

THEORETICAL INVESTIGATION OF CROSS TENSIONED CONCRETE PAVEMENT

by

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ABSTRACT

The deterioration of Portland Cement Concrete Pavement (PCCP) is most often due to poorly performing transverse joints and cracks. This problem could be solved by eliminating the majority of transverse joints and constricting the cracking capability of the pavement by applying an external force to the pavement in the form of post-tensioning. The post-tension strands can be arranged diagonally resulting in Cross Tensioned Concrete Pavement (CTCP). Finite element analyses results show that the maximum tensile stress at the crossing of the strands near the pavement edge is much lower than the recommended allowable stress. The tensile stress between the opposing bearing plates is also reasonable. The proposed design also resulted in maximum compressive stresses and displacements as per design expectation. Thus, the proposed CTCP design appears to be a feasible design solution for longer lasting concrete pavement.

INTRODUCTION

The deterioration of Portland Cement Concrete Pavement (PCCP) is most often caused by intrusion of water into the pavement system. The water usually infiltrates through the transverse joints and cracks. During construction process and routine maintenance, the transverse joints and cracks are typically sealed with a flexible joint sealant. The sealant keeps most of the water out, however, some water does get into the pavement. Eventually the pavement deteriorates due to pumping and subsequently, develops faulting.

Eliminating transverse joints and cracks is one solution to this common problem of PCCP, and this has been demonstrated in the Continuously Reinforced Concrete Pavements (CRCP). Pre-stressing PCCP could also eliminate joints and cracks. By applying an external force in the form of post-tensioning, theoretically all typical cracks and joints in the pavement can be eliminated. The high stresses should also hold the cracks very tight making those impervious to water. Extended pavement life should also be expected as a result of pre-stressing PCCP. Pre-stressed PCCP's should have better ride quality too due to absence of transverse joints. Pre-stressing also should increase the load carrying capacity of the pavement and lower the maintenance costs.

OBJECTIVE

One alternative to the conventional concrete pavement is Cross Tensioned Concrete Pavement (CTCP) (1). CTCP appears to be very promising as the longer lasting pavement. As a result of introducing cross pattern post tension stresses in CTCP, there are many unknown stress effects. Typical stresses developed in CTCP are analyzed and discussed here.

FUNDAMENTAL DESIGN CONCEPTS

Conventional PCCP design is based on the modulus of rupture of concrete and does not directly take advantage of the high compressive strength of concrete. Post-tensioned concrete pavement (PTCP) increases the flexural stress range by introducing compressive stresses in the concrete slab. The resulting pavement has several advantages: (a) absence of cracks, (b) reduced cost through a reduction in slab thickness, and (c) a large increase in load carrying capacity.

The fundamental formula for the design of pre-stressed pavements is (2):

$$f_t + f_p \geq f_{\Delta t} + f_F + f_L$$

where,

- f_t = allowable concrete flexural stress;
- f_p = compressive stress in concrete due to post-tensioning stresses;
- $f_{\Delta t}$ = curling stress due to temperature difference between top and bottom of slab;
- f_F = stress due to subgrade friction; and
- f_L = stress due to traffic load.

The allowable concrete flexural stress may be taken as high as 80 to 100 percent of the modulus of rupture of concrete. Introducing a compressive stress in the concrete pavement changes the criterion for failure from a bottom tension crack to a top circular crack. The failure load is at least twice the load that would produce the first bottom crack. This allows the designer to choose a safety of factor between 1 and 1.25 for f_t (2).

Stresses induced in PTCP should not exceed the compressive strength of the concrete. During construction stresses must be applied before the concrete has reached its maximum compressive strength. Construction stressing resists the formation of shrinkage cracks. However, tensioning to design may cause a compressive failure of the concrete. Therefore, tensioning of post-tension strands should be executed in stages (3).

Allowable stresses in the post-tensioning strands, f_{se} , after all losses including creep should not exceed 80 percent of the ultimate strength, f_s' , of the post tensioning steel (2). A typical post-tensioning mono-strand will be a one-half inch diameter strand, made with six wires twisted around one wire. The ultimate strength of a typical post-tensioning strand is 1,862 MPa (270 ksi) (3). Thus the design stress in each strand should not exceed 1,490 MPa (216 ksi).

Curling stresses in PTCP are caused by warping of the slab due to temperature differential between the top and the bottom of the slab. Concrete slabs curl when one face is warmer or cooler than the other face. The warmer face of the concrete tends to expand while the cooler face contracts. Curling stresses in PTCP can have adverse effects on the stresses within the post-tensioning strands. Shortening of the slab caused by curling will cause some relaxation in the post-tensioning strands. Consequently, unlike typical PCCP design, it is essential to design for curling in PTCP (3). The curling stresses in concrete can be calculated from (2):

$$f_{\Delta t} = \pm \frac{a E_c \Delta t}{2(1 - \nu)}$$

where,

a = coefficient of thermal expansion;

Δt = temperature gradient ;

h = slab thickness;

E_c = Modulus of elasticity of concrete in psi; and

ν = Poisson's ratio for concrete (0.15).

Friction between the slab and the subgrade can give a false indication of compression in PTCP. Consider, for example, that a slab is pinned to the subgrade at two different points between the ends of a post-tensioning strand. When the strand is tensioned a compressive force is exerted into the concrete slab. However, the region between the two pins experiences no compressive force. For this reason the frictional stress between the slab and the subgrade must be considered in the design of PTCP.

The coefficient of subgrade friction is substantial with a value of 0.2 to 1.5 for slabs resting on a sand or granular subbase. For design purposes, the coefficient of subgrade friction can be taken as 0.5 to 0.8. Most historical designs of PTCP incorporate two layers of 6 mil polyethylene sheeting which have a coefficient of friction of less than 0.2 (2). In the Arizona PTCP project, almost no differences in friction between the slab and subgrade on either one or two layers of polyethylene sheeting were found (4). In either case, it is recommended that the designer use a conservative value of 0.5 for the coefficient of friction in design (2).

Friction between the subgrade and the slab produces a tensile stress that is most significant in the middle portion of the slab. For a slab that is less than 213 m (700 ft) in length, the frictional stress between the subgrade and the slab can be estimated as (2):

$$\max f_F = \frac{cgL}{2 \times 144}$$

where,

c = coefficient of subgrade friction;

L = total longitudinal length between each in line post-tension bearing plate; and

γ = unit weight of concrete.

All conventional PCCP designs consider traffic load as the major cause of stresses in pavement. For PTCP, traffic load consideration is no different. Traffic loads induce a tensile stress at the bottom of the pavement. The stress is calculated by the Westergaard's formula. The edge loading of PCCP is always the controlling criteria. The stresses in the pavement induced by repeated traffic loads can lead to the elastic deformation of the slab to the point where the maximum moment beneath the loaded area exceeds the sum of the flexural strength of the concrete and the induced prestressing force. At that point a crack forms a hinge under the load, and repeated load applications will cause a moment in the slab some distance away from the loaded area. If the load repetition continues tensile cracks can form at the top of the pavement. When loading is increased beyond this point, the load will eventually punch through the slab. For this reason it is extremely important to consider traffic load in PTCP (2).

Now the Westergaard's formula for edge loading of PCCP is given by (5):

$$f_L = \frac{0.803P}{h^2} \left[4 \log \left(\frac{l}{a} \right) + 0.666 \left(\frac{a}{l} \right) - 0.034 \right]$$

where,

f_L = maximum edge stress under load;

$$l = \text{radius of relative stiffness} = \left[\frac{Eh^3}{12(1-n^2)k} \right]^{0.25};$$

E = modulus of elasticity of concrete (assume 27,579 MPa or 4,000,000 psi);

k = modulus of sub-grade reaction (assume 27 kPa/mm or 100 psi/in);

P = concentrated load, lbs.; and

$$a = \text{contact radius} = \sqrt{\frac{P}{\text{tire pressure} \times \Pi}}$$

For a typical maximum load of 98 kN (22,000 lbs) per axle on dual wheels, P can be estimated as 24.5 kN (5,500 lbs) and the tire pressure can be taken as 690 kPa (100 psi).

Typical jointed PCCP will deflect at the joints under repeated loads. A large part of the deflection in PCCP's is most often caused by deformation of the subgrade. However, PTCP loads are distributed over a continuous rigid slab. Due to PTCP's interaction with the loading and the subgrade, it behaves much like a spread foundation, where large loads are distributed over wider areas. Also, voids in the subgrade can be spanned due to an increase in the flexural strength of the post-tensioned concrete.

CTCP Design Considerations

Cross-tensioning PCCP may give the designer the option to construct an unjointed, uncracked pavement of any length. The procedure for designing such a pavement is similar to PTCP which is post-tensioned in the longitudinal direction. The only difference is the interpretation of the frictional losses between the concrete slab and the subgrade. In longitudinal post-tensioning design, the designer considers a finite section of pavement resulting in gap slabs between post-tensioned slabs. The length of the pavement between the gap slabs is the effective slab length that is subjected to the frictional force between the PCCP slab and the subgrade. In CTCP, the designer post-tensions the pavement in both diagonal directions. By cross tensioning, the concrete slab cannot expand in any direction. This results in unjointed, continuous, and seemingly infinite pavement (1).

The appropriate angle, at which the cross tensioning should be applied, should be less than 45 degrees to the longitudinal direction of the pavement. This allows the majority of the stressing force in the strands to act against the weak plane of the concrete, the transverse plane. The less than 45-degree specification also resists cracking in the longitudinal direction, as did the Arizona PTCP.

Strand location in the slab is most important. Historically the strands of post-tensioning steel have been placed 12.5 mm (0.5 inches) below the mid-depth of the slab. At this depth, the strands gain

tension under heavy loads through elongation. Lowering the strands to 12.5 mm (0.5 inches) below mid-depth causes the slab to have an induced negative moment. When a heavy load traverses the pavement, the induced negative moment is canceled by a positive moment. This allows a much thinner slab than a conventional concrete pavement.

Strand placement at the edge of the pavement is also very significant. It is important that when the strands are stressed in different directions on the same side of the pavement very near to each other, they be placed so that compression happens in between the strands. This requires that the strands be crossed very close to the pavement edge. For example, assume that a pavement is stressed with the 45-degree post-tensioned strands. Consider now that the strands are laid out in such a way that two strands, perpendicular to each other, are very close, but not crossing at the pavement edge. This will cause a tensile stress in the concrete between the two strand ends. If the tensile stress is too great, the concrete may develop a transverse crack.

Now consider the same two strands as crossing very near the pavement edge. The only stress that will exist between the two strands in that case is a compressive stress. It is well known that concrete cannot support excessive tensile forces. The tensile strength of concrete is highly variable and is usually only considered to be 10 to 15 percent of the compressive strength.

The thickness of the concrete slab used in PTCP is less than conventional concrete pavement. Pavements as thin as 89 mm (3.5 inches) have been developed for use with longitudinally post-tensioned pavements. However, problems associated with coverage and uniform paving make this an unfavorable choice on most highway pavements. ACI (3) recommends that a pavement thickness at least 65% of the thickness of an alternative plain concrete pavement be used for PTCP's. This allows for appropriate coverage and variations in construction. For most cases, a pavement thickness of 150 mm (6 inches) is sufficient for coverage and construction tolerances.

Special attention needs to be given to the stressing operation. The strands cannot be stressed to design until the concrete has gained sufficient strength. Arizona stressed its longitudinally post-tensioned PCCP in three stages (4). Since cracking occurs from volume change, thermal gradient, and subgrade restraint, it is imperative that the first stage tensioning be applied to the cables at the earliest practical time, usually within 24 hours. Some small cracks may form before initial jacking; however, they should close upon application of the jacking force. The second application of stressing should be done within 24 hours of the previous operation. Lastly, the final jacking should be done when the concrete strength has reached at least 21 MPa (3,000 psi), independent of time. It is imperative not to jack the strands beyond the strength of the concrete. Jacking forces should be determined considering the size and thickness of the bearing plate end anchors and minimum concrete strength necessary to withstand the applied force. It may be necessary to increase the end anchor bearing plate size to distribute the high bearing stresses at the slab edges (1).

FINITE ELEMENT ANALYSIS OF STRESSES NEAR THE PAVEMENT EDGE

Finite element (FE) analyses provide a significant basis for the development of mechanistic design of pavements. Available finite element programs are powerful tools for stress-strain analysis in pavement structures. Therefore, it is expected that they can be used to investigate the stresses and strains in CTCP.

To investigate the stress at the edge of CTCP, a three-dimensional finite element model was built using ANSYS 5.5 FE software. The software enabled the modification of the geometry of the FE model grid and selection of several element types. These options allowed performing more specific analyses, such as, changes in geometry, boundary conditions, input parameters, material properties density, elastic modulus, and friction coefficient. SOLID45 element was used to capture behavior of the CTCP and subbase layers in three dimensions. CONTAC174 and TARGE170 elements were used to model the interface friction between the CTCP slab and subbase layers.

Meshing, Model Dimensions and Mechanical Properties

Automatic mesh generator option that can perform structured and unstructured mesh generation was used to mesh the CTCP slab and subbase layers. Mesh dimensions were kept small enough to allow detailed analysis of the edges. The mesh was made finer around the region with the strands. However, as the mesh was made finer, the number of elements increased resulting in increased memory and computational time requirements. The software was limited to 32,000 nodes. Thus, some modifications (smaller dimension) were required in the modeling process.

A model which contains more strands was desirable. Several FE models with different dimensions were tried. Mesh problems occurred with models containing higher numbers of strands. Less accurate results were expected with coarser mesh structures. Figure 1 shows the non-smooth stress distribution on the loading edge. Due to memory and convergence problems, the best possible model structure was a slab 3.1 m (120 inch) long (x direction), 3.8 m (150 inch) wide (z direction), and a typical 300 mm (6 inches) thick (y direction). Below the CTCP slab, a 300 mm (6 in) thick subbase layer was assumed. The elasticity moduli of the CTCP slab and the subbase were 27,579 MPa (4,000,000 psi) and 690 MPa (100,000 psi), respectively. A typical value of Poisson's ratio (0.15) was assigned to both layers. The weights of the layers were also included in the model. Figures 2 and 3 show the layer dimensions and the element mesh used to model the layers, respectively.

The friction behavior between the CTCP slab and the subbase layer was modeled with the contact elements. Contact problems are highly non-linear and require significant computer resources to solve. This was another reason for using small structural dimensions. The temperature and tangential velocity effects on the friction were neglected. Classical Coulomb friction was considered.

The contact problems were categorized into two general classes in the software: rigid-to-flexible and flexible-to-flexible. In the FE analysis the rigid-to-flexible contact option was used since one of the contacting surfaces, CTCP, was assumed as rigid because it had a much higher stiffness relative to the deformable body, subbase, it is in contact.

The software supported three contact models: node-to-node, node-to-surface, and surface-to-surface. Each type of model uses a different set of contact elements. In this analysis, surface-to-surface option was used. The surface-to-surface elements have several advantages over the node-to-surface elements. These elements:

1. Support lower and higher order elements on the surface;
2. Support large deformations;
3. Provide better contact results needed for normal pressure and friction stresses;
4. Have no restrictions on the shape of the target surface; and
5. Require fewer contact elements than the node-to-surface elements.

Contact elements were generated using the contact pair option in order to include surface-to-surface and rigid-to-flexible options. Contact pair consists of target surface and contact surface. In this research, the TARGE170 and CONTA174 elements were used to represent target surface and contact surface, respectively. Elastic Coulomb friction was allowed, where sliding was along the target base. The coefficient of friction, μ , was chosen as 0.5.

Loading and Boundary conditions

Two loading positions were considered. The CTCP edges were subjected to 119 kN (26,800 lbs) force acting +30 and -30 degree angles with the z direction. The strands along the CTCP edge was primarily been set at 1.5 m (5 feet) between +30 strands and 1.5 m (5 feet) between -30 strands. The strands were also set so that the -30 and +30 strands were opposing each other in compression with a spacing of 0.3 m (1 foot). The bottom of the subbase was constrained in the x, y, z directions. Symmetry option was used at the centerline of the 7.6 m wide CTCP pavement (3.8 m width was modeled in this study).

Finite Element Analysis Results

Figure 4 shows the compressive and tensile stress distributions in the z direction. The stress distributions at the loading surface and at the center line of the CTCP are of particular interest in this study.

Figure 5 shows the stress distribution in the z direction (toward centerline) through the loading edge. The “-“ and “+” symbols refer to compressive and tensile stresses, respectively. Stress distribution at the loading surface revealed that the maximum tensile stress occurred between two opposing strands. The stress values were as high as 400 kPa (55 psi) which is much less than 80% of the concrete modulus of rupture, 3 MPa (440 psi) suggested by ACI. The lowest tensile stress, 120 kPa (17 psi), occurred at the middle of the loading edge. As expected, the maximum compression stress of 6.2 Mpa (approximately 900 psi) occurred at center of the strands on the loading edge. The compressive stress at center line of the CTCP slab varied from 500 kPa to 600 kPa (80 psi to 90 psi).

Figures 6 and 7 show the horizontal displacements in the z direction toward the centerline. The “-“ symbols refer to the displacements in the direction of the centerline. The maximum displacement

occurred at the strand locations and was 0.04 mm (0.0015 inch). As expected, no displacements occurred at the centerline.

Figure 8 shows the vertical deflection in the y direction which would indicate upward or downward curling. It can be noticed that the CTCP is curling down as per the design expectation due to the eccentricity of load application. The maximum curling was at the loaded edge and was 0.075 mm (0.003 inches).

CONCLUSIONS AND FUTURE RESEARCH

The fundamental design and some advanced analyses for the Cross Tensioned Concrete Pavements (CTCP) are outlined. Finite element analyses were done using ANSYS to investigate the stresses in CTCP. The results show that the maximum tensile stress at the crossing of the strands near the pavement edge is much lower the recommended allowable stress. The tensile stress between the opposing bearing plates is also reasonable. The proposed design also resulted in maximum compressive stresses and displacements as per design expectation. Thus, the proposed CTCP design appears to be a feasible design solution for longer lasting concrete pavement. However, constructability of this innovative design using current paving technology needs to be investigated.

REFERENCES

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ILLUSTRATIONS

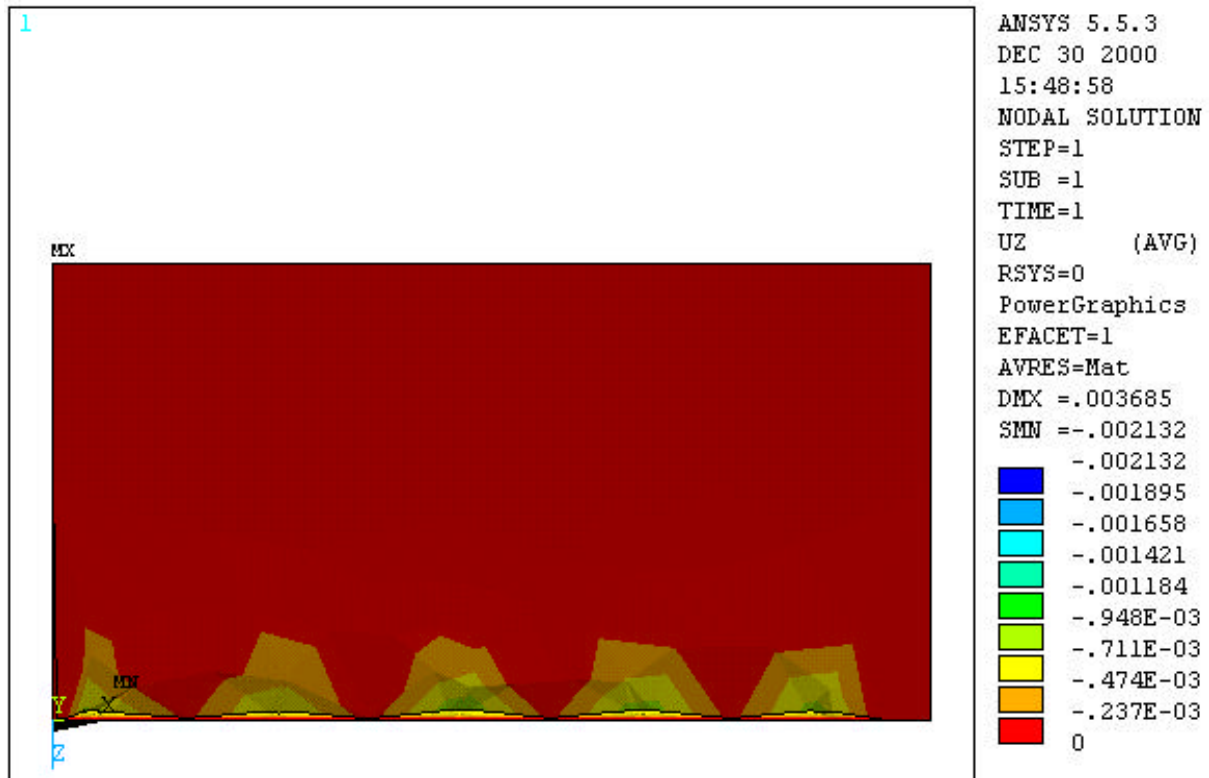


Figure 1 Non-Smooth Mesh Plan View with Five Strands

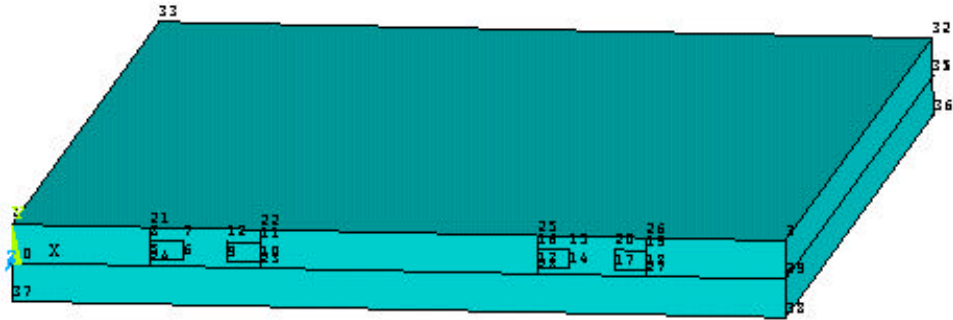


Figure 2 View of the 3-D Model with Four Strands, CTCP and Subbase Layers

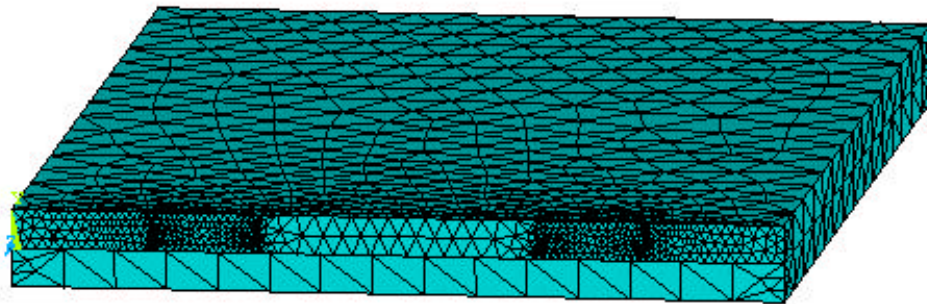


Figure 3 Three Dimensional (3-D) Mesh of the Structure

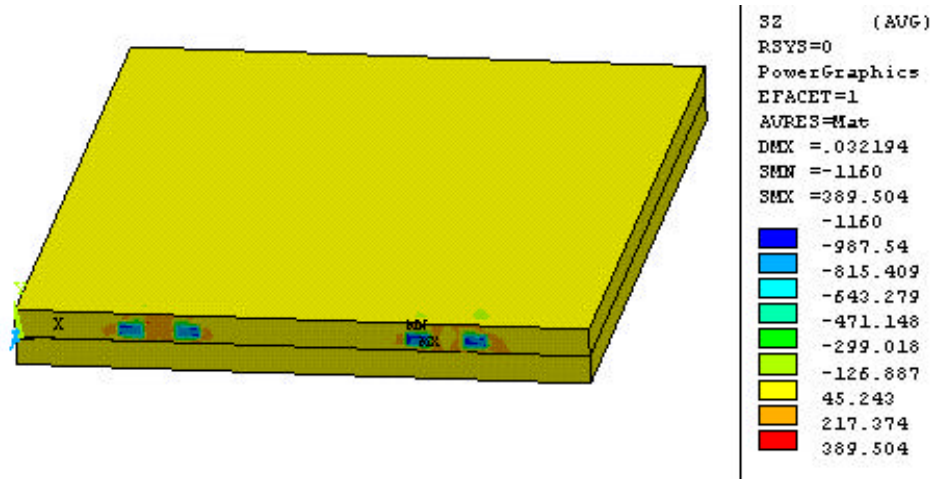


Figure 4 Stress Distribution in the z-Direction (toward the centerline)

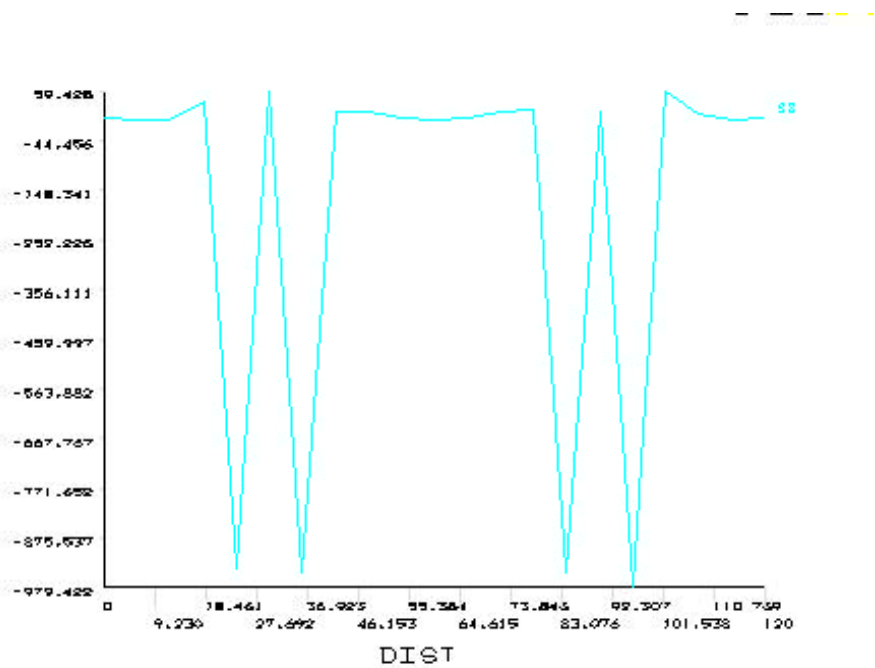


Figure 5 Stress Distribution on the Loading Edge in the z direction

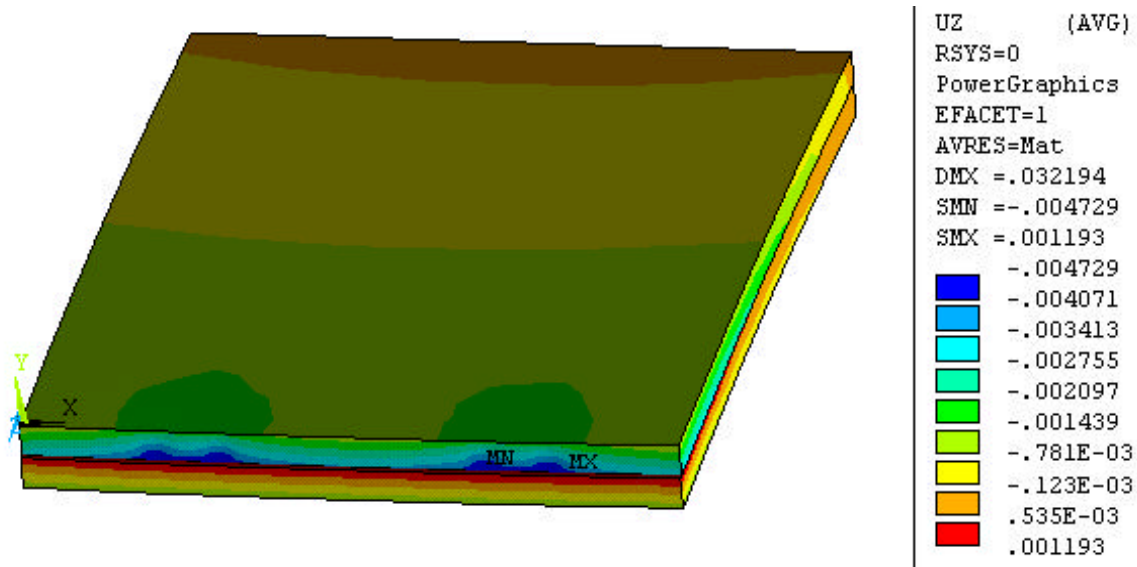


Figure 6 Displacements on the Loading Edge and the Centerline of the CTCP slab in the z Direction

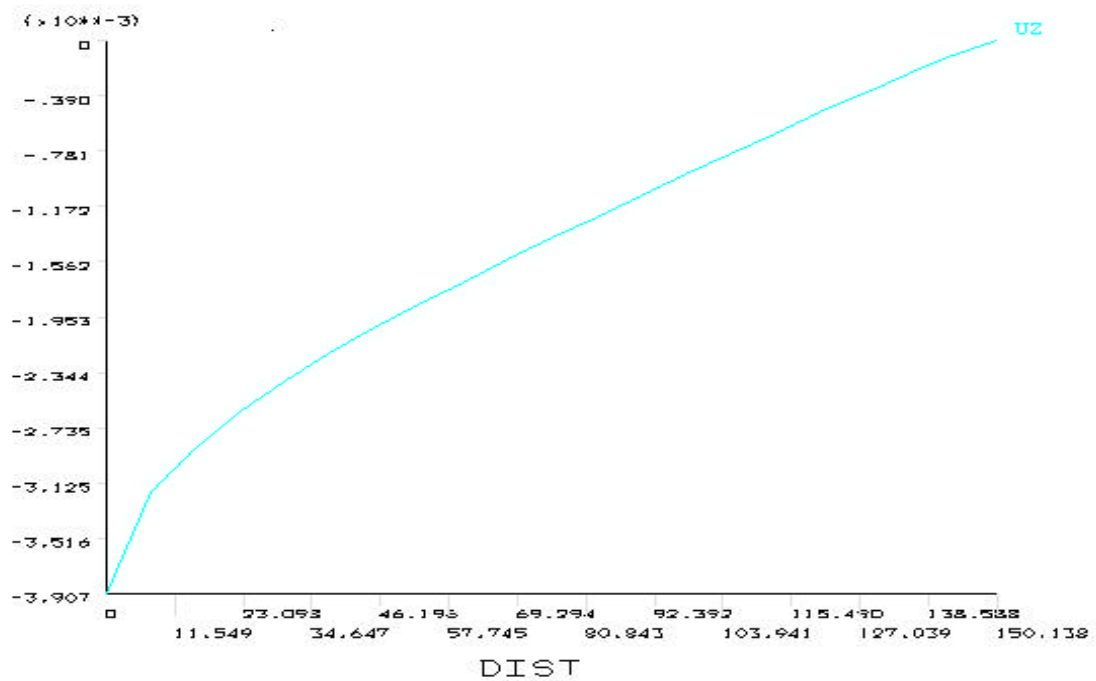


Figure 7 Displacements in the z Direction toward the Centerline of the CTCP slab

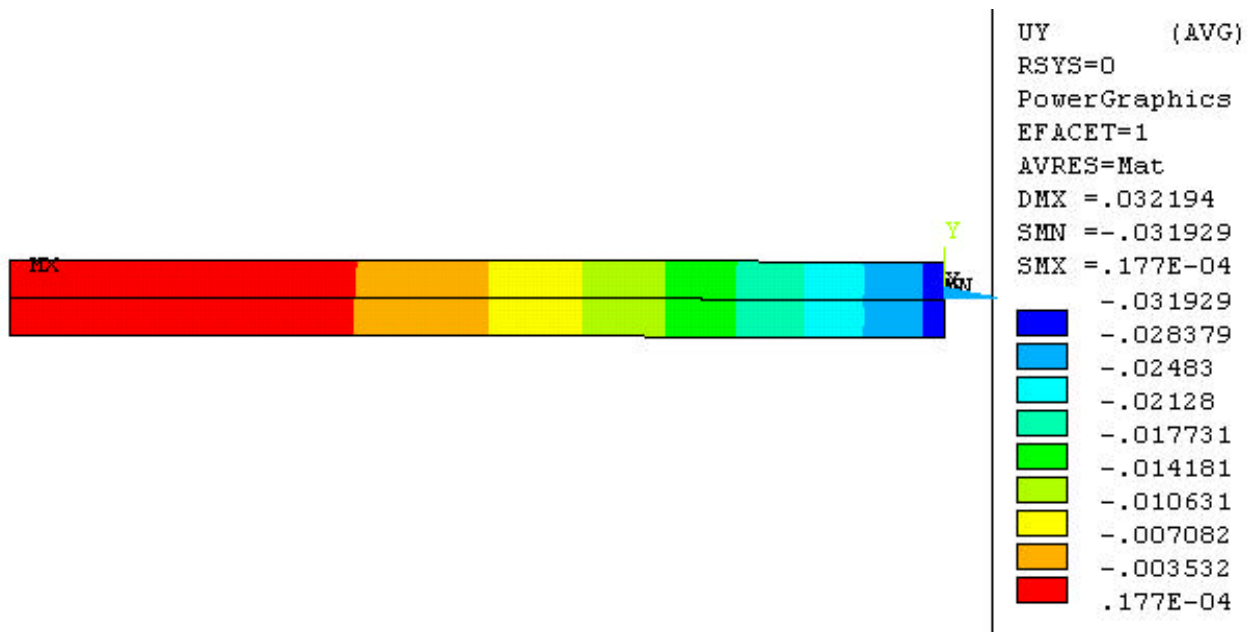


Figure 8 Curling of the CTCP Slab Due to Compressive Load