0500\, X_L - 0.2444\, X_{P2}$$

$0.60 < FF_3 < 0.78$; $R^2 = 0.90$; $-0.030 < \text{ERROR} < +0.030$

Table. A.8. Moment Fractions for strengthening scheme [D].

$$MF_1 = 0.4763 - 1.3346\ X_S + 0.1545\ X_L + \frac{0.1003}{X_L} + 0.5963\ X_{P2} + \frac{0.1720}{X_{P2}}$$

$0.50 < MF_1 < 0.75$; $R^2 = 0.96$; $-0.030 < ERROR < +0.030$

$$MF_2 = 0.7626 + 0.1591\ X_S - 1.5176\ X_L + \frac{0.5503}{X_L} - 1.2904\ X_{P2} + \frac{1.0697}{X_{P2}} + 1.7569\ X_L\ X_{P2} - \frac{0.4462}{X_L\ X_{P2}}$$

$1.00 < MF_2 < 1.30$; $R^2 = 0.95$; $-0.035 < ERROR < +0.040$

$$MF_3 = 0.2304 - 0.8381\ X_S + 0.0655\ X_L + \frac{0.0405}{X_L} + 0.6248\ X_{P2} + \frac{0.3385}{X_{P2}} + 0.0760\ X_L\ X_{P2}$$

$0.75 < MF_3 < 0.84$; $R^2 = 0.93$; $-0.020 < ERROR < +0.010$

$$MF_4 = 1.5390 - 1.4148\ X_S - 0.5483\ X_L + \frac{0.3146}{X_L} - 0.8432\ X_{P2} + \frac{0.3868}{X_{P2}} + 0.9180\ X_L\ X_{P2} - \frac{0.2036}{X_L\ X_{P2}}$$

$0.60 < MF_4 < 0.78$; $R^2 = 0.94$; $-0.040 < ERROR < +0.025$

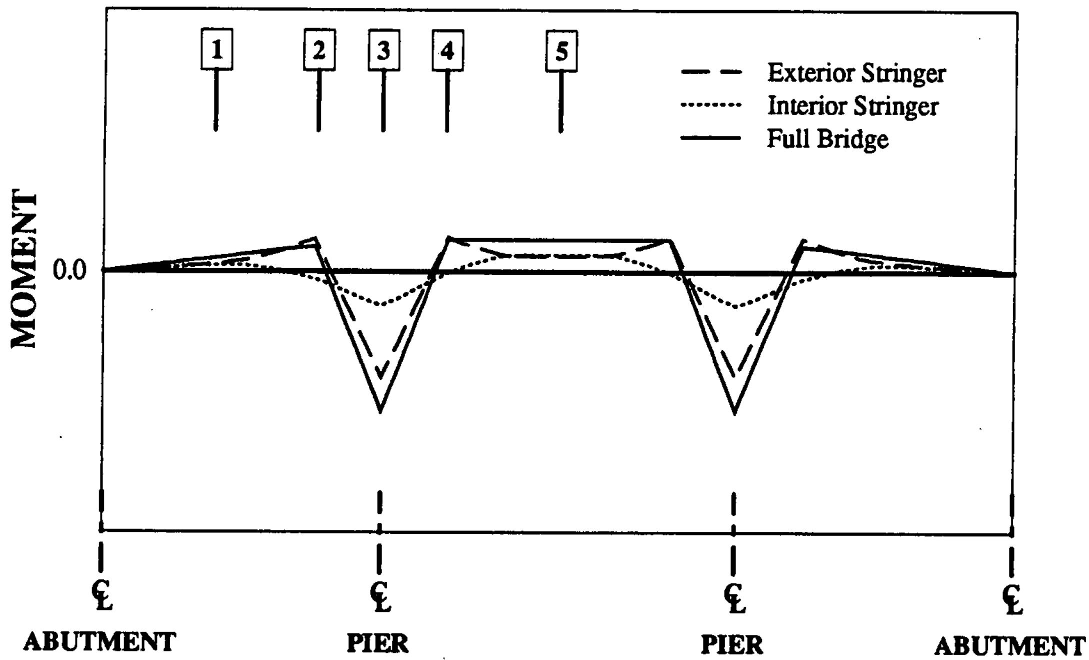


Fig. A-5. Locations of distribution fractions for strengthening scheme [E].

Table. A.9. Moment Fractions for strengthening scheme [E].

$$MF_1 = 0.8058 - 0.9633\ X_S - 0.4868\ X_L + 0.1297\ X_{P3} + 0.4863\ X_{P3}\ X_L + \frac{0.2024}{X_L}$$

$0.15 < MF_1 < 0.85$; $R^2 = 0.99$; $-0.020 < \text{ERROR} < +0.015$

$$MF_2 = 1.0614 - 0.8774\ X_S + \frac{0.1419}{X_L} - 0.1127\ X_{P3} + \frac{0.5645}{X_{P3}} - 0.3796\ X_L\ X_{P3} - \frac{0.1302}{X_L\ X_{P3}}$$

$1.00 < MF_2 < 1.45$; $R^2 = 0.97$; $-0.050 < \text{ERROR} < +0.030$

$$MF_3 = 1.4033 - 0.9035\ X_S + 0.0520\ X_L - 0.2553\ X_{P3} - 0.1892\ X_L\ X_{P3}$$

$0.55 < MF_3 < 0.90$; $R^2 = 0.99$; $-0.008 < \text{ERROR} < +0.013$

$$MF_4 = 0.8143 - 0.4088\ X_S + 0.7628\ X_L + \frac{0.3008}{X_{P3}} - 1.5101\ X_L\ X_{P3} - \frac{0.0262}{X_L X_{P3}}$$

$0.80 < MF_4 < 1.30$; $R^2 = 0.99$; $-0.020 < \text{ERROR} < +0.025$

$$MF_5 = 0.2333 - 0.3800\ X_S + 0.3370\ X_{P3} + \frac{0.1548}{X_L}$$

$0.25 < MF_5 < 0.70$; $R^2 = 0.99$; $-0.015 < \text{ERROR} < +0.015$

APPENDIX B

DESIGN METHODOLOGY SPREADSHEET TABLES

NOTE: This appendix contains two tables which are printouts from the spreadsheet (STRCONBR.WK1). The tables are TABLE.IV.2 and TABLE.IV.3. Due to their large size only portions of these tables were given in Chp.5. The printout given in this appendix have been reduced in size.

TABLE.IV.2.

Axial forces and bending moments due to the strengthening system:

Distance (ft)	Axial Force (kips)		Bending Moment at standard neutral axis (in.k)	
	Exterior Stringer	Interior Stringer	Exterior Stringer	Interior Stringer
0.00	0.00	0.00	0.00	0.00
1.00	0.52	-0.52	-2.79	-32.70
2.00	1.04	-1.04	-5.59	-65.41
3.00	1.56	-1.56	-8.38	-98.11
4.00	2.07	-2.07	-11.18	-130.81
5.00	2.59	-2.59	-13.97	-163.52
6.00	17.61	23.39	258.28	299.47
7.00	47.13	75.87	805.59	1258.14
8.00	47.40	75.60	797.19	1231.04
9.00	47.67	75.33	788.80	1203.93
10.00	47.95	75.05	780.41	1176.83
11.00	48.22	74.78	772.02	1149.72
12.00	48.49	74.51	763.62	1122.62
13.00	48.76	74.24	755.23	1095.51
14.00	49.03	73.97	746.84	1068.40
15.00	49.30	73.70	738.45	1041.30
16.00	49.58	73.42	730.05	1014.19
17.00	49.85	73.15	721.66	987.09
18.00	50.12	72.88	713.27	959.98
19.00	50.17	72.83	702.11	935.64
20.00	50.12	72.88	689.76	912.49
21.00	50.08	72.92	677.41	889.34
22.00	50.03	72.97	665.06	866.19
23.00	49.99	73.01	652.71	843.05
24.00	49.94	73.06	640.36	819.90
25.00	49.90	73.10	628.01	796.75
26.00	49.85	73.15	615.66	773.60
27.00	49.81	73.19	603.31	750.45
28.00	49.76	73.24	590.97	727.30
29.00	49.72	73.28	578.62	704.15
30.00	49.67	73.33	566.27	681.00
31.00	49.63	73.37	553.92	657.85
32.00	49.58	73.42	541.57	634.70
33.00	20.60	20.40	-14.30	-386.41
34.00	5.98	-5.98	-301.43	-905.52
35.00	5.74	-5.74	-342.65	-928.30
36.00	5.50	-5.50	-452.35	-968.09
37.00	5.25	-5.25	-562.06	-1007.89
38.00	5.01	-5.01	-671.76	-1047.68
39.00	4.77	-4.77	-781.46	-1087.48
40.00	4.53	-4.53	-891.17	-1127.27
41.00	4.28	-4.28	-1000.87	-1167.07
42.00	4.04	-4.04	-1110.57	-1206.86
43.00	3.80	-3.80	-1220.28	-1246.66
44.00	3.55	-3.55	-1329.98	-1286.45
45.00	3.31	-3.31	-1439.69	-1326.25
46.00	3.07	-3.07	-1500.21	-1349.35
47.00	2.82	-2.82	-1413.19	-1322.37
48.00	2.58	-2.58	-1326.17	-1295.39
49.00	2.34	-2.34	-1239.15	-1268.41
50.00	2.10	-2.10	-1152.13	-1241.43
51.00	1.85	-1.85	-1065.11	-1214.45

52.00	1.61	-1.61	-978.09	-1187.47
53.00	1.37	-1.37	-891.07	-1160.49
54.00	1.12	-1.12	-804.05	-1133.51
55.00	0.88	-0.88	-717.03	-1106.53
56.00	0.64	-0.64	-630.01	-1079.55
57.00	0.39	-0.39	-565.47	-1058.59
58.00	0.15	-0.15	-568.35	-1055.70
59.00	0.16	-0.16	-571.24	-1052.81
60.00	0.16	-0.16	-574.13	-1049.92
61.00	44.74	54.60	199.51	33.25
62.00	67.03	81.97	583.83	577.34
63.00	67.06	81.94	578.82	582.35
64.00	67.08	81.92	573.81	587.36
65.00	67.11	81.89	568.81	592.36
66.00	67.13	81.87	563.80	597.37
67.00	67.16	81.84	558.80	602.38
68.00	67.18	81.82	553.79	607.38
69.00	67.21	81.79	548.78	612.39
70.00	67.23	81.77	543.78	617.39
71.00	67.26	81.74	538.77	622.40
72.00	67.28	81.72	533.77	627.41
73.00	67.31	81.69	528.76	632.41
74.00	67.33	81.67	523.75	637.42
75.00	67.36	81.64	518.75	642.42

TABLE.IV.3.

Distance (ft)	Bottom flange stress envelopes due to vertical loads (dead + live + impact) (ksi)				Bottom flange stress envelopes due to vertical loads and the strengthening system (ksi)			
	Exterior Stringer		Interior Stringer		Exterior Stringer		Interior Stringer	
	Maximum Tension	Maximum Compres.	Maximum Tension	Maximum Compres.	Maximum Tension	Maximum Compres.	Maximum Tension	Maximum Compres
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	2.39	0.25	2.50	0.35	2.39	0.29	2.63	0.53
2.00	4.59	0.45	4.82	0.65	4.60	0.54	5.08	1.00
3.00	6.65	0.61	6.98	0.90	6.67	0.74	7.37	1.43
4.00	8.55	0.73	8.97	1.10	8.57	0.90	9.50	1.82
5.00	10.30	0.80	10.80	1.26	10.32	1.01	11.45	2.15
6.00	11.89	0.82	12.46	1.36	10.63	-0.52	11.01	0.04
7.00	13.33	0.80	13.96	1.42	9.49	-3.69	8.16	-4.52
8.00	14.61	0.74	15.30	1.43	10.81	-3.68	9.61	-4.36
9.00	15.75	0.63	16.49	1.39	11.98	-3.71	10.90	-4.24
10.00	16.74	0.47	17.51	1.31	13.00	-3.79	12.03	-4.18
11.00	17.74	0.27	18.56	1.17	14.03	-3.91	13.18	-4.17
12.00	18.63	0.03	19.47	0.99	14.94	-4.08	14.21	-4.20
13.00	19.37	-0.26	20.23	0.75	15.72	-4.29	15.07	-4.28
14.00	19.96	-0.60	20.84	0.47	16.34	-4.55	15.79	-4.41
15.00	20.42	-0.97	21.36	0.14	16.83	-4.85	16.41	-4.59
16.00	20.93	-1.40	21.88	-0.23	17.37	-5.19	17.04	-4.82
17.00	21.29	-1.87	22.24	-0.66	17.76	-5.58	17.50	-5.09
18.00	21.50	-2.38	22.44	-1.13	18.00	-6.02	17.81	-5.42
19.00	21.56	-2.94	22.48	-1.66	18.10	-6.49	17.94	-5.80
20.00	21.54	-3.54	22.45	-2.23	18.13	-6.99	18.00	-6.24
21.00	21.51	-4.19	22.39	-2.85	18.15	-7.55	18.03	-6.73
22.00	21.32	-4.88	22.17	-3.52	18.02	-8.14	17.90	-7.26
23.00	20.99	-5.61	21.79	-4.23	17.73	-8.78	17.60	-7.84
24.00	20.50	-6.40	21.25	-5.00	17.30	-9.47	17.15	-8.48
25.00	19.86	-7.22	20.55	-5.81	16.71	-10.20	16.54	-9.16
26.00	19.07	-8.09	19.69	-6.67	15.97	-10.97	15.76	-9.88
27.00	18.13	-9.01	18.67	-7.58	15.08	-11.79	14.83	-10.66
28.00	17.04	-9.97	17.49	-8.54	14.03	-12.66	13.73	-11.49
29.00	15.88	-10.97	16.25	-9.54	12.93	-13.57	12.58	-12.36
30.00	14.62	-12.02	14.89	-10.60	11.71	-14.52	11.31	-13.28
31.00	13.21	-13.12	13.38	-11.70	10.35	-15.52	9.88	-14.25
32.00	11.65	-14.26	11.71	-12.85	8.85	-16.57	8.31	-15.27
33.00	10.06	-15.44	10.01	-14.05	9.86	-14.51	11.19	-11.51
34.00	8.39	-16.67	8.22	-15.30	9.53	-14.06	11.72	-10.23
35.00	6.61	-17.95	6.34	-16.60	7.92	-15.01	9.93	-11.39
36.00	4.73	-19.27	4.33	-17.95	6.48	-15.48	8.06	-12.50
37.00	2.85	-20.63	2.33	-19.34	5.05	-15.98	6.21	-13.67
38.00	0.89	-22.04	0.42	-11.06	3.54	-16.54	2.69	-8.06
39.00	-0.45	-14.52	-0.79	-11.85	1.63	-10.98	1.57	-8.74
40.00	-1.85	-15.45	-2.07	-12.67	0.54	-11.43	0.38	-9.44
41.00	-3.06	-16.41	-3.00	-13.52	-0.38	-11.90	-0.47	-10.17
42.00	-3.72	-17.80	-3.61	-14.79	-0.73	-12.82	-1.00	-11.33
43.00	-4.40	-19.63	-4.25	-16.31	-1.12	-14.17	-1.56	-12.73
44.00	-5.11	-21.51	-4.92	-17.86	-1.53	-15.56	-2.14	-14.17
45.00	-5.85	-23.43	-5.61	-19.45	-1.97	-17.00	-2.75	-15.64
46.00	-6.26	-24.36	-5.99	-20.23	-2.21	-17.67	-3.08	-16.35
47.00	-5.60	-22.26	-5.38	-18.50	-1.79	-15.96	-2.53	-14.71
48.00	-4.98	-20.21	-4.80	-16.82	-1.40	-14.30	-2.01	-13.10
49.00	-4.38	-18.21	-4.25	-15.19	-1.03	-12.69	-1.51	-11.54
50.00	-3.81	-16.26	-3.72	-13.59	-0.70	-11.12	-1.05	-10.02

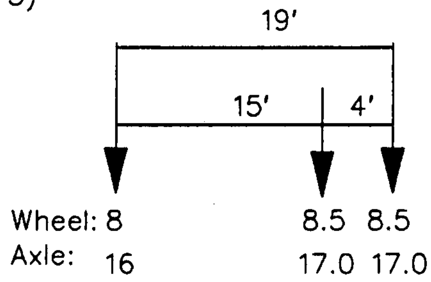
51.00	-3.26	-14.37	-3.21	-12.04	-0.39	-9.62	-0.60	-8.55
52.00	-2.27	-12.52	-2.48	-10.53	0.37	-8.17	0.07	-7.12
53.00	-0.96	-11.10	-1.29	-9.28	1.45	-7.13	1.21	-5.94
54.00	0.10	-16.64	-0.67	-16.08	3.33	-10.25	3.63	-9.62
55.00	1.99	-15.38	1.32	-14.77	4.87	-9.68	5.51	-8.46
56.00	3.80	-14.15	3.23	-13.51	6.33	-9.15	7.32	-7.35
57.00	5.53	-12.98	5.06	-12.30	7.81	-8.50	9.06	-6.26
58.00	7.19	-11.84	6.80	-11.14	9.48	-7.35	10.79	-5.11
59.00	8.76	-10.75	8.46	-10.03	11.06	-6.24	12.44	-4.02
60.00	10.25	-9.71	10.03	-8.97	12.56	-5.17	14.00	-2.97
61.00	11.65	-8.71	11.51	-7.95	10.29	-8.51	10.63	-7.24
62.00	12.96	-7.76	12.89	-6.98	9.77	-9.70	9.58	-8.93
63.00	14.18	-6.85	14.18	-6.06	11.01	-8.75	10.85	-8.04
64.00	15.30	-5.98	15.37	-5.19	12.16	-7.85	12.03	-7.20
65.00	16.33	-5.16	16.46	-4.37	13.20	-6.99	13.09	-6.40
66.00	17.26	-4.39	17.44	-3.60	14.15	-6.17	14.06	-5.66
67.00	18.09	-3.66	18.32	-2.87	15.00	-5.40	14.92	-4.96
68.00	18.82	-2.97	19.09	-2.19	15.75	-4.68	15.67	-4.31
69.00	19.44	-2.33	19.76	-1.57	16.40	-3.99	16.32	-3.72
70.00	19.97	-1.73	20.31	-0.98	16.94	-3.36	16.85	-3.16
71.00	20.38	-1.18	20.75	-0.45	17.37	-2.77	17.28	-2.66
72.00	20.70	-0.68	21.09	0.03	17.71	-2.22	17.59	-2.21
73.00	20.90	-0.21	21.31	0.47	17.93	-1.72	17.80	-1.80
74.00	21.00	0.20	21.42	0.85	18.06	-1.26	17.89	-1.44
75.00	21.00	0.58	21.42	1.19	18.07	-0.85	17.87	-1.13
MAX.	21.56		22.48		18.15		18.03	
MIN.		-24.36		-20.23		-17.67		-16.35

APPENDIX C

AXLE LOADS FOR 1980 IOWA DOT RATING TRUCKS

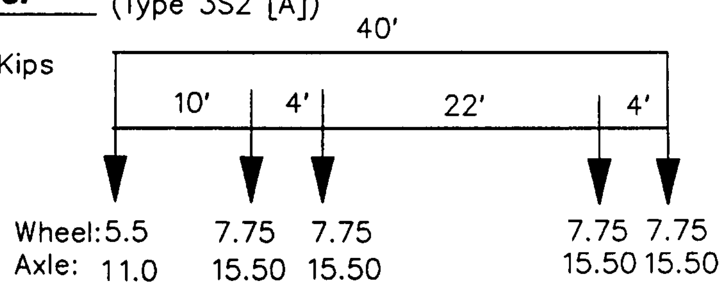
Straight Truck (Type 3)

Total Wt. = 50 Kips
(25 Tons)



Truck + Semi-trailer (Type 3S2 [A])

Total Wt. = 73 Kips
(36.5 Tons)



Truck + Semi-trailer (Type 3S2 [B])

Total Wt. = 80 Kips
(40 Tons)

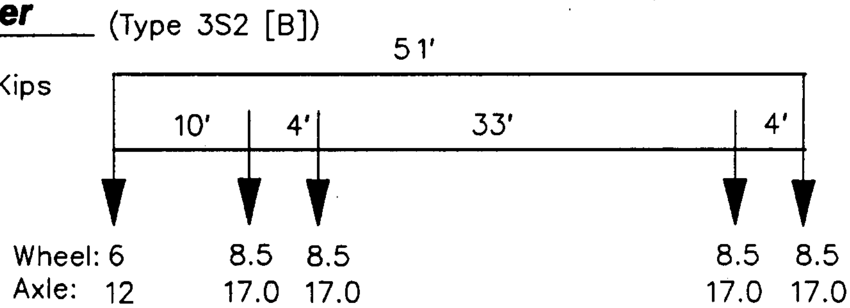
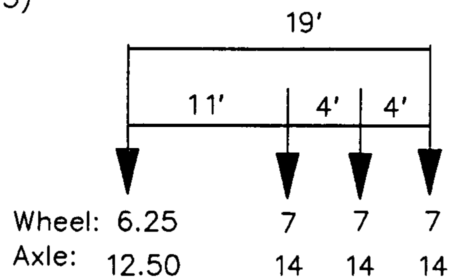


Fig. C-1. Iowa Department of Transportation legal dual axle truck loads.

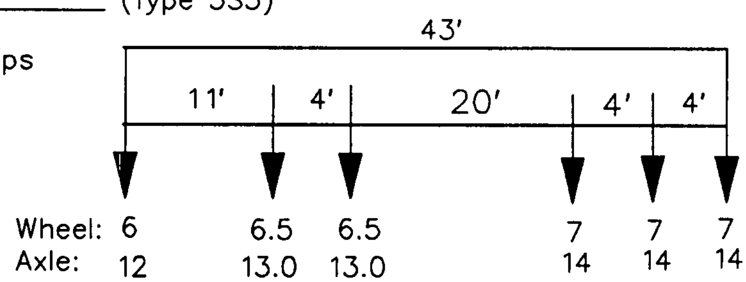
Straight Truck (Type 3)

Total Wt. = 54.5 Kips
(27.25 Tons)



Truck + Semi-trailer (Type 3S3)

Total Wt. = 80 Kips
(40 Tons)



Truck + Semi-trailer (Type 3–3)

Total Wt. = 80 Kips
(40 Tons)

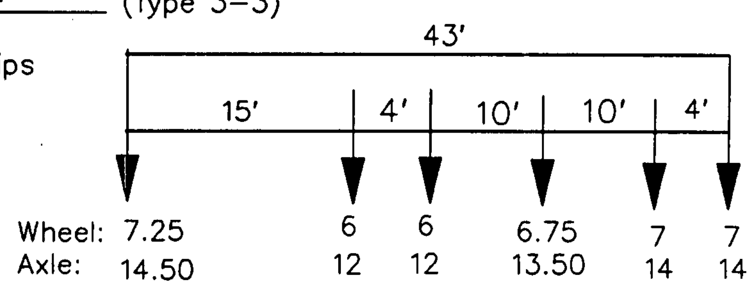


Fig. C-1. Continued.