

ANALYSIS OF A STIFFENED CONCRETE PAVEMENT SYSTEM

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A concept has been developed for stiffening concrete pavements. The stiffening is a result of modifications to the section geometry. Simple wood models of a conventional concrete slab with uniform thickness and the stiffened slab show that the stiffened slab's bending and torsion stiffnesses are increased significantly. Conventional concrete pavements represent a complex analysis problem. This is particularly true when the pavement structure is supported by a layered system of bound or unbound granular subbase and subgrade. In service pavements are subjected to the combined stresses of loads and restraint from curling and warping caused by temperature and moisture gradients. In some cases the resulting stresses are additive. The proposed stiffened pavement geometry is complex and cannot be represented with standard models used for pavements.

The only way to represent and analyze the proposed pavement structure was to utilize the finite element method (FEM). In previous research, FEM has been applied to analysis of flexible, rigid and composite pavements. Loading has included static, moving and dynamic loads. There was significant effort expended to verify that the FEM predicted responses were in agreement with measured responses for various pavement sections and loading conditions. Extension of FEM to the case of curling and warping is logical and is verified with past research. Also, judicious application of reinforcement was desired which can be included in FEM analysis.

Application of the FEM to the stiffened slab required study of several parameters. The pavement section was assumed to consist of a concrete surface on an asphalt bound subbase layer and fine grain subgrade. Mesh size and geometry were varied to understand their effect on the analysis. The effect of boundary conditions was also studied. Material models considered included elastic, viscoelastic and elastic-plastic. As a baseline for comparison purposes two thicknesses of slabs were analyzed. Also, interior and edge loadings were considered.

Analysis indicates that deflections and associated stresses are reduced with a stiffened pavement geometry. The analysis included a number of options for the stiffening such as location and dimensions. These are considered for their effect on stresses and cost of construction. The FEM proved to be a powerful tool in the analysis of the complex sections. Results of the research are being considered in a proposal to build and instrument a full scale pavement section.

INTRODUCTION

The finite element method (FEM) is very effective in the analysis of problems with complex geometry and material properties [Zaghloul, 1993]. Pavements, particularly concrete pavements, can be categorized as belonging to this class of problems. Pavement response to applied loads is utilized in design of new pavements and evaluation of existing pavements. Those responses of interest for concrete pavements are the maximum stresses and deflections. Typically in FEM analysis the material properties and boundary conditions are known and analysis is relatively straightforward. Often there are simple, closed form solutions that can be used for validation. However, in this study pavement cross section geometries are non-standard. The FEM is used to predict the responses of such non-standard cross section concrete pavements and the effectiveness of cross section geometry is evaluated on a relative basis.

Pavements with five different cross sections were analyzed and compared. The finite element program, ABAQUS [ABAQUS, 1994], was used in the analysis. Structural analysis and sensitivity of model parameters are presented. Stresses and deflections in the concrete layer were determined for edge and interior loads. In the analysis, S11 is the horizontal tensile stress perpendicular to the traffic direction, S22 is the stress in longitudinal direction and S33 is the vertical stress. Vertical deflection is U3.

MODEL GEOMETRY

To simplify the analysis a three-layer pavement system was assumed. Also, only the pavement response due to static wheel loads was considered and temperature effects were ignored. Pavement cross sections analyzed are shown in Figures 1 through 4. In addition, a conventional flat slab, 12 inches thick, was analyzed. Pavement segments included in analysis are 20 ft long in the traffic direction.

For convenience the pavement cross sections are identified by the following nomenclature:

SEEDGE [Figure 1]: Standard conventional cross section with an edge loading. The pavement section consists of an eight-inch thick concrete slab, an eight inch thick asphalt subbase, and a six foot thick subgrade layer. The eight-inch thick asphalt layer was adopted as a reasonably bound subbase layer. This is the basic structure in this study and its response will be compared with the response of the other pavement structures.

SMID [Figure 1] : This pavement structure has the same geometry as SEEDGE but with interior loading.

TEDGE [Figure 2]: The cross section consists of an eight inch thick concrete slab with two downward projecting trapezoidal webs. Loading is at the edge. The top and bottom widths of the trapezoids are 45.3 in and 12 in, respectively. Center of each trapezoidal web is located at the quarter point of the transverse section, i.e., 3 ft from the slab edge. The distance between the centerlines of the two webs is 6 ft.

TMID [Figure 2]: This pavement structure has the same geometry as TEDGE but with interior loading.

PEDGE [Figure 3]: The cross section consists of an eight-inch thick concrete slab with two downward projecting rectangular webs. Center of each web is located at the quarter point of the transverse section, i.e., 3 ft from the edge. The loading is at the edge.

PMID [Figure 3]: This pavement structure has the same geometry as PEDGE but with interior loading.

EEDGE [Figure 4]: The pavement consists of an eight in concrete slab with two downward projecting rectangular webs at the edge. The loading is at the edge.

EMID [Figure 4]: This pavement structure has the same geometry as EEDGE but with interior loading.

SEEDGE12 [Figure 1]: Cross section and loading are the same as the SEEDGE pavement except that the concrete slab is 12 in thick. This pavement section was analyzed to consider the use of a thicker, conventional slab.

SMID12 [Figure 1]: Same geometry as SEEDGE12 but with interior loading.

LOADING MODEL

Edge and interior loading utilized are shown in Figures 5 and 6, respectively. In all cases, loading consisted of an 18,000 lb single axle, dual wheel load configuration. This results in a wheel load of 4,500 lbs. Tire pressure and contact area were taken as 100 psi and 45 in², respectively. For analysis, the contact area was taken as rectangular. Typical dual wheel tire contact areas and dimensions are shown in Figures 7 and 8, respectively [Huang, 1995]. As noted above, because of structure and loading symmetry, one-half and one-quarter of the pavement were modeled for the edge and interior loading, respectively.

FINITE ELEMENT MESH

The following factors were considered in developing the finite element mesh for analysis:

1. Pavement geometry, which controls the general size of the mesh
2. Load configuration, such as distance between wheels, axles, and loaded area
3. Degree of detail, i.e., location where pavement response parameters will be predicted
4. Element properties, such as material, geometry, and boundary conditions

Most mesh refinements in this study were applied around the loaded area and where there is a change of material. Mesh development is a process of trial and refinement. The steps, using TMID (Figure 9) as an example, are:

1. Initially a model was developed with a coarse mesh. An ABAQUS input file was created within PATRAN3 reference and executed. ABAQUS Post [ABAQUS/Post, 1994] was used to plot stress and deflection contours.
2. A model with finer mesh was developed and (1) repeated until the displacement contour lines drawn by ABAQUS/Post were continuous. To obtain more accurate predictions of stress, the model was further refined until the stress contour lines were also roughly continuous around the area of interest.

In the traffic direction every structure has the same mesh. In the loading region the mesh is 2.9 in the longitudinal direction. This mesh dimension is increased gradually to 29.5 in, maintaining a ratio of 1.26 between adjacent elements. Because of symmetry, as noted above, half and quarter models of the pavement were analyzed for the edge and interior loading cases, respectively.

BOUNDARY CONDITIONS

For the bottom of the model two boundary conditions were considered, infinite element and elastic foundation. Both were tried and the resulting stresses were the same. To simplify the ABAQUS input file, the elastic foundation option was selected to represent the bottom boundary condition.

The elastic foundation option was also used to represent the passive pressure of material beyond the lateral extent of the finite element model. Along the line of symmetry, YSYMM, the displacement boundary condition was specified so that in the Y direction displacements were restrained and the deflection angle zero. As a result, only the x direction and vertical displacements were allowed to occur.

Sensitivity of the elastic foundation modulus of subgrade reaction k was tested with the standard pavement structure (SEDGE). The bottom foundation stiffness was fixed at 50 pci while the lateral (edge) foundation stiffness value was varied between 5 to 100 pci. The results are summarized in Table 1. The pavement maximum and minimum vertical displacements changed from $4.5E-3$ to $-2.8E-4$ and from $-3.7E-2$ to $-3.2E-2$, respectively. However, the stress responses were not very sensitive to the magnitude of the elastic stiffness of the foundation. Because stress was the primary response of interest, a single, intermediate stiffness value of 50 pci was used in all subsequent analysis.

MATERIAL MODELS

The material option *CONCRETE in ABAQUS was used to model the concrete. Since asphalt is a time-dependent material and subgrade is a stress-dependent material, initially they were modeled using the models *VISCOELASTIC and *DRUCKER-PRAGER respectively. However, the *CONCRETE, *VISCOELASTIC, and *DRUCKER-PRAGER material models are not linear elastic material models and the ABAQUS analysis based on these material properties is very time consuming. By comparing stresses using both non-elastic material and elastic material models, it was found that the results were approximately the same. Therefore, the materials were taken as elastic. Young's modulus and Poisson's ratios specified for each material are shown in Table 2.

ANALYSIS MODEL

*STATIC option is a static stress/displacement analysis and *VISCO option is a "static stress/displacement analysis with history dependent material response" [ABAQUS, 1994]. Both *STATIC and *VISCO analysis were conducted with nonlinear material models and the structure responses were compared. The node displacement history can be obtained easily with the aid of ABAQUS/Post. Displacement history of nodes was plotted and inspected. The plots from *STATIC analysis were straight lines while the plots from *VISCO were curves. This implies that the effect of material time dependent behavior should be considered. However, for any structure, SEDGE or TEDGE, the difference in stress response for the *STATIC and *VISCO analysis was 15 to 28 percent. This was not considered significant for the relative analysis being conducted. Since the *STATIC analysis provides reasonable accuracy for comparing structures, and would reduce the program running time from 8-20 hours to 0.5-1 hour. Consequently, the *STATIC analysis procedure was utilized in lieu of the *VISCO analysis procedure.

*STATIC analysis was also conducted with linear elastic material models. Comparison of results for *STATIC linear and *STATIC nonlinear analysis indicated that the same stress responses were obtained. This implies there is no geometry nonlinearity effect in this problem. The small deflection values also reflect there are no large displacements.

RESULTS

Concrete has relatively high compression strength but low tension strength. Concrete cracking is associated with tension stress. Therefore, in this study positive stress values are compared.

EDGE LOADING CASE

Stresses for the edge loading case are shown in Figure 10. Compared to the standard structure, EEDGE and PEDGE have larger values of S11 while TEDGE and SEDGE12 have smaller values. The difference in value of the maximum S33 among all of the structures is not significant. Values of S11 and S33 are much smaller than the S22 in each structure. The S22 would control transverse cracking. Figures 11 and 12 show contours of S11 and S22 and S33 and U3, respectively for the TEDGE structure. Similar plots for all structures are given by Fei, 1996.

PEDGE has interior webs similar to a double "T" slab. Compared to the standard structure, the tensile stresses in PEDGE are decreased. However, as shown in Table 3 the quantity of concrete materials is increased. The PEDGE section is not as effective as expected. In the PEDGE structure, the exterior portion of the concrete flange acts like a cantilever resulting in high tensile stresses. Also, the right angle at the juncture of the web and the slab is a location of high compressive stress concentration. Moving the webs to the pavement edge as with the E section can reduce the high tensile stresses. Changing the angle of intersection between the web and slab such as the T section can reduce compressive stress concentration. These two structures are discussed in the following.

Among the five cross section structures, EEDGE has the smallest maximum S22. For example, with edge loading the S22 decreases from 208.4 psi in the SEDGE structure to 101.3 psi in the EEDGE structure, more than a 50 percent decrease. This is because with edge loading, one set of tires is above the web. From a mechanics point of view, when the two webs are at the edges, the concrete layer acts like a slab with partial restraint at the edge. The EEDGE structure has the same material quantity as PEDGE but the maximum EEDGE S22 stress is 34 percent less than that of PEDGE.

The web of the TEDGE structure has a smoother geometry transition, which results in a decrease of the compressive stress. Although the exterior portion of the concrete slab still acts like a cantilever, the length of the cantilever portion is much shorter than in the PEDGE structure. Consequently, there is a decrease of the maximum S22 with edge loading. However, this section uses 46 percent more material than the PEDGE and EEDGE structures and 120 percent more than the standard structure. Also the S22 is only decreased by 27 percent compared with the PEDGE structure. The S22 with edge loading is even higher than for the EEDGE structure.

For comparison purposes, a structure designated as SEDGE12 was analyzed. SEDGE12 is a conventional flat slab with a concrete thickness of 12 in. As expected, when compared with the SEDGE structure, the SEDGE12 stresses are lower when compared with the other structures. SEDGE12 has the smallest S11 and S33 stresses. Its S22 is larger than the S22 of TEDGE and EEDGE structures and 20 percent smaller than S22 of the PEDGE structure.

The EEDGE structure has the least critical S22 stress. Three structures, EEDGE, TEDGE and SEDGE12, have approximately the same S22 stresses, ranging from 40 to 50 percent less than the standard structure.

INTERIOR LOADING CASE

Stresses from interior loading are shown in Figure 13. Compared to the standard structure, the EMID structure has a larger value of S11 while TMID, PMID and SMID12 have smaller values of S11. The S33 stress of the standard cross section is slightly higher than the other four structures. Also, as in the edge loading case the S11 and S33 stresses are much smaller than the S22 stress in each structure.

The webs of the TMID and PMID structures are significant in reducing the S22 stress. For the TMID structure, the load is carried partly by the web and partly by the exterior cantilever of the PMID structure. As a result, the TMID and

PMID structure's S22 is 57 and 38 percent lower, respectively, than the SMID section. In the EMID structure the slab acts like a simply supported slab with interior loading, and the webs do not have as much effect as in the PMID or TMID structures. Interior loading of EMID and TMID structures is discussed in the following paragraphs.

The SMID12 structure has the smallest S33 relative to any other structure, and its S11 is much smaller than that of the EMID structure. The S22 is almost equal to the S22 of PMID structure and is between the values for the TMID and EMID structures.

For interior loading, based on the stress analysis, the TMID structure is the optimum structure. It has a maximum stress 57 percent less than the standard structure and 34 percent less than the SMID12 structure.

CONCLUSIONS

As would be expected, the maximum S22 in the edge loading case is larger than the interior loading case for each structure. The largest difference occurs in the T section structures between TEDGE and TMID. The smallest difference occurs in the E section structures. The E section has approximately the same maximum stress for both edge and interior loading.

When compared to the standard structure, the critical stresses of T section structures decrease significantly for both loading cases. The E section structures are almost as good as the T section structures in edge loading but are worse than the T section structures for interior loading. Based on stress consideration, the T section structure is the optimum structure. The second best structure is the S12 (SEEDGE12 and SMID12) structure.

However, the S12 structure uses less concrete and asphalt than the T structures and would also require less labor. As a result, the S12 structure could be a better choice than the T section structure based on economic as well as stress response consideration.

Further, detailed finite element analysis should be conducted to determine the optimum structure. For example, if the T structure is selected as the optimum structure, its web depth and the angle between the web and slab should be studied. Also, the effect of temperature and moisture gradients when combined with load stresses is significant. Including these effects may modify the current results of the study.

It is suggested that laboratory or field-testing be conducted and the results compared with finite element analysis. Such a study should provide better definition of material properties for the finite element analysis.

Table 1 Effect of Foundation Stiffness

Stiffness(psi)		5	15	50	100
S11(psi)	Max	60.95	60.83	60.48	60.12
	Min	-82.05	-81.81	-81.18	-80.61
S22(psi)	Max	208.5	208.4	208.4	208.4
	Min	-241.7	-241.7	-241.6	-241.5
S33(psi)	Max	18.01	18.01	18.0	17.99
	Min	-150.3	-150.3	-150.3	-150.3
U3(in)	Max	4.5E-3	3.5E-3	1.3E-3	-2.8E-4
	Min	-3.7E-2	-3.6E-2	-3.4E-2	-3.2E-2

Table 2 Material Elastic Properties

	Concrete	Asphalt	Subgrade
Young's modulus(psi)	4.0E+6	3.0E+5	1.0E+4
Poisson's ratio	0.15	0.45	0.35

Table 3 Comparison of Material Volumes

Section Type	S	T	E	P	S12
Area of Concrete (in ²)	1152	2527.2	1728	1728	1728
Area of Asphalt (in ²)	1152	516	960	960	1152

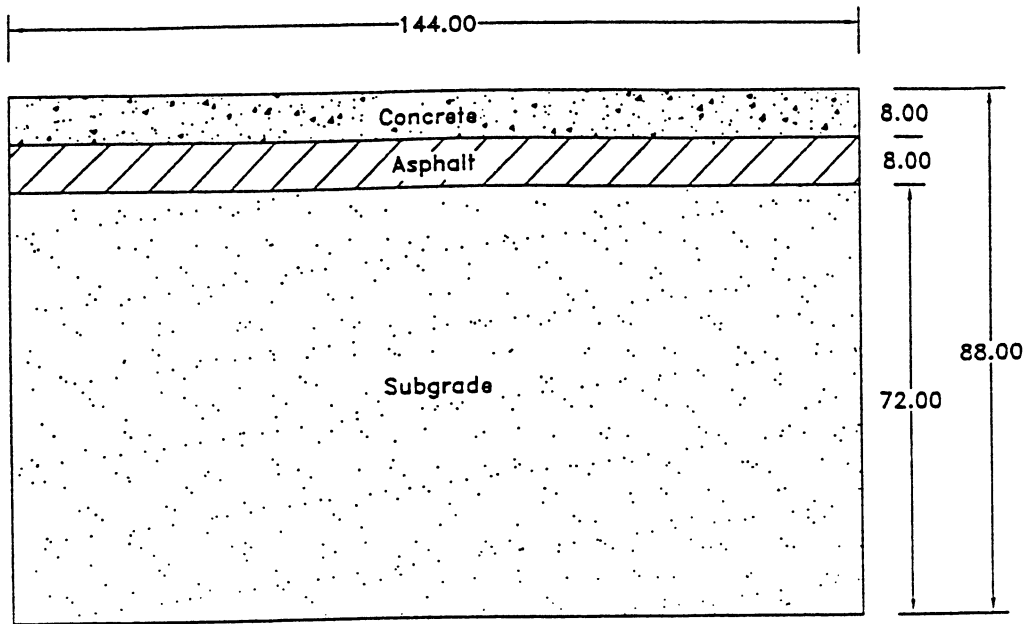


Figure 1 Cross Section of S Structure (SEGE and SMID)
(Unit: inch)

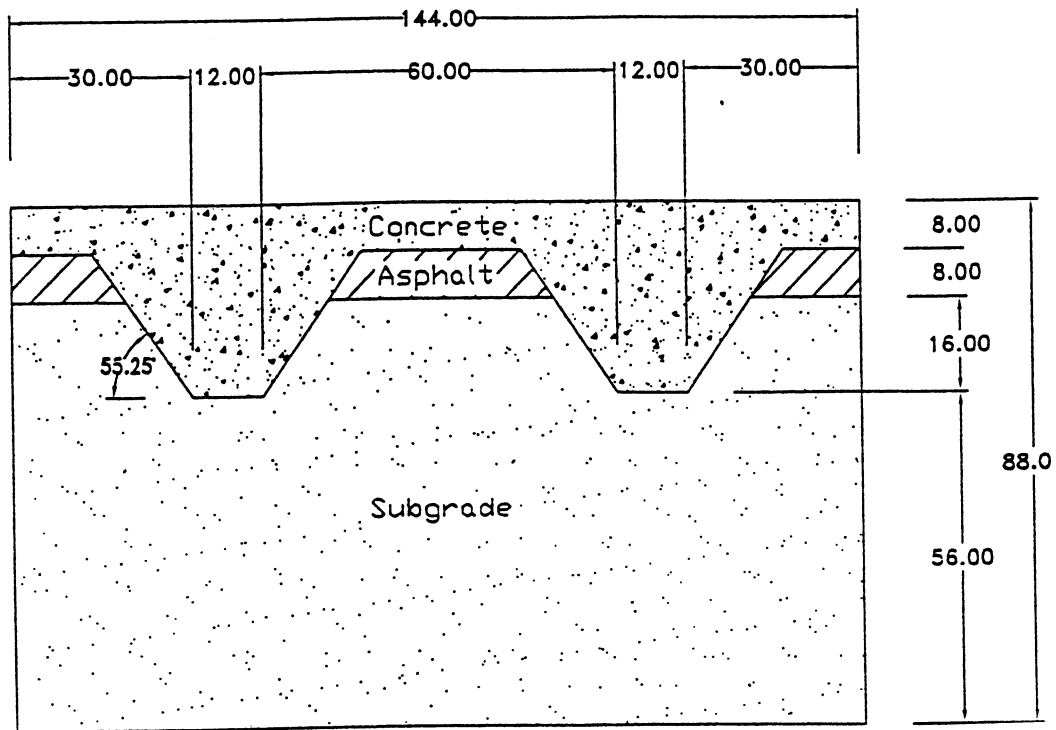


Figure 2 Cross Section of T Structure (TEDGE and TMID)
(Unit: inch)

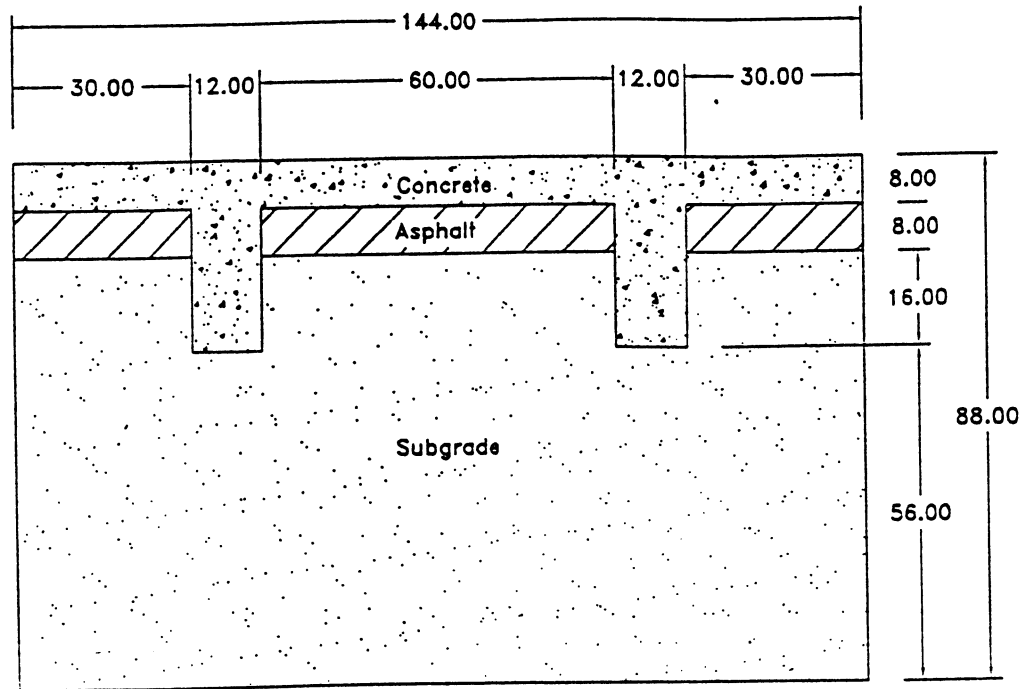


Figure 3 Cross Section of P Structure (PEDGE and PMID)
(Unit: inch)

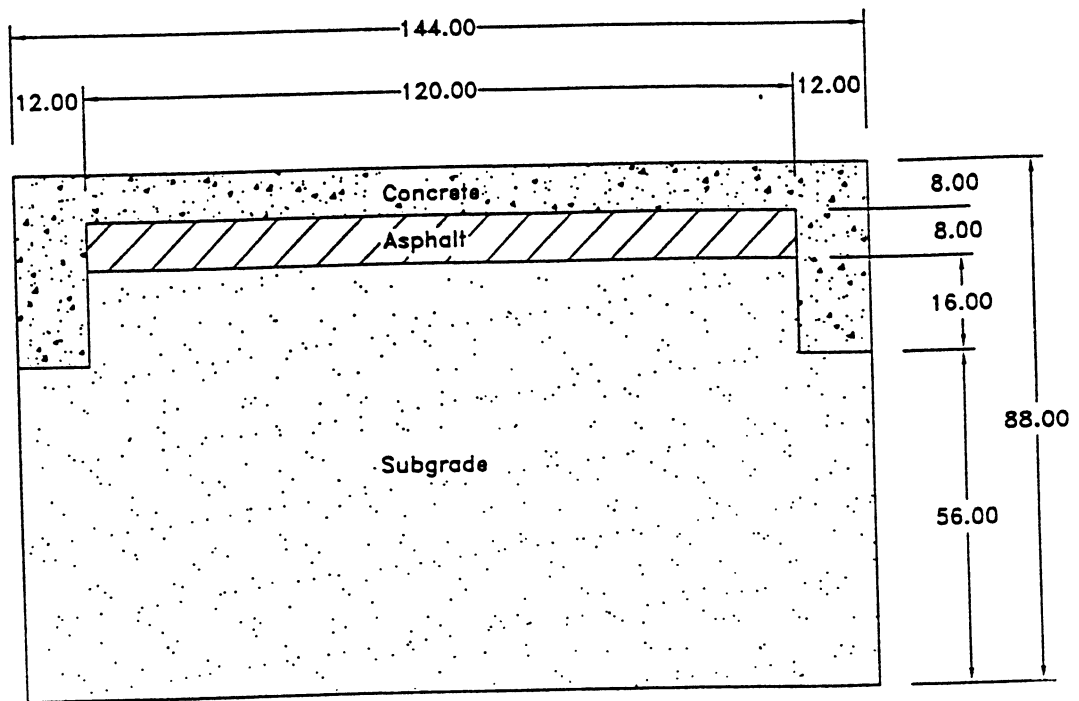


Figure 4 Cross Section of E Structure (EEDGE and EMID)
(Unit: inch)

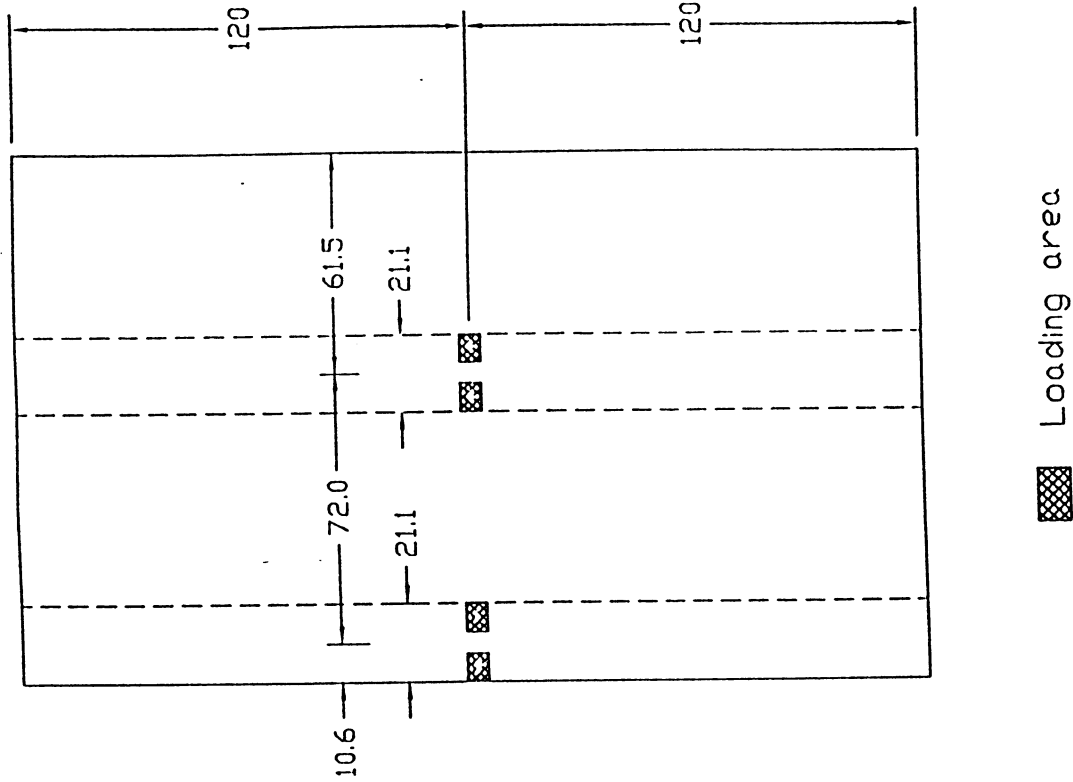


Figure 5 Plan View of Edge Loading
(Unit: inch)

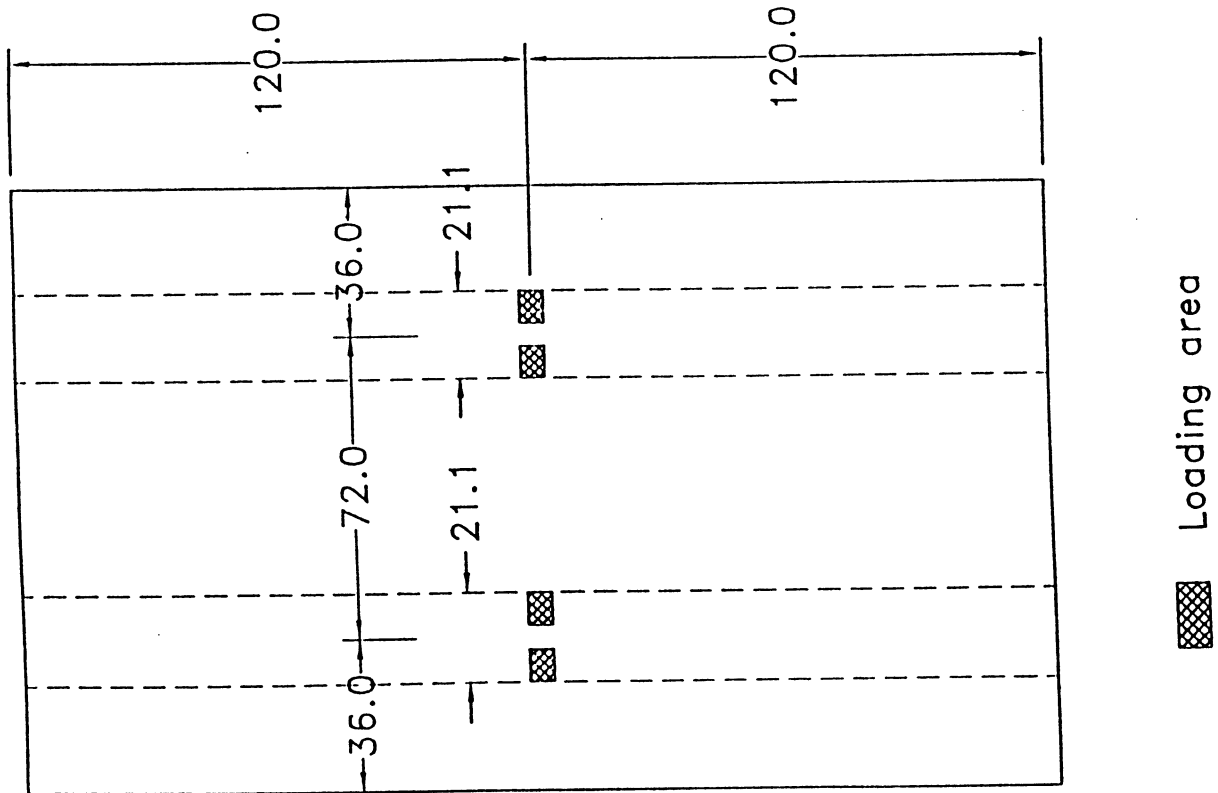


Figure 6 Plan View of Interior Loading
(Unit: inch)

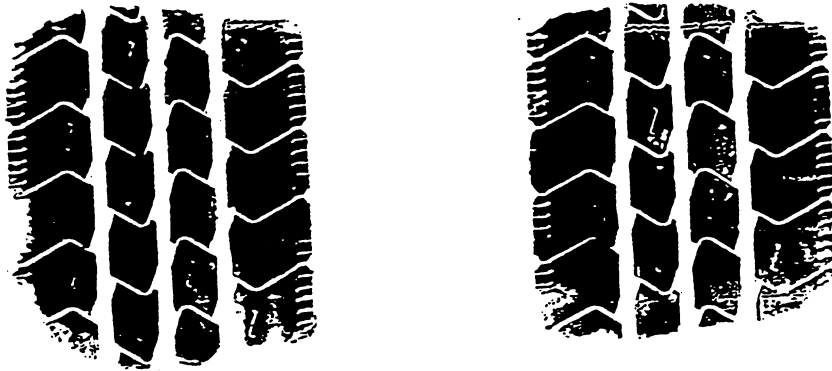


Figure 7 Tire Print of a Pair of Tires

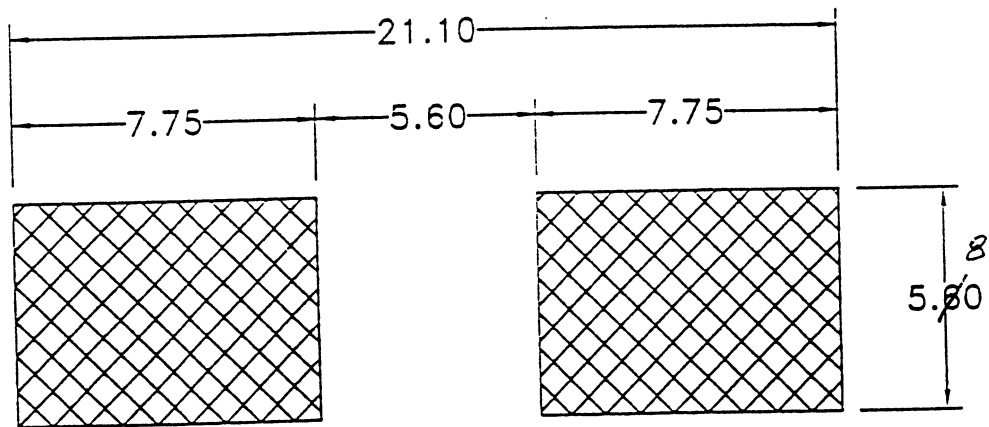


Figure 8 Detail of One Pair of Wheel Loadings Area
(Unit: inch)

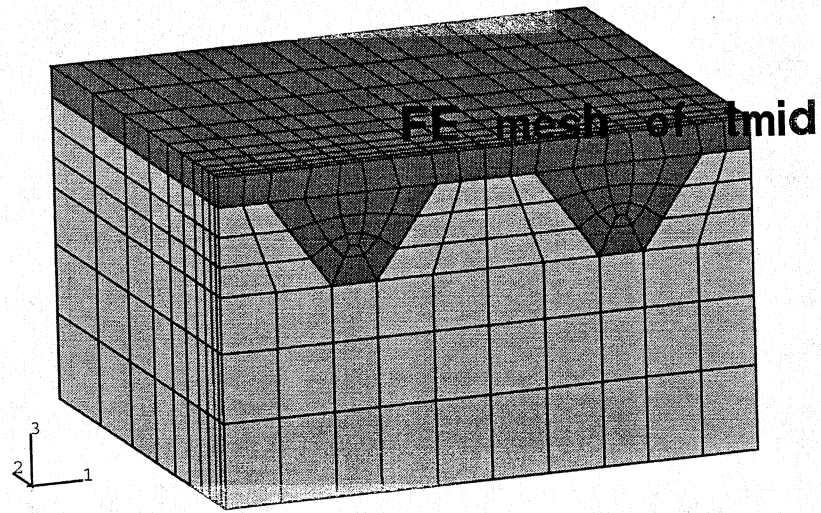


Figure 9 Finite Element Mesh of TMID

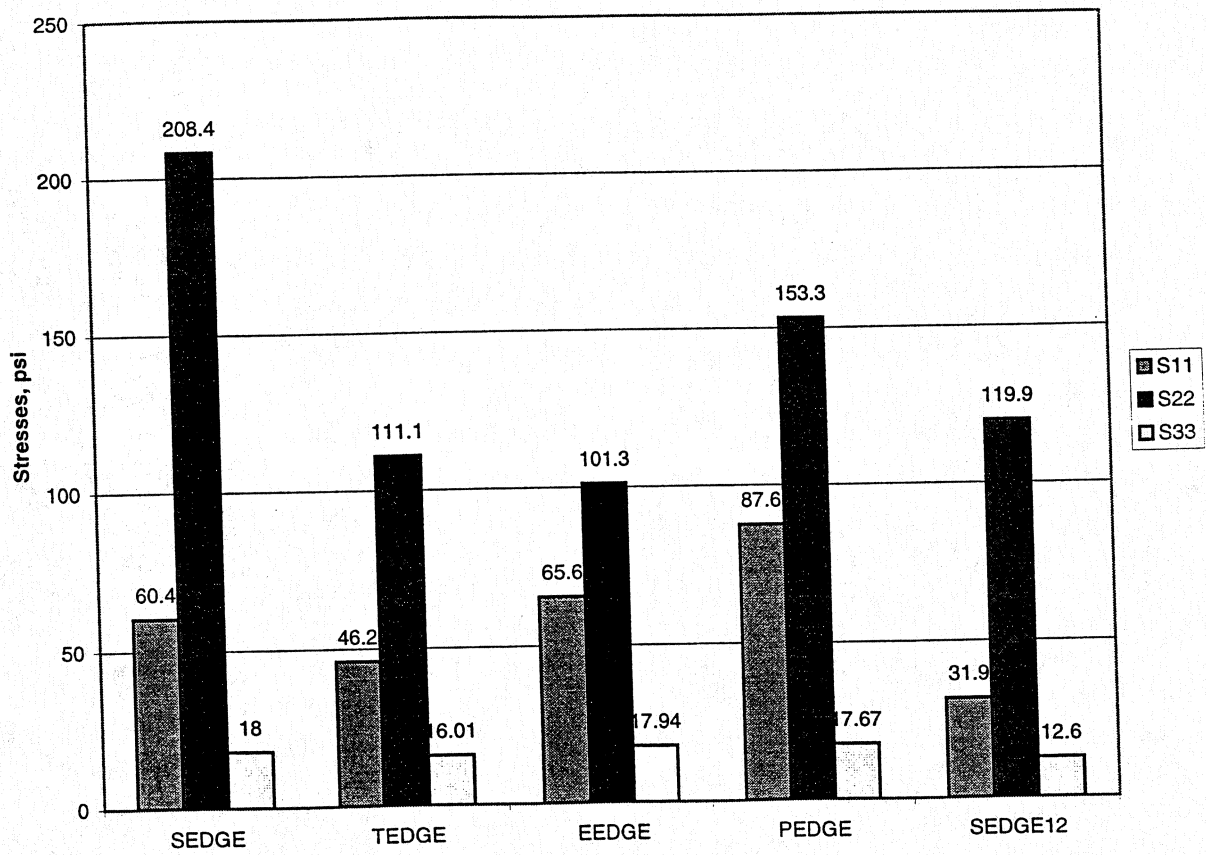


Figure 10 Maximum Stresses in Edge Loading Case

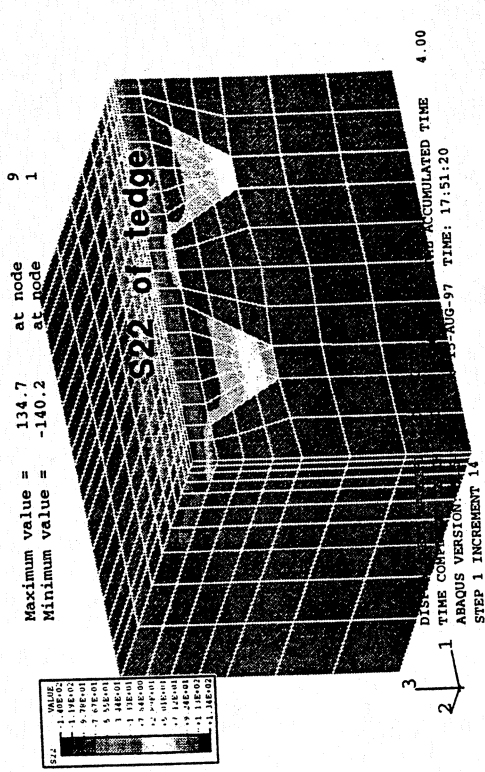


Figure 11 Contour Plot of TEDGE
(S11 and S22)

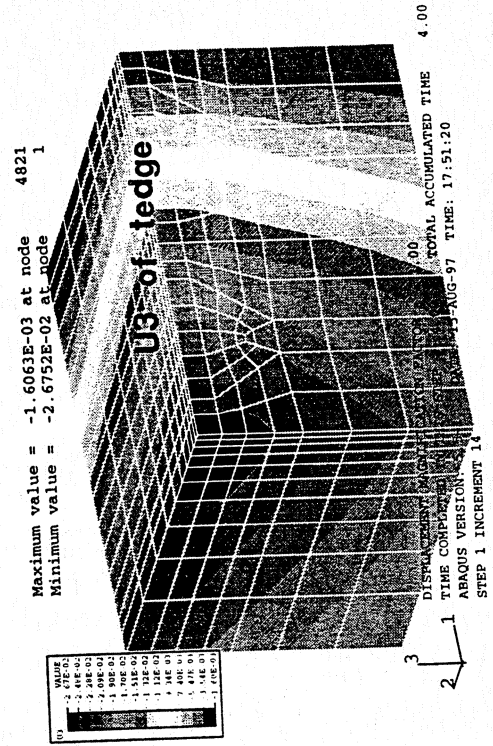
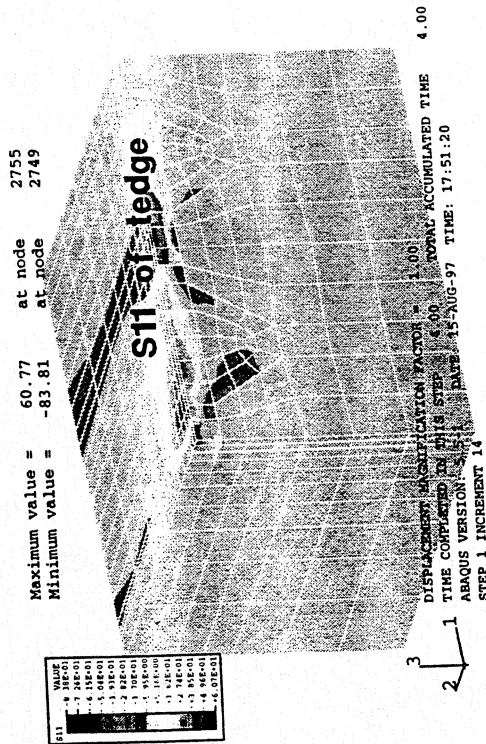
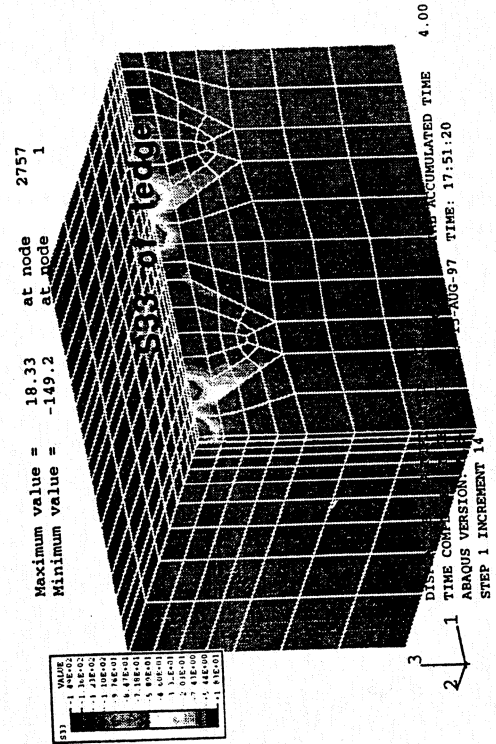


Figure 12 Contour Plot of TEDGE
(S33 and U3)



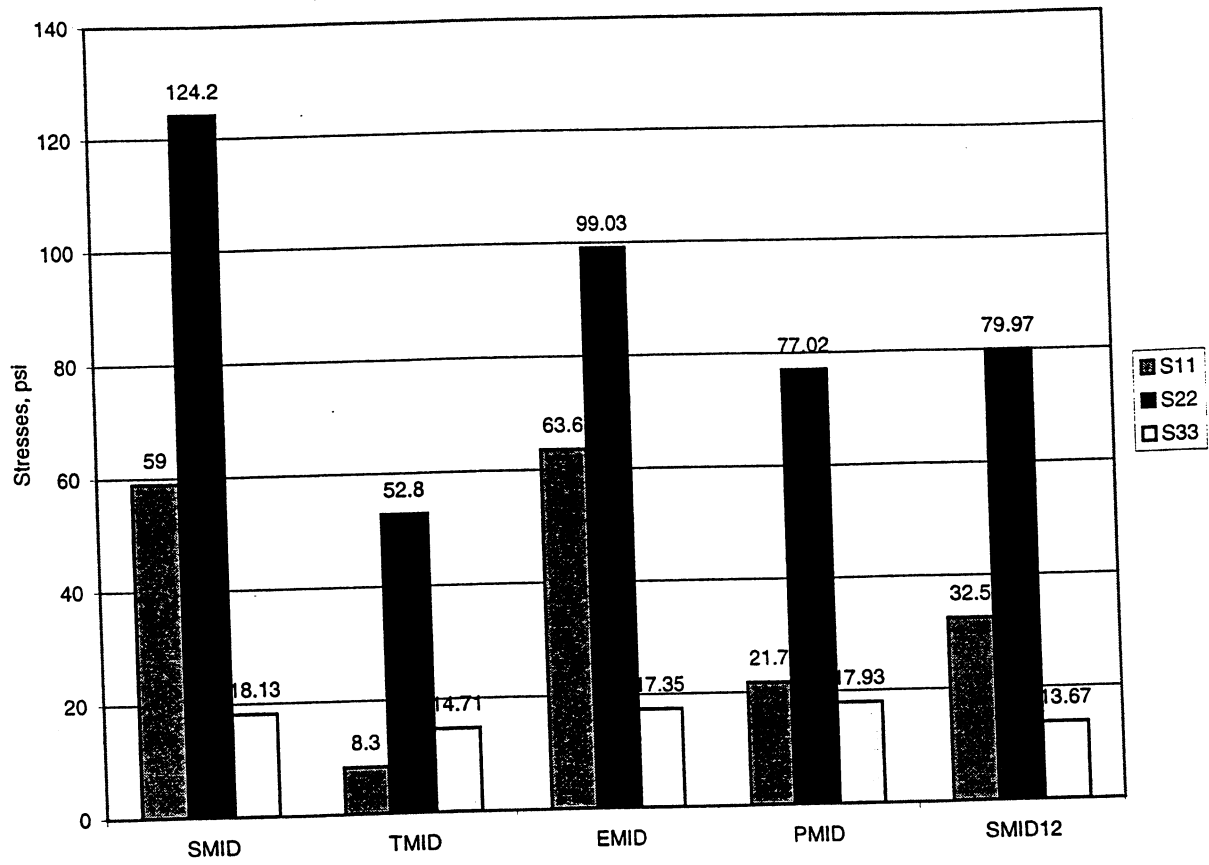


Figure 13 Maximum Stresses in Interior Loading Case

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