DEVELOPMENT OF A THICKNESS DESIGN PROCEDURE FOR STABILIZED LAYERS UNDER RIGID AIRFIELD PAVEMENTS

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BACKGROUND

In October of 1985 a Federal Aviation Administration (FAA) report (1) reviewing their 1978 airfield pavement design guide was published. This report was primarily concerned with evaluating the existing FAA pavement design procedures for high traffic volume pavements (pavements receiving over 100,00 annual departures). In the design review and data collection phases of this project, it was determined that there was no uniform method employed in the design of the pavement sections with regard to the thickness determination of the stabilized base layers. Several facilities were designed using a very detailed theoretical analyses, while others used empirical methods to perform the design of the slab stabilized base system.

Most of these facilities were constructed in the early 1970's. Since that time, the FAA has published Advisory Circular 150/5320-6c, dated December 7, 1978. This circular incudes a requirement for stabilized bases (when gross aircraft weight exceeds 100,000 pounds), and presents a methodology to adjust the k values of the subgrade for the addition of stabilized base. This method is easily applied to determine the thickness of the concrete slab required. However, determination of the stabilized base thickness is left to an iterating process. A suggestion is presented in the design guide that the thickness of the base course be as thick as the required slab. This statement has often been interpreted in an incorrect fashion by some designers. The statement has been taken literally where a concrete thickness will be determined for a given k-value and then a base course the thickness of the required slab designed into the project. This is done without the next iteration on the base course to determine a new k-value. Other problems identified in the current approach are as follows:

a. There is no adjustment for the quality of stabilized materials either in terms of modulus elasticity or modulus or rupture.

b. The table adjusts the k-value to a maximum value of 500 pci beyond which there is no adjustment.

c. The chart used to adjust the k-value of the subgrade is currently truncated at a stabilized base thickness of 12 inches. This is not sufficient for high volume airfield pavements.

PURPOSE

The purpose of this study was to develop a design procedure for the selection of the thickness of a stabilized base course material for rigid airfield pavements. The design method was material for rigid airfield pavements. The design method was developed accounting for the materials properties of the stabilized base course, and was designed to be completely compatible with the current FAA design procedure. The method was also designed so that it would be compatible with the elastic layer analysis being used by the U.S. Army Corps of Engineers.

SCOPE

The methodology employed in this study is applicable to the design of rigid (portland cement concrete) pavements utilizing cement treated aggregate as the base course material (CTB). The

method developed has been designed using three wheel load conditions namely a single wheel load, a dual gear load (Boeing 727), and a dual tandem gear load (Boeing 767). The use of the FAA mixed traffic equation will allow the procedure to be used in mixed traffic conditions as long as one of the above wheel loads is used as the design wheel load.

The procedure utilizes elastic theory as the stress determination method. Thus, it is feasible the method could be extended to other stabilized materials provided that their materials properties are within the boundaries used in this study, and that their primary failure mechanism is tensile fatigue.

DESIGN CONSIDERATIONS

In order to develop a design procedure that will allow for varying the stabilized material's properties, the relevant constitutive properties and failure mode of the materials need to be identified. In the case of cement treated bases, Williams (2) has identified the modulus of elasticity, modulus of rupture, and flexural fatigue as the critical materials parameters to be utilized in design. Other researchers have identified flexural strain (Mitchell and Chen, Pretorios, Raad) (3, 4, 5) as the failure parameter. Costigan (6) in his work for the U.S. Air Force used the flexural stress approach. This study was concerned with thin asphalt surfacing over cement treated materials. The failure mechanism was identified as flexural fatigue cracking. In order to maintain consistency with the current FAA and U.S. Army Corps of Engineers (COE) concrete design procedures, the flexural stress approach was selected for use in this study.

The basic elements of this study were as follows:

a. Identification of the variables necessary to cover the possible range of materials properties.

b. Selection of the aircraft type to be used.

c. Analysis the stress state for the selected aircraft and materials combinations.

d. Development of the design procedure based on the stress state of the paving layers.

e. Compare the new procedure to the existing design scheme.

The practical range of each of these factors is required to develop a manageable analysis of the tensile stress conditions for combinations of concrete surface and CTB base course layers. The following levels were considered for each factor in the analysis:

a. Thickness of concrete (Hconc, in.), 8, 10, 14, 22, and 26.

b. Elastic modulus of concrete (Ec, psi), 4000000.

c. Thickness of cement treated base (Hctb, in.), 4, 8, 10, 14, and 22.

d. Elastic modulus of CTB (Ectb. ksi), 250, 500, 1000, and 2500.

e. Elastic modulus of subgrade (Esub, psi), 5000, 10000, 20000, and 30000.

f. Traffic types, single wheel, B-727, B-767.

g. Frictional Factor - 300 between concrete and CTB, CTB and subgrade.

This resulted in a total of 1200 cases in which the stress state in the concrete and CTB layers was determined.

SELECTION OF STRESS ANALYSIS PROCEDURE

The selection of the theoretical analysis procedure to define the stress state in the multilayer system was the next decision point. For a rigid pavement system, there are several analysis procedures available such as Westergaard, finite element methods, or elastic layer theory to analyze the stress state in the pavement structure. Of these approaches only the Westergaard and finite element procedures can be used to determine the pavement responses caused by the edge load condition. However, these methods have not been totally adapted to the multilayer case with different interface friction conditions.

Analysis of the NDT data obtained on the high traffic volume pavement project has shown the the basin matching program, BISDEF (11) could provide better estimates of the field deflection basins if the friction value between the layers was varied. This fact lead to the use of the "BISAR"(12) elastic layer procedure

for use in the stress analysis. BISAR is structured to model frictional interface conditions between layers on a continuous scale.

The disadvantage to the use of the BISAR system is the methods inability to handle the edge (or joint) load condition. The inability to handle the edge load condition has been considered a serious draw back to the elastic layer analysis. Parker et. al. (7) have shown that there is a strong relationship between the edge and interior load conditions that remains fairly constant over a range of thicknesses and subgrade conditions.

STRESS ANALYSIS

As previously mentioned the current FAA design procedures are based on the edge stress loading condition. In order to relate the FAA edge load design to the BISAR elastic layer interior load condition, it was necessary to determine the interior stress condition for the case of a concrete slab on subgrade. For this set of systems, the frictional factor was set to the full slip condition and the range of thicknesses was changed to 8, 10, 14, 18, 22, and 26 inches over the same subgrade conditions. This resulted in an additional 72 cases to be analyzed. The selection of the full slip case for the slab-on-grade was made to provide a measure of safety, since the full slip condition results in greater stress values.

In all of the analyses, the maximum tensile stress was located in the concrete and cement treated layer. This was also performed for the slab-on-grade cases. For the multiple wheel load cases, the search for the maximum tensile stress was performed under a wheel, at the centriod of the gear, and between each group of wheels. Figure 1 presents the general layer structure and interface conditions used in the analysis.

RESULTS OF STRESS ANALYSIS

The results of the 1272 systems analyzed are presented in this section of the paper. Table 1 is illustrative of the computed maximum tensile stresses. All stresses presented are the maximum radial tensile stress for the condition represented.

Prior to starting the analysis procedures, graphic representations of the stress in the concrete (STRC) and stress in the base course (STRB) were prepared. Plots were developed of the stress factors against each of the major variables.

STRESS IN THE CONCRETE

Figures 2 through 5 present some representative relationships for the stress in the concrete slab. As shown in Figure 2 the relationship between the stress in the concrete and Hconc is certainly a power function and as follows from the analytical solutions of a beam on an elastic foundation it is a function of the inverse of the square of thickness. Scott (8) presents an excellent summary of the analytical approaches to calculating the tensile stress in a slab resting on either a Winkler or elastic foundation.

Other general observations made regarding the stress in the concrete were as follows:

1. The elastic modulus of the subgrade (Esub) alone does not have a major effect on the stress (Figure 2).

2. The thickness of the stabilized base has a fairly linear reduction effect on the stress in the concrete and the rate of the reduction is dependent on the value Ectb (Figure 3).

3. For given base and subgrade conditions high Ectb moduli influences the inverse relationship between thickness and stress (Figure 4).

All these relationships are generally diminished as the slab thickness becomes very large (Figure 5). Thus, for a given load condition, the concrete slab thickness can over power all parameters if it is extremely thick.

STRESS IN THE BASE COURSE

Figures 6 and 7 show two of the relationships for the stress in the stabilized base course (STRB). In general, similar relationships held for the STRB value and the STRC value. The thickness of overlying slab has a large influence on the value of the STRB. The stress in the base as a function of the thickness of the base was found to be the most difficult relationship. As shown in Figures 6 and 7, this relationship tends toward a parabolic form. This relationship had to be accounted for in the transformation to a linear function.

Unlike the value STRC, the stress in the base is not influenced greatly by the thickness of the base until better quality (higher Ectb) materials are used.

Again, the relationships for the dual and dual tandem gears were found to follow the same general trends. The slopes and magnitudes of the changes in stress are different but they do remain similar.

BOUNDARY RELATIONSHIPS

The relationships found for the pavements in the core of the factorial were also investigated at the corners of the matrix. Figure 5 is examplary of the relationships holding in a general sense, but it is apparent that interaction effects are present. Also, the non-linear behavior of the STRB value becomes magnified at the extremes of the factorial.

These graphics present the general relationships between the stress values (STRC, STRB) and the materials and slab stress characteristics governing the design problem. The review of these graphs lead to the possibility that a single form could be used for determining the stress values for any gear configuration (given the equation was modified by a gear factor). This can be expressed in the following form:

Stress = f(G)*f(h,Esub, Ectb)

where f(G) = gear factor, and

f( ) = general function form in terms of materials properties.

The other conclusion was that the determination of the stress in the base would be a more complex function since the parameter exhibited the parabolic nature especially at the extremities of the factorial.

SELECTION OF VARIABLES

Based on the graphical results, it was apparent that interactions existed between the factors considered in this study. The need to consider interactions between the factors was also identified by obvious patterns in early stage residual plots and by strong intercorrelation between the factors in the correlation matrix when only the main effects were considered. The figures also illustrated that power and log functions represent most relationships between the different factors.

Based on these observations, a large set of variables consisting of interactions between the factors investigated and other related variables was created. Trial and error procedures were used to select the appropriate power functions.

Westergaard's stress solution for an interior load on a slab supported by a dense liquid indicated that the radius of relative stiffness of the slab is a very important parameter. However, without performing a transformation of thickness, there is no established slab theory to take into account the base course material. An attempt was made to develop an equivalent radius of relative stiffness for the two rigid layers using such an equivalent thickness approach. However, this attempt was unsuccessful since it did not account for the variability observed in the pavement behavior (STRC). A radius of relative stiffness was determined for the surface (L1) and base (L2) slab assuming they are supported by the same subgrade. Interactions between L1 and L2 or between functions of L1, L2 and/or other variables accounted for most of the variability in STRC.

The equivalent slab thickness based on equal tensile stress at the bottom of the slab developed by beam theory (Kohn and Rollings, 10) indicated that the ratio of the modulus of the different layers is an important variable. Consequently, these ratios were considered in the analysis.

The second step in the variable selection process involved using the stepwise variable elimination procedure provided by SPSS. This procedure reduced the number of variables to a manageable number without greatly affecting the accuracy in predicting STRC.

The third step was to check the adequacy of the model to ensure the selection of a sound statistical model. This part of the process is required to eliminate gross errors in the prediction of the stress. Normal probability plots and residual plots were used to complete this part of the process.

RESULTS OF ONE RIGID LAYER SYSTEM

The maximum tensile stress in the concrete slab was predicted for this case. One equation form was developed

for all three gear configurations. Naturally, different regression coefficients were computed for each gear type. The general form of the equation is as follows:

$$SC = P/P1\ (CONSTANT + a1*\ln(E_{sub}) + 1/H_{conc}^{2}*[\ a3*L + a4*K\ ]_{3} + \ln(L)*[a5*H_{conc} + a2*\ln(E_{sub})] + a6*1/H_{conc}^{3}) \quad (2)$$

Where:

$L = (\ [E_{conc} * H_{conc}^{3}] / [12\ (1 - u^{2})* K]\ )^{0.25}$

$\log K = (\log E_{sub} - 1.415) / 1.284$

ai = regression coefficients,

SC = maximum tensile stress, slab-on-grade

Er = Modulus ratio,

H_{conc} = concrete thickness,

L = radius of relative stiffness, and

K = modulus of subgrade reaction.

P = design gross aircraft load

P1= 84,000 lbs. for single wheel aircraft
190,000 lbs. for dual wheel aircraft
305,000 lbs. for dual tandem aircraft

The values of the regression coefficients, ai, the correlation coefficients and the standard error for each gear type are given in Table 2. The regression equations provided excellent predictions for the maximum tensile stress as seen in the values of Rsquare and standard error. A standard error of 2.7 psi was computed which represents 0.63 % of the mean stress value for the dual wheel gear. The maximum standard error calculated was equal to 0.75 % and corresponded for the single wheel gear type. For this case the result is expected since the a priori knowledge of the Westgaard variables were used in the regression.

RESULTS TWO RIGID LAYER SYSTEM

For this case, the maximum tensile stress in the concrete slab and the cement treated base were predicted. The equations were selected to provide the best fit using one equation form for all gear types.

The equation for the stress in the concrete slab (STRC) is as follows:

$$STRC = P/P_{1}(CONSTANT + a1\ \ln(L_{1})/L_{1} + H_{conc}*\ln(L_{1})\ \{\ a2 + a5\ *\ L_{2}] + 1/H_{conc}^{2}*\ (\ a3*\ L_{1} + a6*\ Er_{1}*L_{1} + a9*\ L_{2} + a_{11}*\ K*(L_{1}/L_{2}) + a8*\ L_{2}*L_{1}\ \}\ +\ B\ *\ \{\ a4 + a7*\ Er_{2} + a_{10}*\ L_{2} + a_{12}*\ (Er_{1}/E_{sub})^{0.25}\ \})) \quad (3)$$

Where:

ai = regression coefficients (see Table 3)

$Er_{1} = E_{conc} / E_{ctb}$; $Er_{2} = E_{ctb} / E_{sub}$

$L_{1} = (\ [E_{conc} * H_{conc}^{3}] / [12\ (1 - u^{2})\ *\ K]\ )^{0.25}$

$L_{2} = (\ [E_{ctb} * H_{ctb}^{3}] / 12\ (1 - u^{2})*K]\ )^{0.25}$

$\log K = (\log E_{sub} - 1.415) / 1.284]$

$B = 1/H_{conc}^{0.33} * \ln(L_{1}/H_{conc}) * (H_{ctb}/H_{conc})^{2} * (Er_{1})^{0.25}$

STRC = maximum tensile stress in the concrete,

H_{conc} = concrete thickness,

H_{ctb} = cement treated

L = radius of relative stiffness,

K = modulus of subgrade reaction.

P = design gross aircraft load

P_{1}= 84,000 lbs. for single wheel aircraft
190,000 lbs. for dual wheel aircraft
305,000 lbs. for dual tandem aircraft

The values of the regression coefficients along with other statistical parameters are presented in Table 3. Relatively good correlation was obtained for all gear types considering the complexity of the 3 layer pavement system. The maximum standard error computed for the regression equations was equal to 2.55 % of the mean tensile stress. This value corresponds to the dual tandem gear. The high degree of variability associated with this gear type can be explained by considering the following factors. The predicted pavement response is the maximum tensile stress in the concrete slab not the tensile stress at one location within the pavement system. As the thicknesses and material properties were varied, the location of the maximum tensile stress within each of the rigid layers also change. It is believed that this variation in the maximum tensile stress location accounts for most of the variability observed in the regression results. The same phenomenon was also observed, but to a lesser degree, in the dual wheel results. The magnitude of the variance caused by this phenomenon is much greater for the stress in the base.

The largest magnitude of the standard error observed for all gear types is equal to 5.55 psi which is acceptable for all practical design applications.

Figures 8 and 9 show the agreement between the predicted and computed stress values for the dual gear type. These residuals do not show any gross violations for the assumptions (i.e. normality and equal variance of the error term) made in the statistical analysis.

The stress in the cement treated base course was also predicted. For this value the natural log of the maximum tensile stress in the base was predicted. The logarithmic transformation was required to reduce the variance in the error term which, otherwise, would have violated one of the basic assumptions of statistical analysis. This high magnitude of the variance can be explained in part by the change in the maximum tensile stress which was addressed in the previous paragraphs, and the nonlinear behavior of the function at the extremes of the factorial.

The selected model fit all gear types with an acceptable level of accuracy. The regression equation developed is as follows:

$$Ln(STRB) = CONSTANT + (Er_1/E_{sub})^{0.25} (a5\ H_{conc} * ln(L_1) + a6 * Er_2 + a10 * Er_1 + a12) + K/H_{conc}^2 (a1\ H_{ctb}^2 + a4\ L_1/L_2) + Ln(L_1) * H_{conc}^{(a3} L_1/H_{conc}^2 + a7 B + a11\ Ln(L_1)/L_1) + Er_1 * (a2 + a8\ L_2) + a9\ Ln(L_1)/L_1 \quad (4)$$

$$STRB = P/P_1 (\exp(Ln(STRB)) \quad (5)$$

Where:

$Er_1 = E_{conc} / E_{ctb}$

$Er_2 = E_{ctb} / E_{sub}$

$L_1 = \{ [E_{conc} * H_{conc}^3] / [12 (1 - u^2) * k] \}^{0.25}$

$L_2 = \{ [E_{ctb} * H_{ctb}^3] / [12 (1-u^2) * k] \}^{0.25}$

$\log K = (\log E_{sub} - 1.415) / 1.284$

$B = 1/H_{conc}^{0.33} * \ln(L_1/H_{conc}) * (H_{ctb}/H_{conc})^2 * (Er_1)^{2.5}$

ai = regression coefficients (see Table 4),

STRB = maximum tensile stress in the CTB

H_{conc} = concrete thickness,

H_{ctb} = cement treated base thickness

L = radius of relative stiffness

K = modulus of subgrade reaction

P = design gross aircraft load

P_1= 84,000 lbs. for single wheel aircraft
190,000 lbs. for dual wheel aircraft
305,000 lbs. for dual tandem aircraft

The maximum standard error was equal to 1.11 % of the logarithmic mean of the stress values. A high degree of correlation was observed between the predicted and computed stress values as indicted by the high Rsquare values. Table 4 summarizes the coefficients and associated error estimate. The prediction and residual plot presented in Figures 10 and 11 are representative of the dual gear.

DEVELOPMENT OF THE DESIGN PROCEDURE

The new design method was developed to supplement existing rigid pavement design methods used by the FAA and not to replace them. The new method is based on providing a two rigid layer pavement structure equivalent in terms of performance to the concrete slab (one rigid layer) designed using current FAA procedures. The equivalence between the two pavement structures is achieved by equating the maximum tensile stress in the concrete slab without exceeding the tensile strength of the CTB.

ASSUMPTIONS

Current rigid pavement design procedures are based on limiting the maximum tensile stress at the edge of the pavement. The critical stresses condition occurs when the load is located close to the edge of the pavement. However, because BISAR uses elastic theory to compute the pavement's responses to loading, the edge loading condition couldn't be modeled. This limitation arises from an assumption made by the elastic theory, namely, the pavement dimensions extend to infinity in the horizontal plane. For this reason, interior stresses were evaluated instead of edge stresses. The main assumption made during the course of developing this design procedure is that similar performance will be achieved by equating the maximum interior tensile stress at the bottom of the concrete layer in both pavement structures. In other words, if the maximum interior tensile stress is equal in both pavement structures, so is the maximum edge tensile stress.

A limitation to this design procedure is that the method is valid only within the range of the factorial design. This limitation arises from the use of regression analysis to predict the required pavement response. However, the same approach can be used if the stress can be accurately determined outside the range of the factorial.

Strength and failure criteria of the CTB have been obtained from limited published data. These relationships should be modified as more data becomes available.

INPUT REQUIREMENTS

The design variables required for the new design method are similar to those required by the current FAA procedure. These variables are listed below:

a. Traffic in aircraft departure per year

b. Aircraft type

c. Gross aircraft load, P

d. Modulus of rupture of the concrete, Mr psi

e. Modulus of subgrade reaction, k in pci

The strength property of the CTB (i.e. modulus of rupture) is an additional input required by the new method.

The factorial design performed using the BISAR computer program required elastic material properties to compute the tensile stresses in both rigid layers. Therefore, relationships were needed to transform k of the subgrade and Mr of the CTB into elastic moduli. These relationships are listed below:

$$k = 10\ (\log\{Esub\}-1.415)/1.284 \quad (6)$$

$$Ectb = \{Ln(UC) - 7.0\ \} / 3.597E\text{-}4\ , \text{(ksi)} \quad (7)$$

$$Mrctb = 218.2\ EXP^{\,3.597E\text{-}07*Ectb} \quad (8)$$

$$Mr = UC/5 \quad (9)$$

Where

Esub = subgrade modulus

UC = unconfined compressive strength of CTB, psi

Ectb, Mrctb = modulus of elasticity and modulus of rupture of the CTB

The new design method is based on a fixed condition of the CTB. It is assumed that the condition of the CTB will remain constant over the life of the pavement. Therefore, a criteria is set against fatigue of the CTB. The PCA fatigue failure criteria for concrete pavement is applied to the CTB. This criteria states that the slab can resist an infinite number of load applications provided the stress ration, i.e. maximum tensile stress in the CTB divided by the modulus of rupture of the CTB. remains below 0.5.

The following failure criteria is used to determine the number of allowable load repetitions if the stress ration is greater than 0.5:

$$\text{Log}\ (N) = [(0.972 - SR)/0.0825] \quad (10)$$

Where:

N = allowable load repetitions

SR = stress ration

It is recommended that the stress ratio be kept under 0.5 for the final selection of the layer thicknesses.

Presently, the limit on the value of the stress ratio is not a limiting criteria. However, as more data becomes available regarding the fatigue behavior of the CTB, the limiting criteria should become a controlling factor in the final selection of the layer thicknesses.

COMPUTER PROGRAM

The time required in the manual selection of the concrete slab and CTB thicknesses using the new design procedure is large. To alleviate this problem a computer code was developed to automate the new design.

A description of the program is provided in the following sections of this paper.

GENERAL DESCRIPTION

CTBDES is an interactive and user friendly program which is used to design two-rigid layer pavement systems. The program solve the regression equations obtained from the large factorial design. The source code is written in the BASIC computer language and is suitable for use with an IBM-compatible microcomputer. Minor changes may be required to the source code, particularly in input/output operations such as opening and closing files, in order to be used on other computer systems.

DESCRIPTION OF CTBDES

CTBDES is used to select the concrete and CTB slab thicknesses. This program provides all concrete-CTB thickness combinations that satisfy the maximum tensile stress equality criteria described earlier in this paper. All concrete and CTB thicknesses within the valid range of the regression equations are evaluated. Figure 12 presents the flow chart of CTBDES(13).

The input requirements include the concrete slab thickness obtained from the current FAA design procedure for a given aircraft type and design gross load, the subgrade and CTB strength properties. The computer code has been structured such that more than one strength property can be used to characterize a given layer of the pavement system. For example, the modulus of subgrade reaction, k, or the resilient modulus of the subgrade, Esub, could be entered. Similarly, the compressive strength or the elastic modulus of the CTB could be entered.

Figure 13 presents an example of the output obtained from CTBDES. The user input is echoed in the top portion of the output. The subgrade and base properties which were not entered by the user and were needed for the solution of the regression equations are computed internally by the program using the relationships presented earlier.

The concrete and CTB thickness combinations are presented in the lower portion of the output. The concrete slab thickness is increased by half inch for each step and the required CTB thickness is determined. In addition, the maximum tensile stress in the concrete slab of the rigid layer pavement system (predicted) is compared with that of the one rigid layer pavement system (design).

The stress ratio in the CTB is also printed along with the resulting allowable load repetitions (i.e. passes).

DESIGN COMPARISON

The new design procedure was compared to the current FAA method. A Corps of Engineers procedure for determining the composite modulus was also used to calculate a k value for the subgrade CTB system. This k value was then used in the FAA design.

The design methods were compared over a range of conditions. The set of variables and the resulting thickness from the new procedure are presented in Table 5. The same parameters were also used in the FAA method.

Over the range of the input values, the differences in the new and FAA methods were found to be both plus and minus. The range of the differences for the FAA method was -1.4 to 2.6 inches (where the difference is defined as New-FAA). A similar range in the differnces was found when the Corps of Engineers composite modulus was employed. For this case the difference range was -1.9 to 2.7 inches.

Figures 14 and 15 show the differnces in the methods for two cases. Figure 13 is representative of the case with a CTB layer of 6 inches and an elastic modulus of 250 ksi, while Figure 14 was developed from the data of a CTB layer of 10 inches and an elastic modulus of 1000 ksi. As shown in the figures, the new method in comparison with existing procedures requires both thinner and thicker concrete over the CTB layer.

Primarily, the new method shows that if higher quality CTB is used a thinner concrete layer can be used to satisfy the equivalent stress condition. However, if the CTB modulus is reduced the new procedure reveals thicker layers of concrete are required. This comparison indicates that both over and under designed pavements are possible when using the existing procedures to design pavements with stabilized bases.

SUMMARY

This paper has presented the development of a design procedure for the determination of the thickness of a cement stabilized base under a rigid pavement system. The procedure has been developed based on an equivalent interior stress criteria. Allowance has been made for the determination of the allowable pass level on the CTB material.

A computer program has been developed in conjunction with the study. The procedures have been developed using the stress results from an elastic

layer analysis in the form of the BISAR program. The method had been structured around the existing FAA design procedures and is completely compatible with the current design procedures.

From a design point of view the benefit to this analysis procedure is that the designer is allowed to utilize the materials properties of the CTB. In area where CTB is a common construction material or for large projects, the reductions in concrete thickness and replacement with a higher quality CTB may provide an opportunity for economic savings. Also, the designer is provided with information regarding the allowable pass level on the CTB material. This information is not presently provided in any conventional design method.

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Table 1

Results of single wheel stress analysis (5k subgrade)

THICKNESS, in.		CTB MODULUS, ksi							
CONC.	CTB	250		500		1000		2500	
		STRC	STRB	STRC	STRB	STRC	STRB	STRC	STRB
8.0	4.0	624.0	59.5	582.0	101.0	535.0	166.0	469.0	308.0
	8.0	526.0	62.6	457.0	103.0	385.0	162.0	286.0	281.0
	10.0	483.0	60.3	405.0	96.6	326.0	149.0	223.0	245.0
	14.0	412.0	52.5	326.0	80.2	245.0	117.0	149.0	177.0
	22.0	330.0	36.5	248.0	51.6	175.0	69.4	98.0	94.8
10.0	4.0	455.0	40.2	430.0	69.2	399.0	114.0	357.0	213.0
	8.0	401.0	43.0	357.0	71.9	311.0	115.0	247.0	207.0
	10.0	375.0	42.2	325.0	69.3	273.0	109.0	203.0	189.0
	14.0	330.0	38.4	273.0	60.5	216.0	91.1	144.0	146.0
	22.0	271.0	28.7	212.0	42.1	158.0	58.8	96.2	84.5
14.0	4.0	271.0	21.9	258.0	38.2	243.0	63.8	221.0	119.0
	8.0	248.0	23.5	228.0	40.2	204.0	65.9	172.0	121.0
	10.0	237.0	23.5	213.0	39.7	187.0	64.2	151.0	116.0
	14.0	217.0	22.4	188.0	36.8	157.0	57.7	117.0	99.1
	22.0	186.0	18.6	152.0	28.7	120.0	42.2	80.7	65.7
22.0	4.0	123.0	9.2	119.0	16.5	113.0	28.1	104.0	52.9
	8.0	116.0	9.9	110.0	17.4	101.0	29.0	88.4	53.8
	10.0	113.0	10.0	105.0	17.4	95.2	28.9	81.3	53.2
	14.0	107.0	9.9	96.7	17.0	84.9	27.6	68.8	49.8
	22.0	96.6	9.1	83.0	14.9	69.1	23.2	51.2	39.4
26.0	4.0	89.6	6.7	87.1	12.0	83.5	20.6	77.2	39.0
	8.0	85.8	7.1	81.3	12.5	75.5	21.1	66.7	39.2
	10.0	83.9	7.2	78.5	12.6	71.7	21.1	62.0	39.0
	14.0	80.1	7.2	73.1	12.5	64.9	20.5	53.6	37.3
	22.0	73.2	6.8	63.9	11.3	54.0	17.9	41.2	31.0

Table 2

Regression Coefficients - Interior Stress for Slab-On-Grade

REGRESSION COEFFICIENTS	GEAR TYPE: SINGLE WHEEL	DUAL WHEELS	DUAL TANDEM
a1	79.87059	70.87699	-104.54994
a2	-20.83124	-13.20461	41.08126
a3	1043.40315	1886.23113	1754.38235
a4	-28.99054	-35.41080	31.44690
a5	1.11244	0.91015	-1.86926
a6	33382.69811	----	-74244.45618
Constant	-54.80360	-307.15867	-601.92659
R2	0.99988	0.99991	0.99987
Std. Error (psi)	2.08718	2.70057	2.09560
Std. Error (% error)	0.75	0.63	0.67

Table 3

Regression Coefficients - Interior Stress in the Concrete Slab for the Two Rigid Layer System

REGRESSION COEFFICIENTS	GEAR TYPE SINGLE WHEEL	DUAL WHEELS	DUAL TANDEM
a1	3152.60047	3903.81004	5463.62830
a2	0.74036	1.06777	----
a3	1206.42011	1839.96268	1304.04836
a4	40.117044	79.37649	66.63757
a5	2.891281E-03	----	----
a6	3.8000969811	6.99535	5.63003
a7	0.02337	0.03171	0.03013
a8	----	----	-5.30015
a9	-925.25867	-1421.66496	-820.59149
a10	0.45975	0.73535	0.36554
a11	-5.58656	-10.42594	-7.26875
a12	-44.92398	-195.49499	-139.49406
Constant	-307.75101	-388.66280	-41.35524
R2	0.99912	0.99905	0.99814
Std. Error (psi)	3.66431	5.55339	5.26719
Std. Error (% error)	1.96	1.98	2.55

Table 4

Regression Coefficients - Interior Stress in the CTB layer for the Two Rigid Layer System

REGRESSION COEFFICIENTS	GEAR TYPE SINGLE WHEEL	DUAL WHEELS	DUAL TANDEM
a1	-1.54962E-04	-1.14871E-04	-9.69983E-05
a2	-.09001	-0.08893	-0.09306
a3	0.32334	0.33870	0.36498
a4	-0.02994	-0.02350	-0.02921
a5	-0.01850	-0.01829	-9.29258E-03
a6	-6.82371E-03	-7.46144E-03	-8.35922E-03
a7	-7.93621E-03	-7.78525E-03	-7.47100E-03
a8	2.778992E-04	5.404066E-04	7.70275E-04
a9	22.59014	20.06895	17.86815
a10	0.47821	0.46020	0.45719
a11	-0.15486	-0.12404	-0.08699
a12	-22.51655	1.92671	-23.879356
Constant	1.57794	-388.66280	1.46192
R2	0.99827	0.99852	0.99772
Std. Error (psi)	0.03965	0.03443	0.03970
Std. Error (% error)	1.11	0.84	1.0

TABLE 5

Required Concrete Thickness As Determined by New Design Method

CTB Thick. (in.)	CTB Modulus (ksi)	Traffic Level (Dep./Yr.)	Dual Gear Subgrade Elastic Modulus (ksi)				Dual Tandem Subgrade Elastic Modulus (ksi)			
			5	10	20	30	5	10	20	30
		3000	15.8	14.6	13.7	13.4	16.6	15.2	14.1	13.3
	250	15000	17.4	16.2	15.2	14.7	18.4	16.9	15.7	14.7
		25000	18.1	16.7	15.7	15.3	19.2	17.4	16.1	15.2
		3000	14.8	13.8	12.9	12.7	15.4	14.1	13.2	12.4
6	500	15000	16.5	15.3	14.4	14.1	17.1	15.8	14.6	13.9
		25000	17.1	15.8	14.9	14.6	17.9	16.2	15.2	14.2
		3000	13.9	12.9	12.2	12.1	14.3	13	12.2	11.6
	1000	15000	15.6	14.4	13.7	13.5	16	14.7	13.8	13
		25000	16.2	14.9	14.2	14	16.7	15.3	14.2	13.4
		3000	15.3	14.1	13.7	13.1	15.9	14.5	13.7	12.9
	250	15000	16.9	15.7	14.8	14.5	17.6	16.2	15.3	14.4
		25000	17.5	16.2	15.3	15	18.4	16.7	15.7	14.7
		3000	14	13.1	12.3	12.2	14.4	13.2	12.4	11.8
8	500	15000	15.7	14.6	13.8	13.7	16.1	14.9	14	13.3
		25000	16.3	15.1	14.3	14.1	16.8	15.4	14.4	13.7
		3000	12.8	11.9	11.3	11.3	12.8	11.8	11.2	10.5
	1000	15000	14.5	13.5	12.8	12.7	14.6	13.5	12.6	12
		25000	15.2	14	13.4	18.2	15.4	14	13.2	12.3
		3000	14.6	13.6	12.8	12.7	15.2	13.9	13.1	12.4
	250	15000	16.3	15.2	14.4	14.1	16.9	15.6	14.6	13.9
		25000	16.9	15.7	14.8	14.6	17.6	16.1	15.2	14.3
		3000	13.3	12.3	11.7	11.7	13.4	12.2	11.6	11.1
10	500	15000	14.9	13.9	13.2	13.1	15.2	14	13.2	12.4
		25000	15.6	14.4	13.8	13.6	15.9	14.5	13.7	12.8
		3000	11.7	10.8	10.3	10.4	11.4	10.4	9.9	9.4
	1000	15000	13.4	12.4	11.9	11.9	13.2	12.1	11.5	10.8
		25000	14	13	12.4	12.3	13.9	12.6	12	11.3

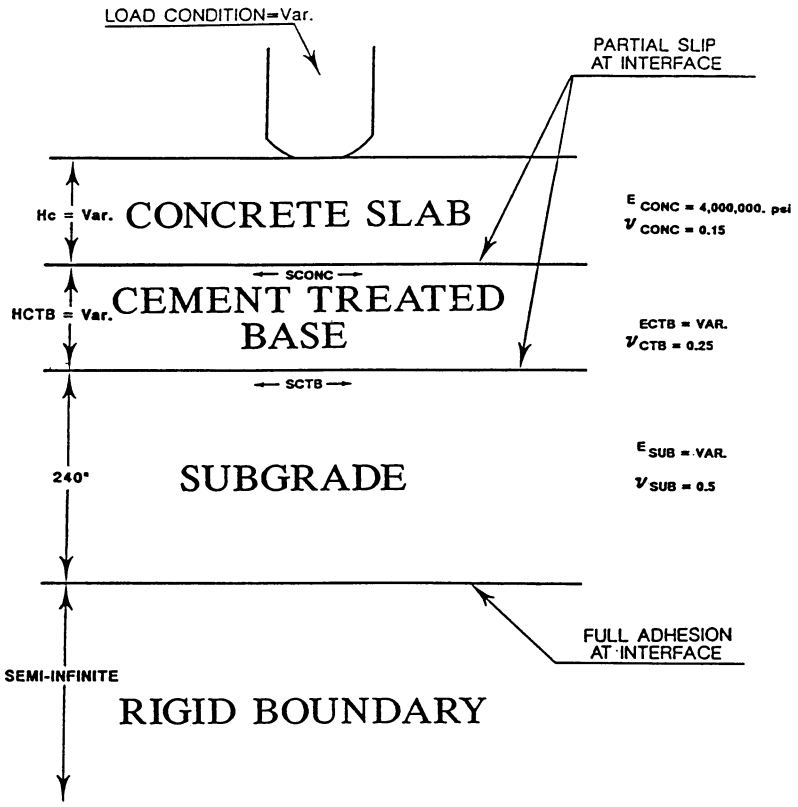


Figure 1. Pavement structure and layer interface conditions used in the stress analysis.

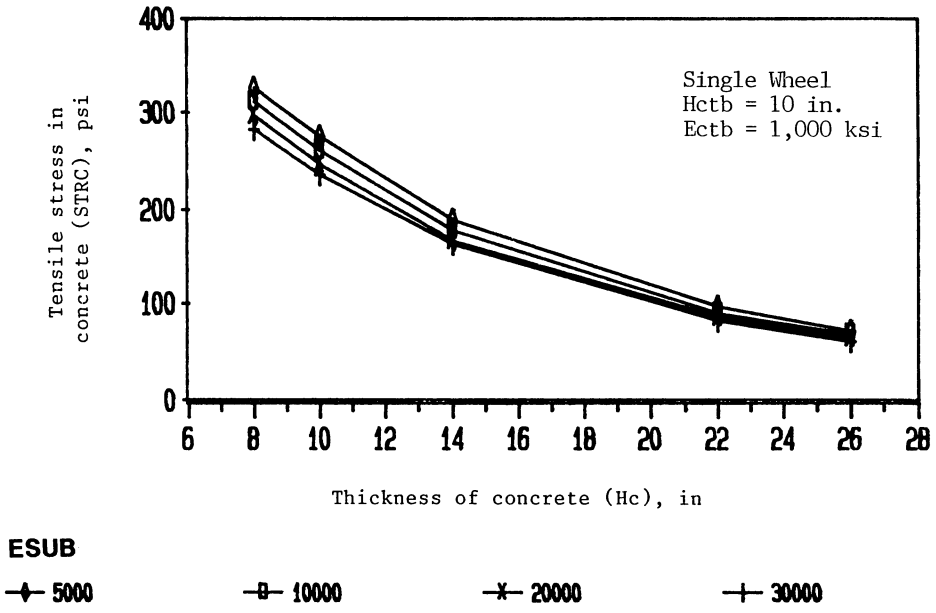


Figure 2. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli

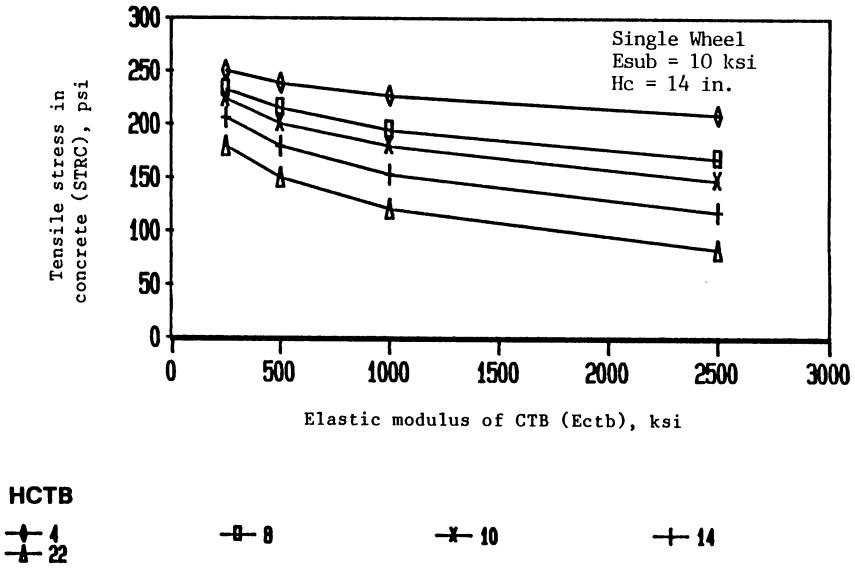


Figure 3. Relationship between CTB moduli and stress in the concrete slab for all CTB thicknesses

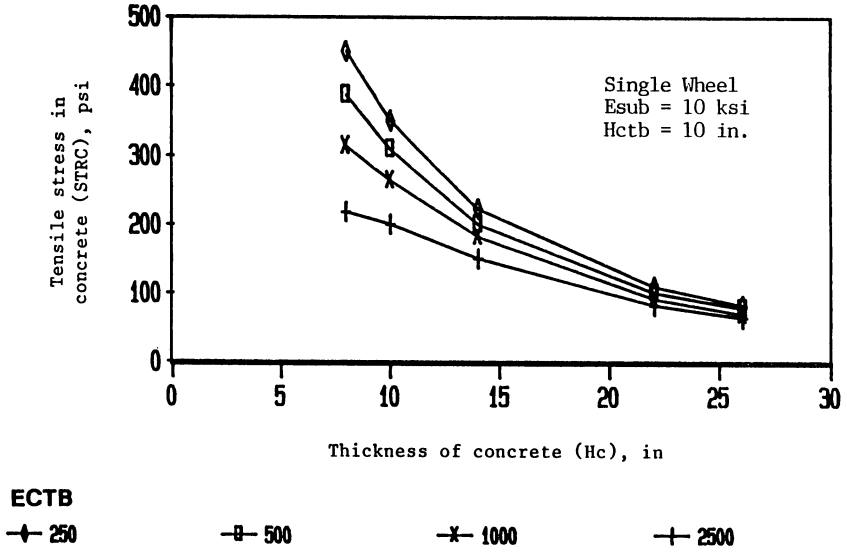


Figure 4. Relationship between concrete thickness and stress in the concrete slab for all CTB moduli

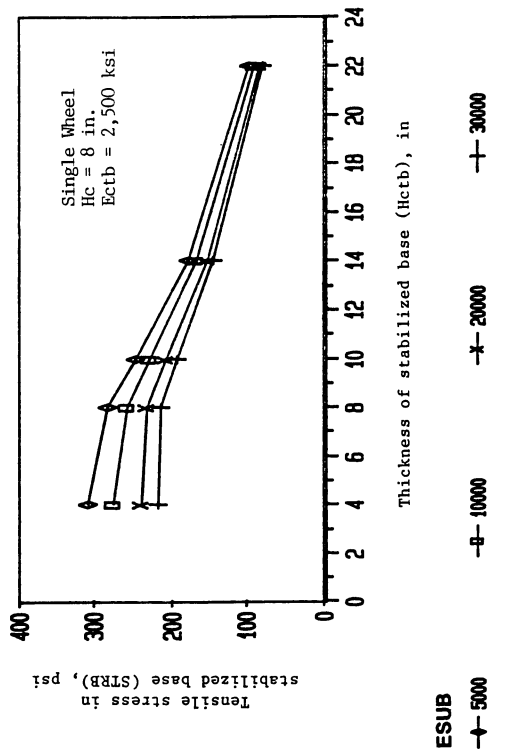


Figure 6. Relationship between CTB thickness and stress in the CTB for all subgrade moduli evaluated at the boundaries of the factorial

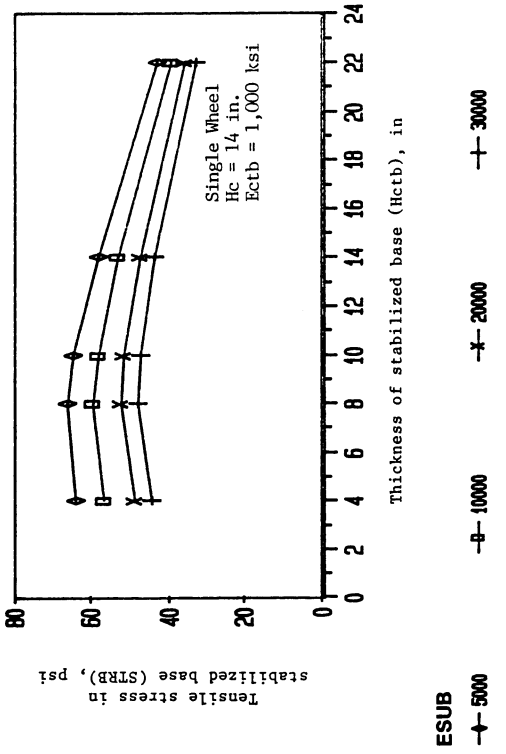


Figure 7. Relationship between CTB thickness and stress in the CTB for all subgrade moduli

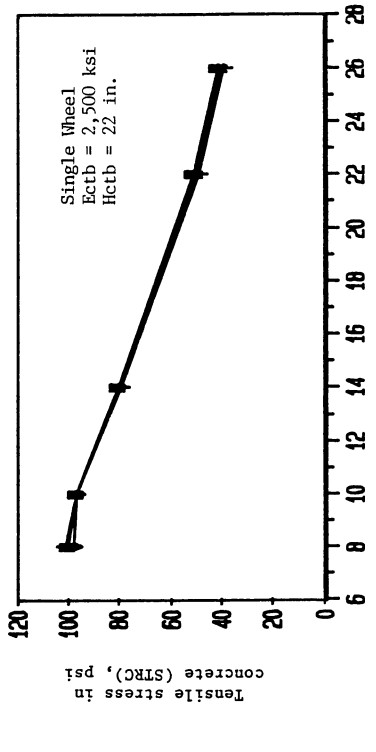


Figure 5. Relationship between concrete thickness and stress in the concrete slab for all subgrade moduli evaluated at the boundaries of the factoria

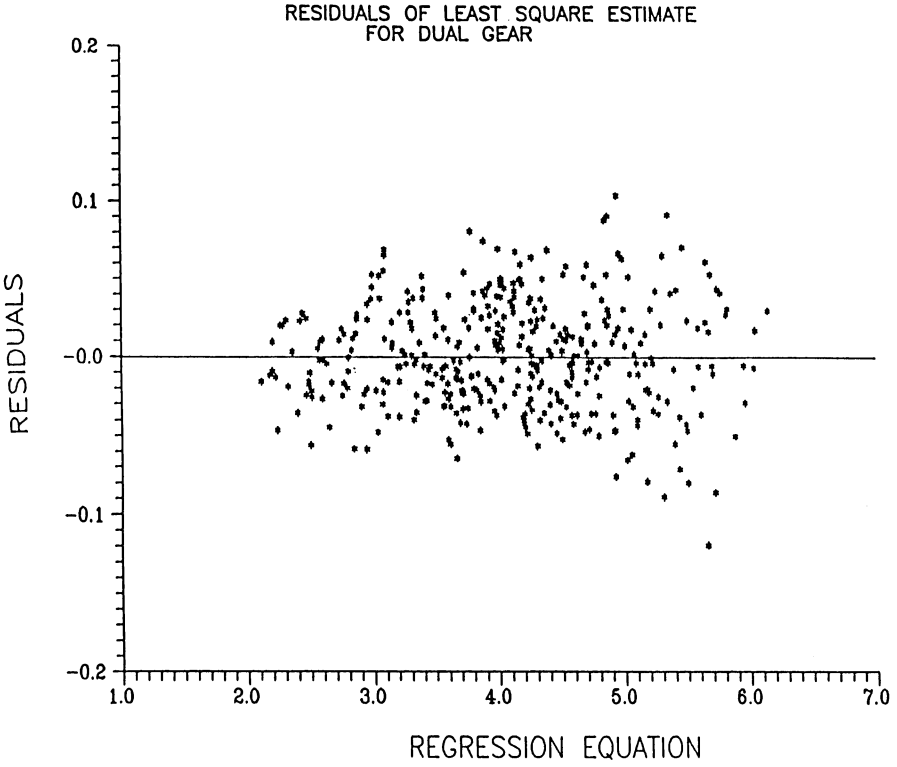


Figure 8. Residual plot obtained from the statistical model selected for the dual wheel gear (two-rigid layer system)

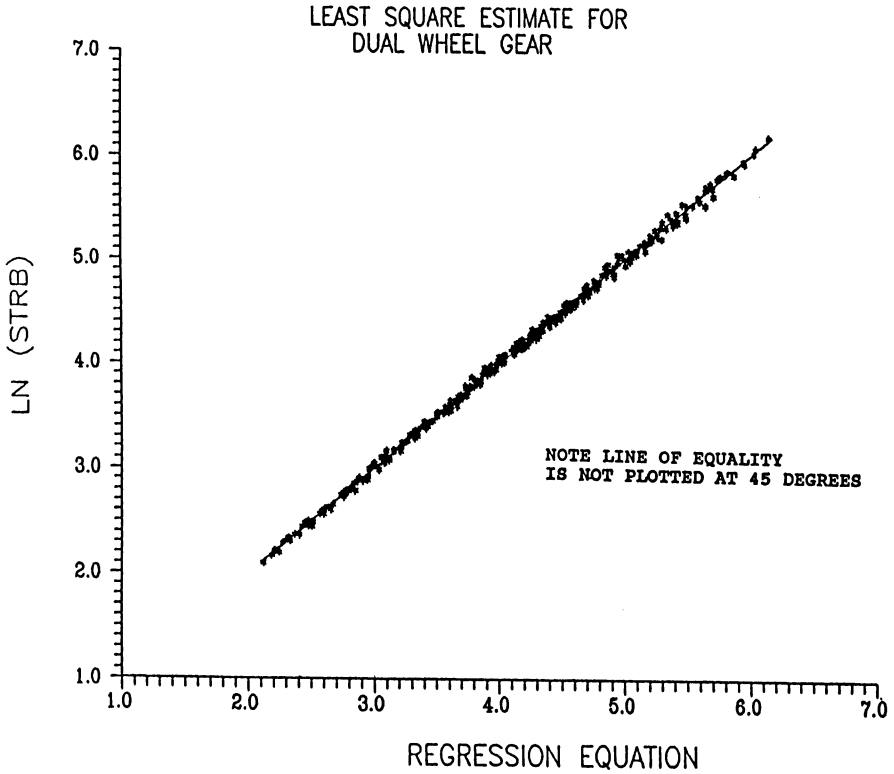


Figure 9. Comparison of predicted versus actual stress values for the case of dual wheel gear (two-rigid layer system)

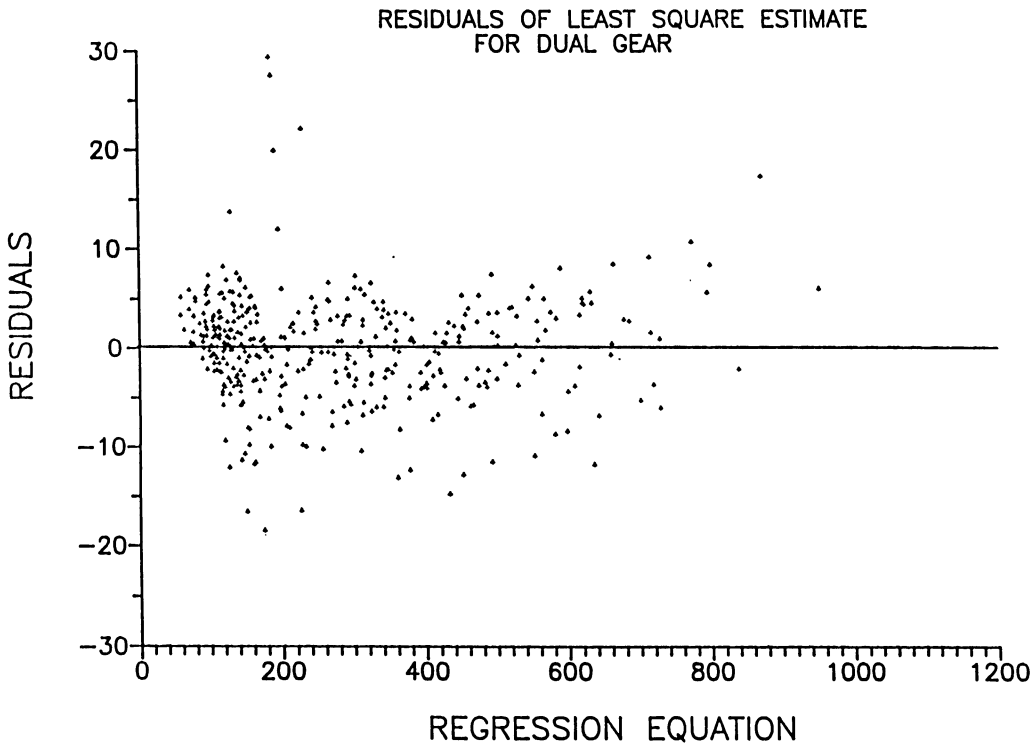


Figure 10. Residual plot obtained from the statistical model selected for the dual wheel gear (two-rigid layer system)

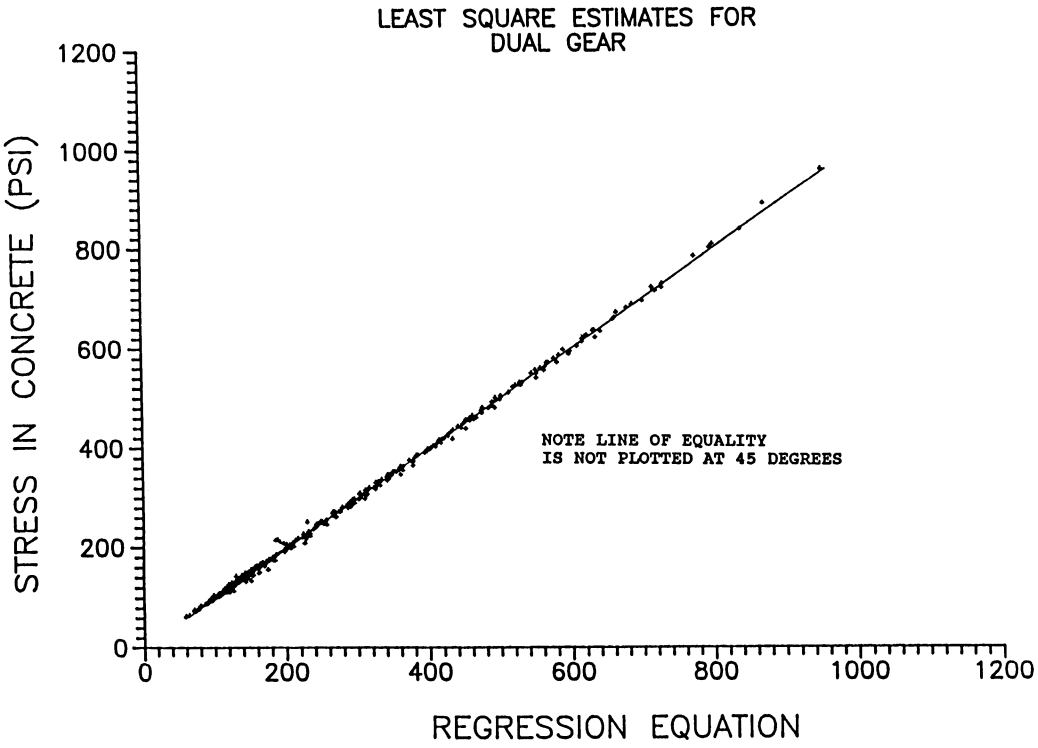


Figure 11. Comparison of predicted versus actual stress values for the case of Dual wheel gear (two-rigid layer system)

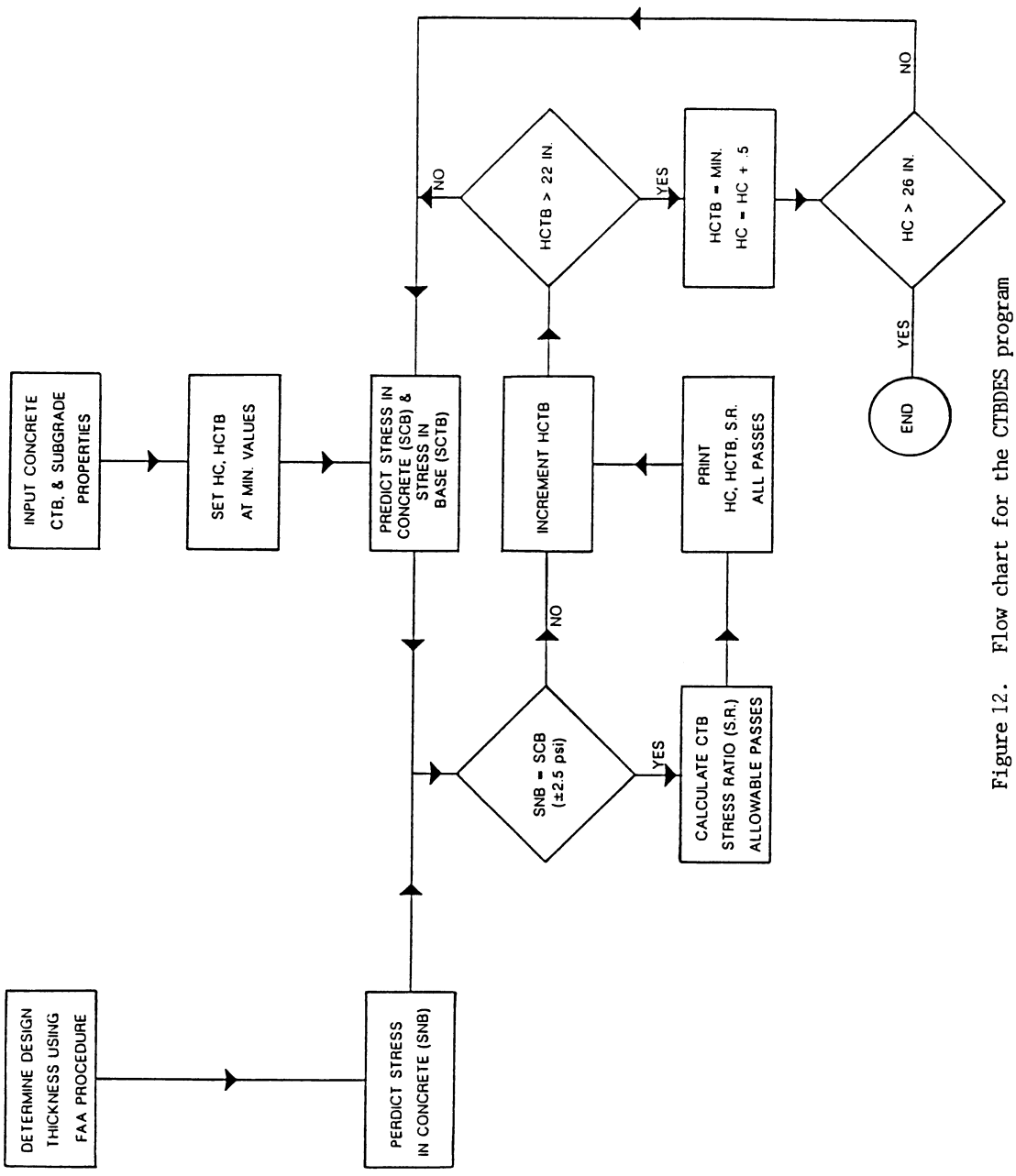


Figure 12. Flow chart for the CTBDES program

```
SUBGRADE PROPERTIES - ESUB   (KSI) =          16.18457
                      K      (PCI) =          150
BASE PROPERTIES -     ECTB   (KSI) =          1684.584
                      FC     (PSI) =          2000
CONCRETE THICKNESS AS CALCULATED BY FAA DESIGN, HC (IN) =   19.40
GEAR TYPE :   DT
GROSS LOAD OF DESIGN AIRCRAFT, P (KIPS) =                   380
```

DETERMINATION OF CONCRETE AND CTB THICKNESS COMBINATIONS

THICKNESS (IN)		STRESS (PSI)		STRESS	ALLOWABLE
CONC.	CTB	PREDICTED	DESIGN	RATIO	PASSES
8.0	12.9	237	235	0.727	9.27E+02
8.5	12.8	237	235	0.673	4.17E+03
9.0	12.6	237	235	0.626	1.57E+04
9.5	12.5	235	235	0.584	5.11E+04
10.0	12.2	234	235	0.546	1.47E+05
10.5	11.9	234	235	0.512	3.80E+05
11.0	11.2	237	235	0.480	9.11E+05
11.5	11.0	234	235	0.453	1.97E+06
12.0	10.6	233	235	0.427	4.00E+06
12.5	10.0	233	235	0.404	7.69E+06
13.0	9.3	235	235	0.382	1.42E+07
13.5	8.8	233	235	0.362	2.45E+07
14.0	8.0	235	235	0.344	4.14E+07
14.5	7.5	233	235	0.327	6.62E+07
15.0	6.9	233	235	0.311	1.03E+08
15.5	6.2	233	235	0.296	1.57E+08
16.0	5.5	233	235	0.282	2.34E+08
16.5	4.7	233	235	0.268	3.41E+08

```
FOR THE LAST ITERATION:
HCTB IS < 4 IN. - USE HCTB= 4 IN. AND HC= 17 IN.
```

Figure 13. Example of the ouput obtained using CTBDES program

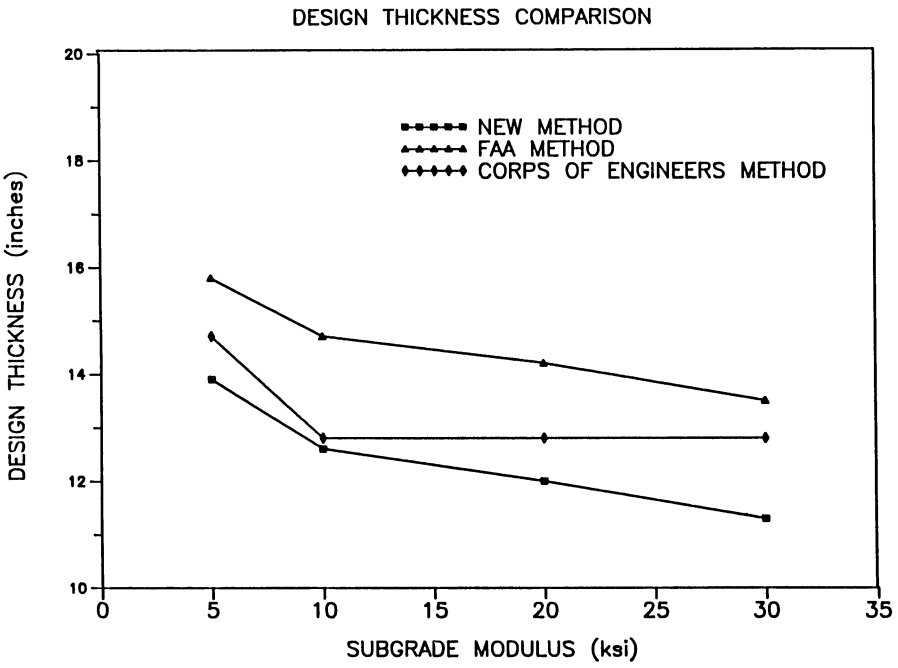


Figure 14. Design comparison for Ectb of 1000 ksi and Hctb of 10 inches.

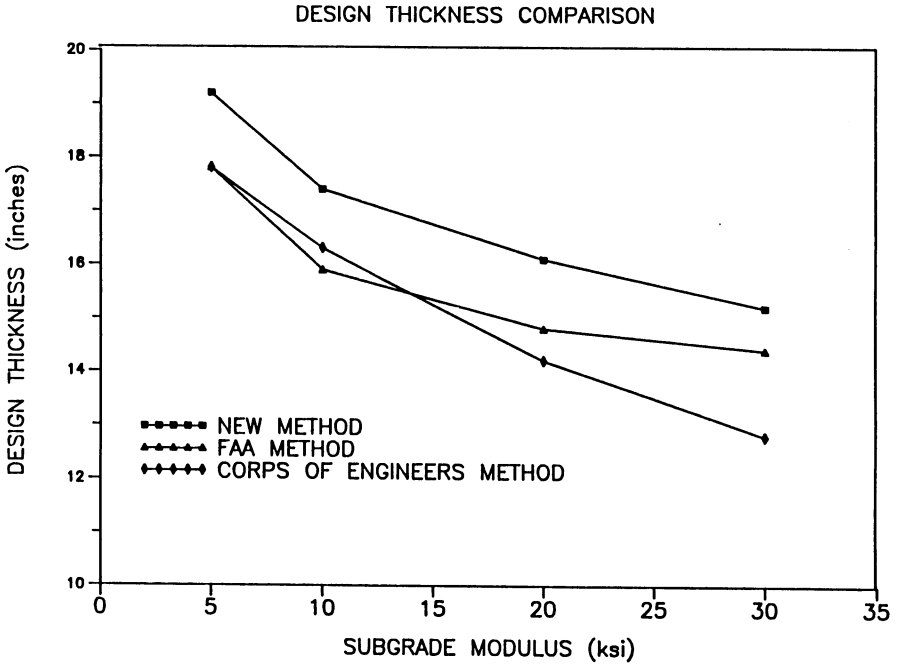


Figure 15. Design comparison for Ectb of 250 ksi and Hctb of 10 inches.