Paper No: 04-3865

In Situ Criteria of Pull-Off Test for Measuring the Bond Strength of Latex Modified Concrete Overlay

By

Kyong-Ku YUN*
Exchange Professor
Slippery Rock University of PA
227 West Cooper Street, Apt #5
Slippery Rock, PA 16057
Tel: +1-724-738-0244
Fax: +1-724-738-2263
E-Mail: kkyun81@hotmail.com

Sung-Hwan KIM
Doctoral Candidate
Department of Civil Engineering
Kangwon National University
Chunchon-shi, 200-701, S. Korea

Won-Kyong JEONG
Doctoral Candidate
Department of Civil Engineering
Kangwon National University
Chunchon-shi, 200-701, S. Korea

Kwang W. KIM
Professor
Department of Regional Infrastructure Engineering
Kangwon National University
Chunchon-shi, 200-701, S. Korea
Tel: +82-33-250-6467
Fax: +82-33-255-6241
E-Mail: kwkim6467@hotmail.com

SUBMITTED FOR PRESENTATION AND POSSIBLE PUBLICATION AT

THE 83rd ANNUAL MEETING
TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.

January 2004

* Corresponding Author

(6,797 words including text, abstract, tables and figures)

ABSTRACT

The purpose of this study was to evaluate the factors influencing a pull-off test on latex-modified concrete overlay by finite element (FE) analysis and experimental verification, and to provide a guideline for measuring the bond strength in field for field engineers and project managers. The purpose of FE analysis was to predict stresses at the interface between substrate and overlay and between disk and overlay. Good agreement has been obtained between the theoretical and experimental results to confirm the following:

The steel disc thickness did not affect to the stress concentration factor (SCF) at the concrete interface, but significantly influenced that of the steel disc. To prevent failure at the steel disc interface the normalized steel disc thickness (thickness/diameter) should be at least 0.3. The effect of overlay thickness was significant to the stress distribution at the concrete interface. The normalized overlay thickness (h_o/D) should be larger than 0.4. The SCF's at all diameters decreased rapidly as the substrate coring depth (h_c) increased from 0.05 to 0.2 of h_c/D. Those with 75mm diameter (D75) and 100mm diameter (D100) became stabilized immediately after reaching 0.2 hc/D.

The stress distributions at concrete interface were not affected by the distance of the core from the edge of the slab(l_e), the distance between cores (l_c), and the typical elastic modulus ratio of latex-modified concrete (LMC) to conventional concrete (OPC).

The experimental results with the major influencing factors (steel disc thickness, core diameter and partial cutting depth) showed good agreement with the finite element analysis results. For theoretical as well as for practical purposes, 100mm (4in) core diameter is optimum; cutting depth should be between 25mm (1in) and 40mm (1.7in).

KEYWORDS: pull-off test, LMC overlay, bond strength, FE analysis, experimental verification

INTRODUCTION

Latex-modified concrete (LMC) is a Portland cement concrete in which an admixture of latex is used to replace a portion of the mixing water. LMC offers the advantages of higher bond and tensile strength, reduced water permeability and improved durability (1). Since the inception of latex-modified Portland cement for bridge deck overlay in 1959, thousands of projects have been completed using styrene-butadiene latex in concrete for overlays in the United States (2). The importance of achieving a good bond between a repair material and its concrete substrate cannot be overemphasized, and many methods of measuring this have been proposed. One test method, developed by Kuhlmann (3), has been adopted by American Society for Testing and Materials (ASTM) in ASTM C 1404-98. This method can accurately measure the strength of the bond of latex-modified mortar or concrete to substrate concrete using steel pipe nipples, but is only suitable for the laboratory.

The pull-off test method, which can be used in the field, can measure the bond strength, in-situ, between a repair overlay and the substrate. The pull-off test involves applying a direct tensile load to a partial-depth core (entirely through the overlay and into the substrate concrete). The test is used for a variety of purposes, from monitoring strength development and quality control of newly cast concrete, to the condition assessment of older concretes.

Although tensile pull-off tests are becoming increasingly popular for both quality control and repairs, little standardization has been made. ASTM has yet not adopted a test method for in-situ pull-off testing. Thus, there is definite need for standardization of the pull-off test as well as analyzing the influencing factors of the pull-off test.

This study was performed by finite element analysis and experimental verification of factors influencing the pull-off test on latex-modified concrete. Guidelines are provided for measuring the bond strength of latex modified concrete overlay in-situ for field engineers and project managers.

FINITE ELEMENT ANALYSIS

Modeling and Analysis

Finite element analysis in this study was based on the idealized assumption of linear elastic in a 3 dimension solid (3D) model. Figure 1 shows the schematic of the pull-off test in a 3D FE model, and Figure 2 describes a typical finite element mesh at symmetric section with the notations of input variables. The stress distributions within the model were predicted by LUSAS (4) finite element commercial program on an IBM-compatible personal computer, after trial analysis in 2D. The element used was hexahederal and triangular isoparametric.

The standard modulus of elasticity for conventional concrete and latex-modified concrete were 30,106 MPa (4,370 kpi) and 28,240 MPa (4,100 kpi), respectively, which were based on the results of previous study (5,6). A Poisson ratio of 0.18 was used for both. An elastic modulus of 28,240 MPa and a Poisson ratio of 0.3 were assumed for the steel disc according to the manufacturer's record.

The applied tensile loads were assumed to be uniformly distributed at the top surface of the disc over the region where the loading bolt was connected to the disc. The compressive reaction forces were applied by providing one fourth of the applied load according to the equipment configuration. The applied load in this model was arbitrarily chosen to the expected failure load because of the linear elastic assumption.

The following input variables were chosen on the basis of a preliminary literature review and field experiences (7); normalized steel disc thickness relative to core diameter (T/D), normalized overlay thickness relative to core diameter (h_o/D), normalized cutting depth relative to core diameter (h_c/D), normalized distance from edge of slab relative to core diameter (l_e/D), normalized distance between cores relative to core diameter (l_c/D), and the elastic modulus ratio (E_O/E_L). The core diameters were selected so that they would be at least three times larger than maximum aggregate size. All input variables were expressed in term of normalized ratio relative to core diameter for simplicity. The input variables used in FEA are given in Table 1.

Figure 3 shows an example of stress contour in vertical direction, σ_z, of a composite slab only for better illustration. Study was given to the stress distribution at steel disc interface and concrete interface. These were chosen along the interface section and expressed as shown in Figure 4. Failure is governed by the maximum stress at each section. Thus, for each condition of input variables, SCF, maximum stress divided by normal stress (applied load divided by normal area), was determined.

Analysis Results and Discussions

Effect of Steel Disc Thickness (T/D)

Finite element analysis was performed to investigate the effect of steel disc thickness on the tensile stress distribution in vertical direction at the steel disc interface and concrete interface. The main input variable was normalized steel disc thickness (T/D), ranging from 0.05 to 0.45, for three core diameters (D = 75, 100 and 150mm).

Comparisons were made on stress concentrations between steel disc interface and concrete interface, Figure 5, confirming that steel disc thickness significantly influenced steel disc interface, but not concrete interface. The SCF's of steel disc interface at 0.1 T/D were larger than 10.0 at all core diameters. These SCF's decreased as T/D increased, and became stabilized after 0.3 T/D. The SCF's of concrete interface, however, remained almost constant regardless of T/D. As a result, the steel disc thickness did not affect the stress concentration of concrete interface, but significantly influenced that of steel disc. Thus, for preventing the failure at steel disc interface the normalized steel disc thickness (T/D) should be at least 0.3.

Effect of Overlay Thickness (h_o/D)

Since this analysis is based on the assumption that overlay concrete is perfectly bonded to substrate concrete and that overlay thickness has no significantly influence on the stress distribution at steel disk interface, only the stress concentrations at concrete interface were examined. The input variable of the normalized overlay thickness (h_o/D), ranged from 0.1 to 0.9, for three core diameters.

Figure 6 shows the effect of overlay thickness on stress concentration with h_o/D. SCF's decreased as overlay thickness increased and those became stabilized after 0.4 h_o/D, even though there were some variations at each diameter. The SCF's of D75 at lower h_o/D indicated smaller values than the others because of its smaller constraint at core center. Thus, to have a pull-off test of relatively uniform stress distribution, the normalized overlay thickness ratio relative to core diameter (h_o/D) should be larger than 0.4. In the case of a fixed overlay thickness in the field, the diameter of the core should be selected according to this guideline.

Effect of Cutting Depth (h_c/D)

It is true that there is interest and questions from field engineers and project managers on the proper depth of a partial core. How deep should the core be for a given overlay system for a given pull-off tester? In this study, the input variable of the normalized cutting depth relative to core diameter (hc/D) varied from 0.05 to 0.8 for three core diameters.

The stress distributions were affected by cutting depth, as illustrated in Figure 7. The SCF's at all diameters decreased rapidly as the cutting depth increased from 0.05 to 0.2 of hc/D. Those of D75 and D100 became stabilized immediately after reaching a minimum at 0.2 of hc/D, while that of D150 increased significantly and then stabilized after 0.6 hc/D. Thus, for practical and theoretical reasons, 75 mm or 100 mm core diameters are preferred. And they should be cut at least deeper than 0.3 hc/D (0.5 hc/D for larger diameter).

Effect of Edge Distance (l_e/D)

Another question by field engineers is how close to the slab edge can a core be cut. The input variable for normalized edge distance (l_e/D) was chosen from 1 to 5. The analysis result is shown in Figure 8. The stress distributions at concrete interface were not affected by the edge distance as long as it was at least one core diameter.

Effect of Core Distance (l_c/D)

The input variable of the normalized distance between cores (l_c/D) ranged from 1 to 5. The core distance did not affect the stress distribution at concrete interface, Figure 9, as long as it was at least one core diameter.

Effect of Elastic Modulus Ratio (E_L/E_O)

The input variable of elastic modulus ratio (E_L/E_O) between overlay concrete (LMC) and substrate concrete (OPC) ranged from 0.2 to 2.0. The analysis is shown in Figure 10. The SCF was 1.2, the largest within this study for this input variable, at 0.2 E_L/E_O, and decreased as elastic modulus ratio increased. This became stabilized after E_L/E_O of 1.0. Considering that the typical elastic modulus ratio of LMC to OPC is 0.95 (8), it would not affect the stress distribution at concrete interface.

EXPERIMENTAL VERIFICATIONS

This experimental program was planned to verify the FE analysis results with the major influencing factors such as steel disc thickness, core diameter and partial cutting depth. The other factors were excluded because of their negligible effects on the stress distribution on concrete interface or steel disc interface. The experimental variable of steel disc thickness included three levels: 18mm (0.7in), 25mm (1in) and 36mm (1.4in). The core diameter included four levels: 50mm (2in), 75mm (3in), 100mm (4in) and 150mm (6in). The core cutting depth included four levels: 0mm, 10mm, 20mm and 30 mm.

Concrete Mixtures

The concrete used for the base layer of the composite slabs had a water-cement ratio of 0.49 and a maximum aggregate size of 25mm (1in), which produced high strength concrete of 39,200kPa (5,700psi). The latex-modified overlay concrete with rapid-setting cement had a 0.38 water-cement ratio, 0.15 latex solids/cement, 58% fine aggregate, 13mm maximum aggregate size, and 390 kg/m^3 (658 lb/yd^3) of cement.

Three cylinders, 100x200mm (4x8in), to determine compressive strength and three beams, 100x100x450mm (4x4x18in), to determine flexural strength, were also cast from each mix. The measured compressive strength and flexural strength at 28 days of base concrete were 44,100 kPa (6,400psi) and 6,860 kPa (995psi), respectively. The corresponding values of the overlay concrete were 50,080kPa (7,268psi) and 8,283 kPa (1,195 psi), respectively.

Concrete Slabs

Six slabs of 1,100x1,100x200 mm (3.6ftx3.6ftx7.5in) with OPC were cast for the pull-off test; the height of the slabs was determined considering real bridge deck slab. After casting, all slabs were cured in moisture for 7 days with wet burlap, followed by air curing in the laboratory of 20°C and 50% RH for an additional 21 days. All base slabs were ground with a steel brush grinder and rubbed with abrasive papers to remove concrete laitance and extraneous material that could inhibit bond. Loose particles and dust were thoroughly removed from all slab surfaces using high pressure air. All of the slabs were wetted and kept moist for 24hours before casting the overlay. After the overlay casting the slabs were moist cured for 48 hours using wet burlap, followed by air curing until pull-off testing. The overlay of latex-modified concrete was 50mm (2in) thick, similar to LMC overlays in the field (5, 8).

Pull-Off Test

Cores with 3 diameters were drilled from top surface to the designated four depths. To minimize damage from coring, cores were cut by fixing the equipment with anchor bolts. Steel plates were glued to the top surface of the core and a pure axial tensile load was applied at a constant rate.

Experimental Results and Discussions

The failure mode could be grouped into 4 types (steel disk interface, overlay material, concrete interface, and base concrete material). This study, however, only used 3 types (steel disk interface and near, concrete interface, and base concrete material) because failure never occurred solely in the latex-modified overlay (due to its high tensile strength). Rather, overlay failure was always mixed with steel disk interface failure. Thus, the three failure modes for this study were:

Failure Mode I: steel disc interface or mixed with overlay concrete near at disc
Failure Mode II: substrate concrete
Failure Mode III: concrete interface

Experimental Effect of Steel Disc Thickness

Figure 11 shows the experimental effects of steel disc thickness on failure mode and on failure strength. The failure mode at the T/D range between 0.1 and 0.2 was mostly governed by mode I and slightly by mode II, which failed to measure the adhesive strength at concrete interface. As the range of T/D increased between 0.2 and 0.3 the portion of failure mode I decreased while the portion of mode II increased, which was favorable. This was due to the decrease in stress concentration at steel disc interface as the steel disc thickness increased, Figure 9(b). This figure indicates lower failure strength due to higher SCF at lower T/D and vice versa at higher T/D.

These results have good agreement with the FEA results, which indicated the SCF's of steel disc interface with T/D of 0.1 were larger than 10.0 at all core diameters and decreased as T/D increased, followed by stabilizing after 0.3 T/D. The SCF's of concrete interface were, however, almost constant regardless of T/D.

Experimental Effect of Core Diameter

The experimental effects of core diameter on failure mode and failure strength at each core diameter (D = 50, 75, 100 and 150mm) are shown at Figure 12. The failures at D50 and D75 were totally governed by mode II, while the failures at D100 and D150 were mostly governed by mode III. These trends are well described in Figure 10(b), which shows higher strength from base concrete and lower strength from concrete interface.

For theoretical purposes, in order to measure the adhesive strength at concrete interface the core diameter should be larger than 100mm (4in). For practical purposes, to reduce the damage from coring the smaller core diameter may be better. Thus, 100mm (4in) of core diameter could be the optimum size based on these theoretical and experimental results.

Experimental Effect of Cutting Depth

Figure 13 shows the experimental effects of cutting depth for core diameters of 100mm (3in) and 100mm (4in). The overall failure strengths were larger at 75mm than at 100mm. This is due to the smaller normalized cutting depth (hc/D) of D100 compared to corresponding experiment at D75 (the smaller cutting depth ratio resulting in higher SCF). The failure strengths became constant as the normalized cutting depth reached 0.25 and became almost equivalent over 0.3 hc/D. The standard deviation decreased as the hc/D increased and became to constant over 0.3 of hc/D. The failure tensile strength increased while the standard deviation decreased as the normalized cutting depth increased within this experiment.

These experimental results well agree with the FEM analysis results, which described the SCF's of D75 and D100 decreasing rapidly as the cutting depth increased from 0.05 to 0.2 hc/D, and became stabilized immediately after reaching a minimum of 0.2 hc/D.

If we accept the result on core diameter of 100 mm from the previous section, the cutting depth should be deeper than 25mm (1in), and not necessarily deeper than 40mm (1.7in).

CONCLUSIONS

The purpose of this study was to evaluate the factors influencing pull-off test on latex-modified concrete overlay by finite element analysis and experimental verification, and to provide a guideline for measuring the bond strength in the field for field engineers and project managers. Good agreement has been obtained between the theoretical and experimental results to confirm the following:

1. The steel disc thickness (T/D) did not affect the stress concentration at concrete interface, but significantly influenced that of steel disc. The SCF's of steel disc interface at 0.1 of T/D were larger than 10.0 at all core diameters. These SCF's decreased as T/D increased, and became stabilized after 0.3 T/D. Thus, to prevent failure at steel disc interface the normalized steel disc thickness (T/D) should be at least 0.3.
2. The effect of overlay thickness was significant to the stress distribution at concrete interface. Stress concentration factors decreased as overlay thickness increased and became stabilized after h_o/D of 0.4. Thus, to have a pull-off test with relatively uniform stress distribution, the normalized overlay thickness ratio relative to core diameter (h_o/D) should be larger than 0.4. In the case of a fixed overlay thickness in a field, the diameter of the core should be selected according to this guideline.
3. The SCF's at all core diameters decreased rapidly as the cutting depth increased from 0.05 to 0.2 hc/D. Those of D75 and D100 became stabilized immediately after reaching a minimum hc/D of 0.2, while that of D150 increased significantly and was stabilized only after 0.6 hc/D. Thus, for the field, 75 mm or 100 mm core diameters are recommended. They should be cut deeper than 0.3 hc/D at least; 0.5 hc/D is preferred for larger diameter.
4. The stress distributions at concrete interface were not affected by the edge distance as long as it was at least one core diameter. The core distance, also, did not affect stress distribution at concrete interface, as long as it was one core diameter. Considering that the typical elastic modulus ratio of LMC over OPC is 0.95 (6), it did not affect the stress distribution at concrete interface.
5. The experimental results with the major influencing factors (steel disc thickness, core diameter and partial cutting depth) showed good agreement with the finite element analysis results.
6. For theoretical and practical purposes, 100mm (4in) core diameter would be the optimum size; cutting depth should be between 25mm (1in), and 40mm (1.7in).

ACKNOWLEDGEMENTS

Thanks are due to Louis A. Kuhlmann for his valuable advice and kind review of this paper.

REFERENCES

1. Ramakrishnan, V., *Latex Modified Concrete and Mortars*, NCHRP Synthesis 179, Transportation Research Board, National Research Council, Washington, D. C. 1992.
2. Sprinkel, M. M. *Twenty Year Performance of Latex Modified Concrete Overlays*, Transportation Research Record 1335, TRB, National Research Council, Washington, D.C., 1980, pp. 27-35.
3. Kuhlmann, L. A. (1990),Test method for Measuring the Bond Strength of Latex Modified Concrete and Mortar, *ACI Materials Journal*, Vol.87, NO.4
4. FEA. Ltd, *LUSAS Manual*, 2002
5. ACI Committee 503, Guide for the Selection and use of Structural Adhesives with Concrete, *ACI Materials Journal*, Vol.89, Issue 1, 1992.
6. Yun, K.K., Hong, C.W., Lee, J.H. and Choi, S.L., "Strength Development and Permeability of Latex-Modified Concrete with Rapid-Setting Cement (in Korean)," Journal of Korea Concrete Institute, Vol.14, No.3, June, 2002, pp299-306.
7. Yun, K.K., Lee, J.H., Choi, S.L. and Kim, K.H., " Bond Strength Properties of Latex Modified Concrete (in Korean)", Journal of Korea Concrete Institute, Vol.13, No.5, October, 2001, pp507-517.
8. Dow Chemical, *A Handbook on Portland Cement concrete & Mortar Containing Styrene/Butadiene Latex, Dow Chemical Company Handbook*, Midland, MI, December, 1994.

LIST OF FIGURES

TABLE 1 Input Variables used for FE Analysis

Variables	Applied values
T/D (disc thickness/ disc diameter)	0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45
h_o/D (overlay thickness/ disc diameter)	0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90
h_c/D (cutting depth/ disc diameter)	0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45
l_e/D (edge distance/ disc diameter)	1.0, 2.0, 3.0, 4.0, 5.0
l_c/D (core distance/ disc diameter)	1.0, 2.0, 3.0, 4.0, 5.0
E_l/E_o (E.M. of LMC/ E.M. of OPC)	0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0

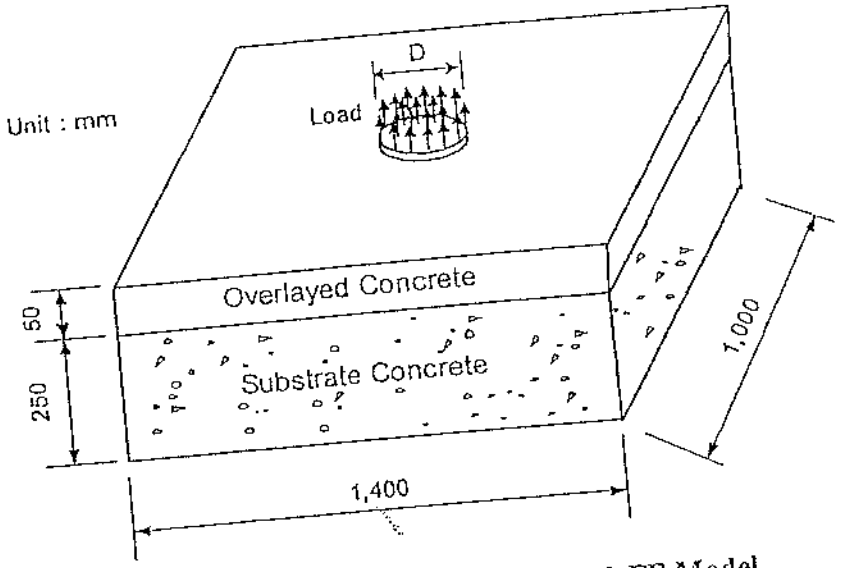


FIGURE 1 Schematic of Pull-off Test in 3D FE Model.

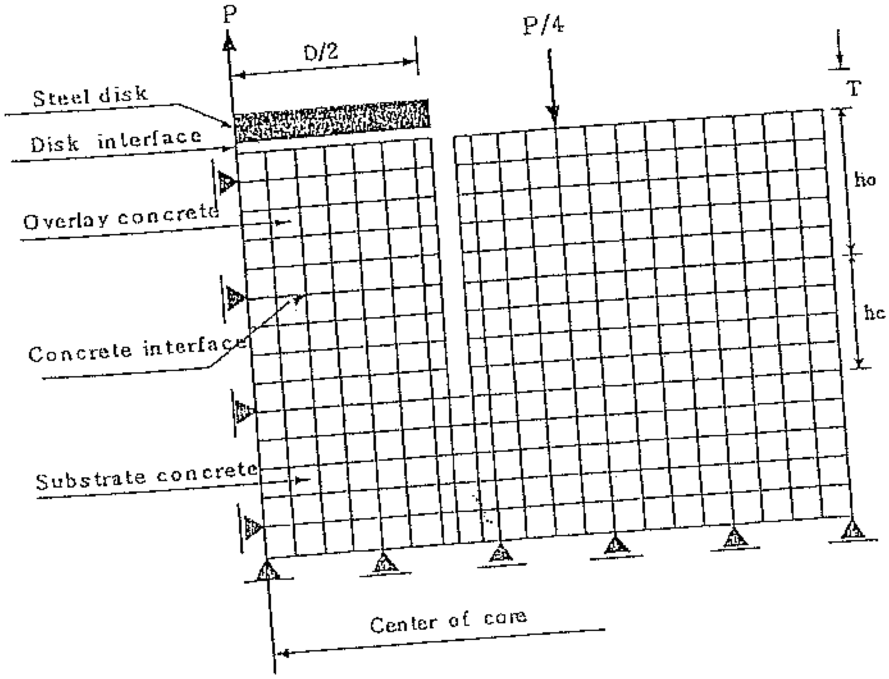


FIGURE 2 Symmetric Section and Notation of Pull-off Test for FEA.

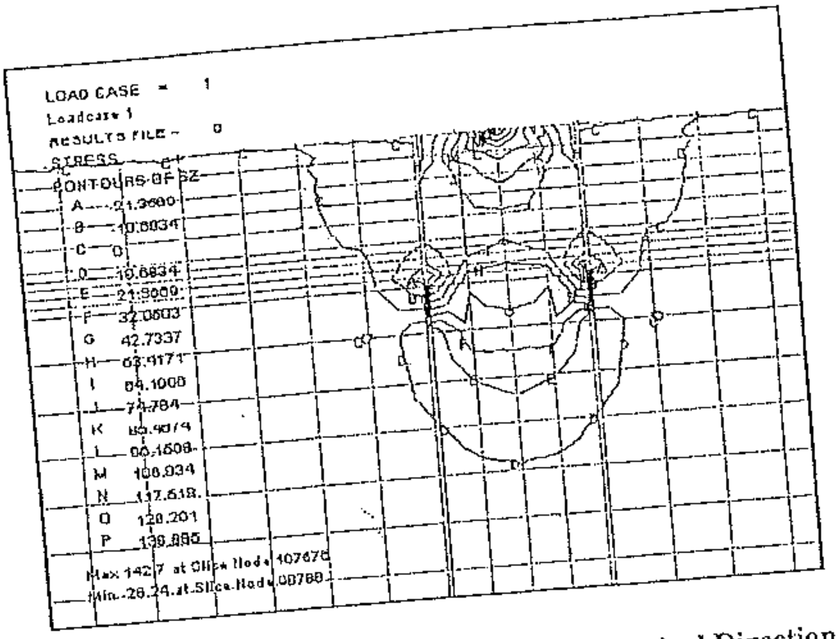


FIGURE 3 Example of Stress Contours in Vertical Direction.

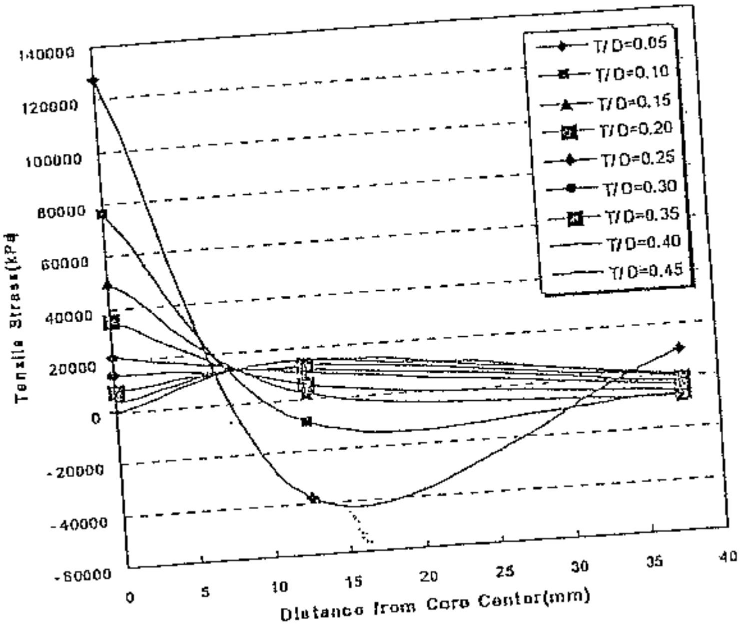


FIGURE 4 Tensile Stress Distribution at Interface Section with T/D.

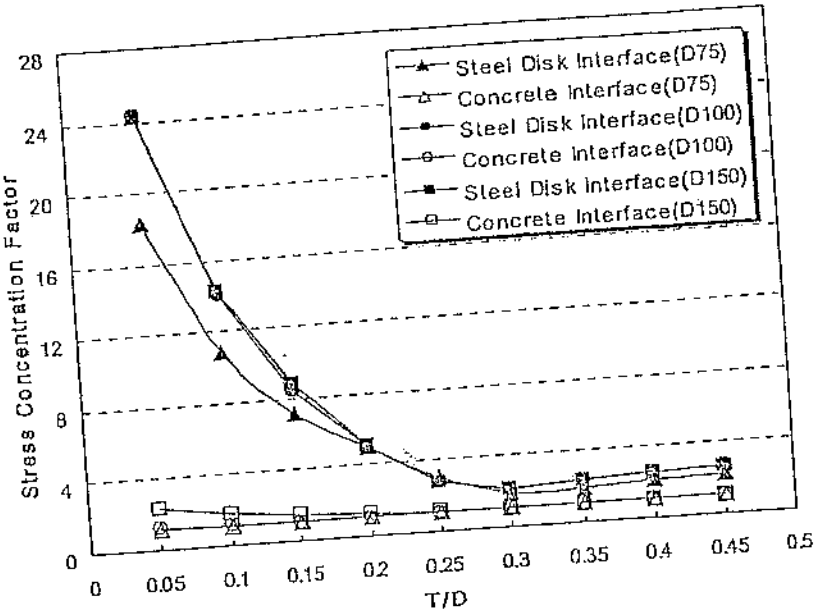


FIGURE 5 Effect of Steel Disk Thickness on Stress Concentration.

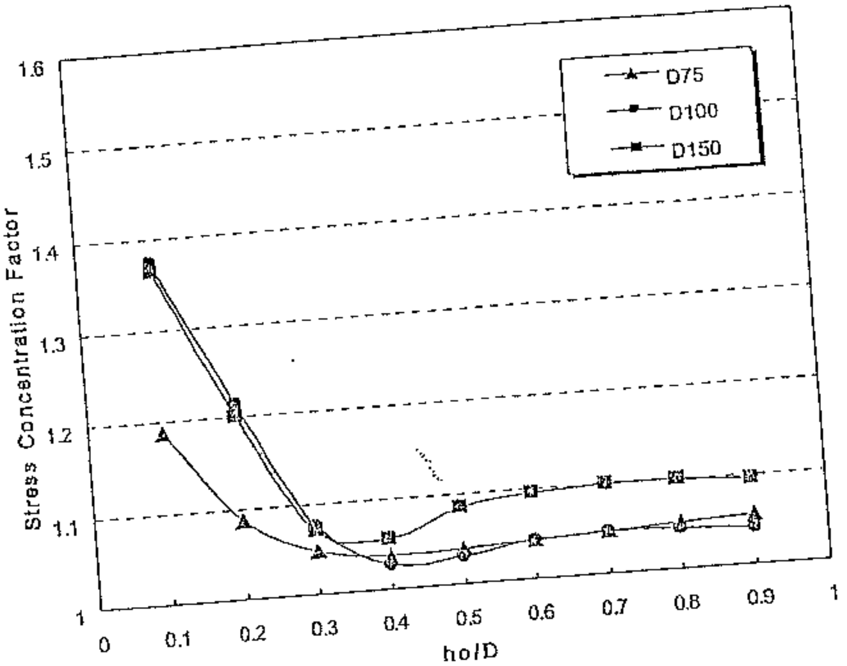


FIGURE 6 Effect of Overlay Thickness on Stress Concentration.

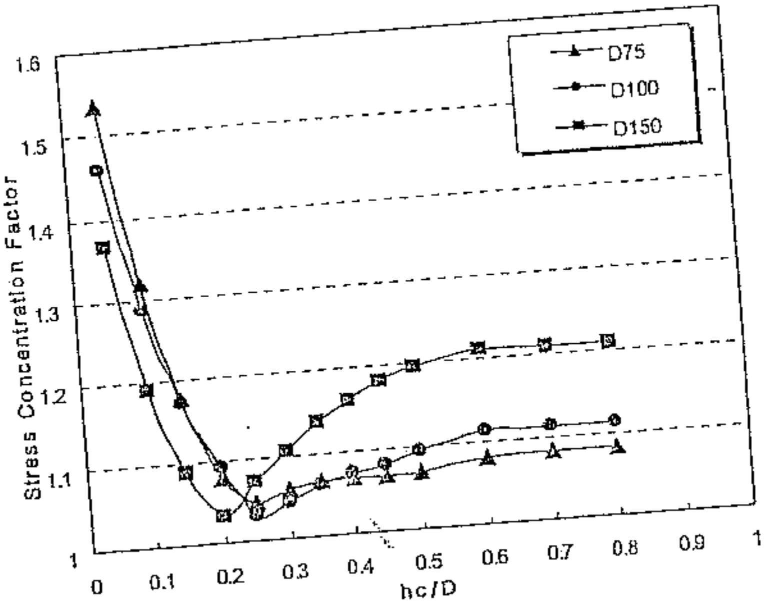


FIGURE 7 Effect of Cutting Depth on Stress Concentration.

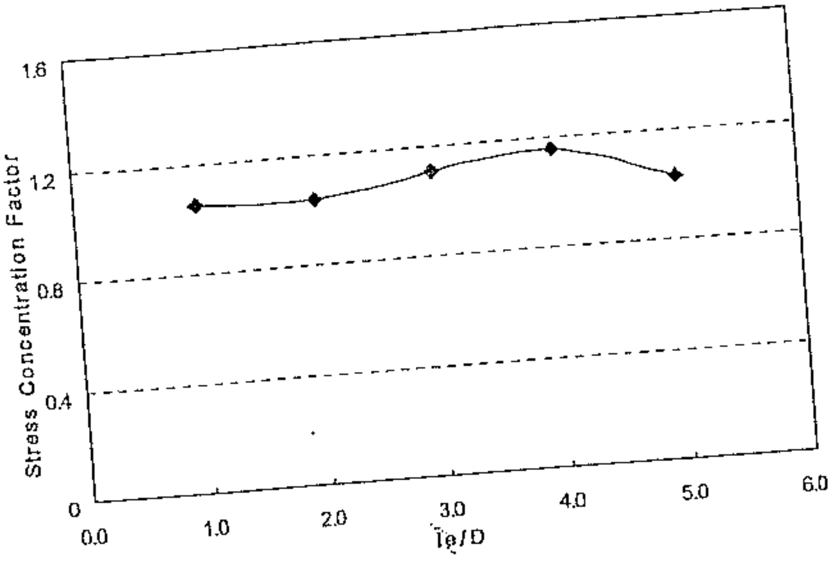


FIGURE 8 Effect of Edge Distance on Stress Concentration.

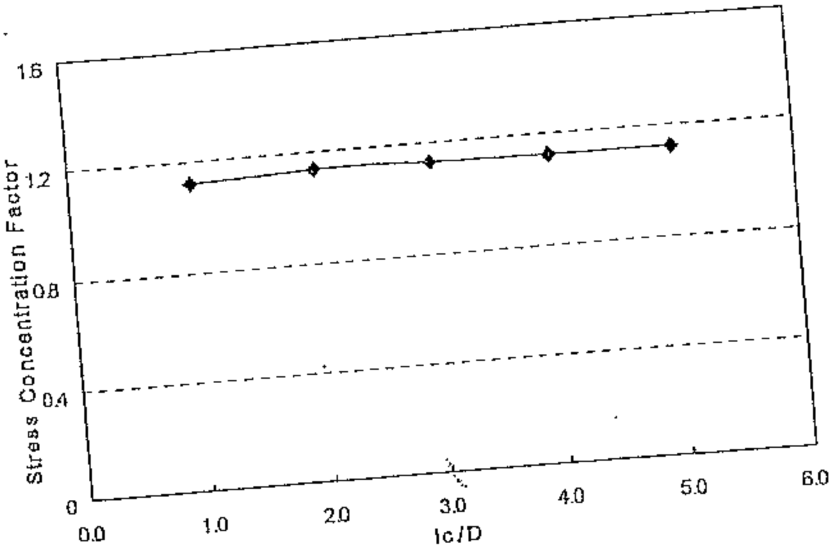


FIGURE 9 Effect of Core Distance on Stress Concentration.

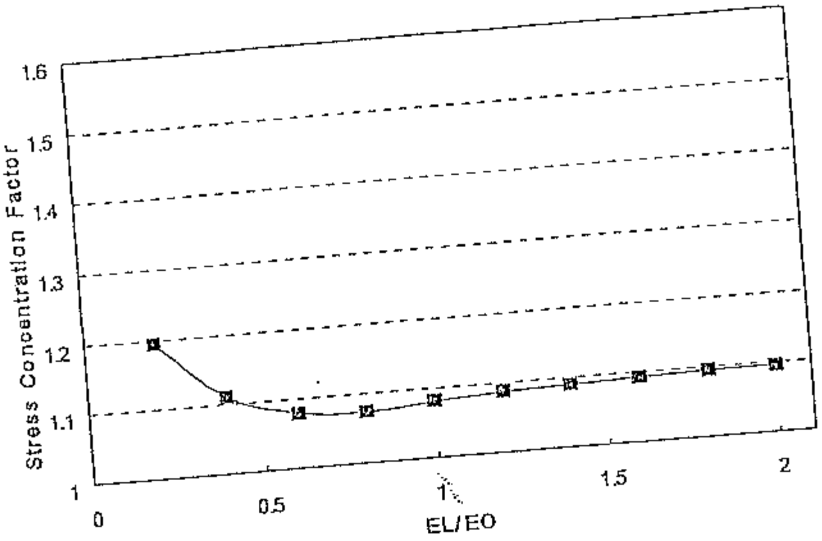
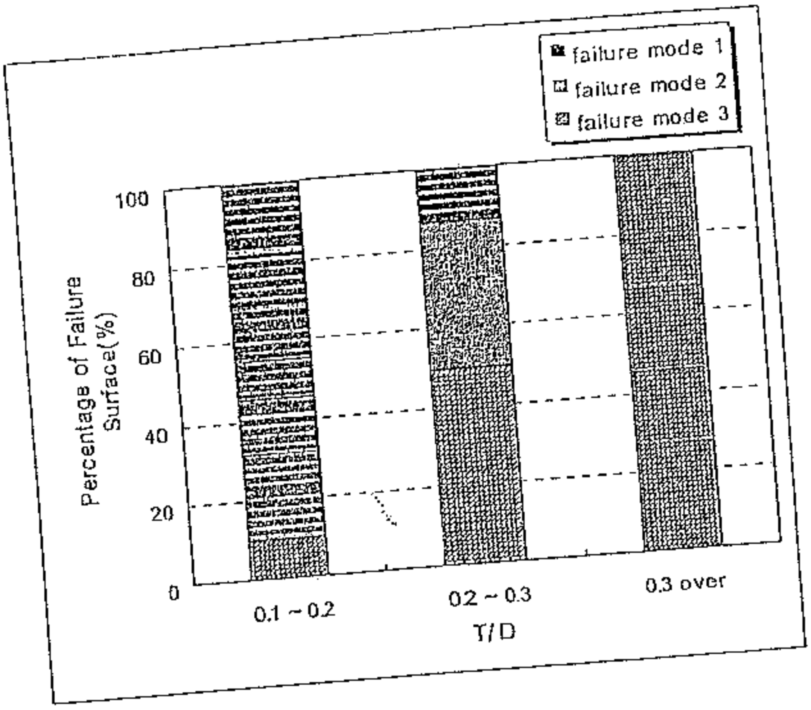
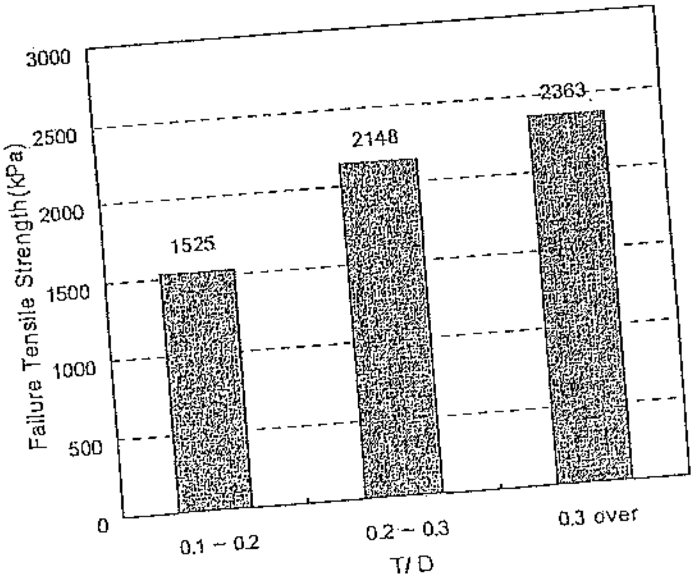


FIGURE 10 Effect of Elastic Modulus Ratio on Stress Concentration.

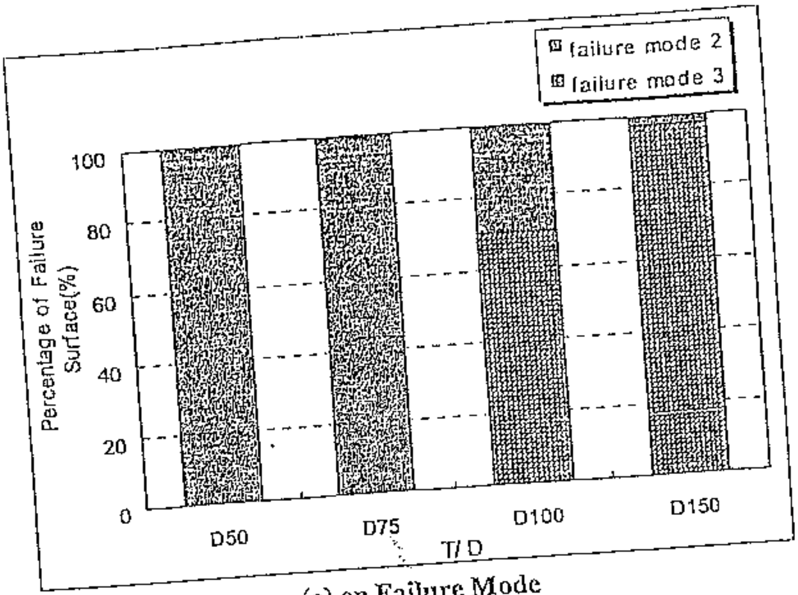


(a) on Failure Mode

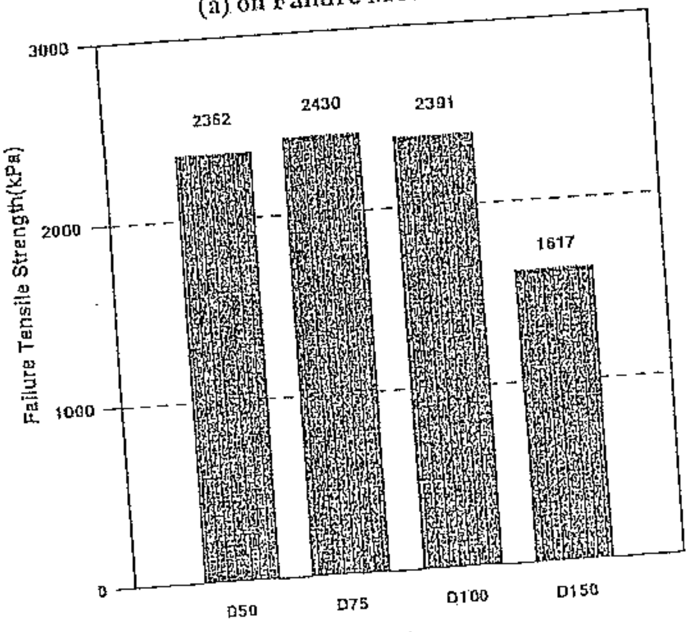


(b) on Failure Tensile Strength

FIGURE 11 Experimental Effect of Steel Disk Thickness.

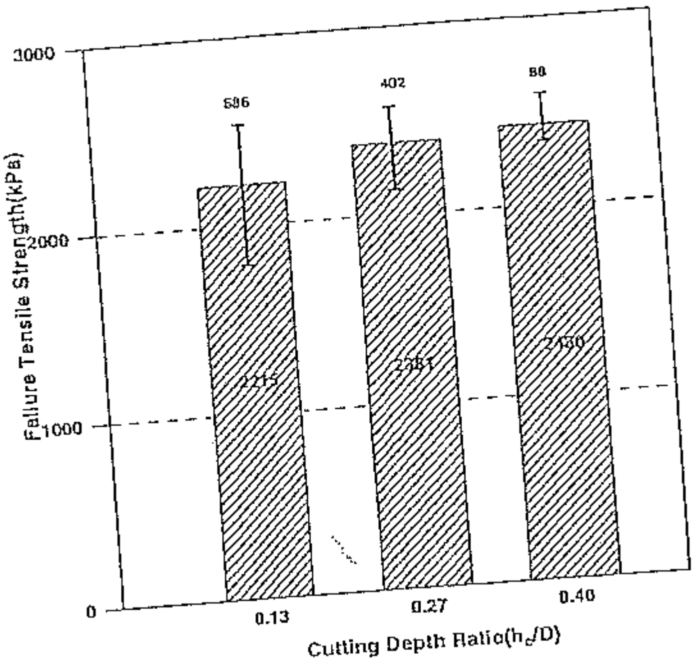


(a) on Failure Mode

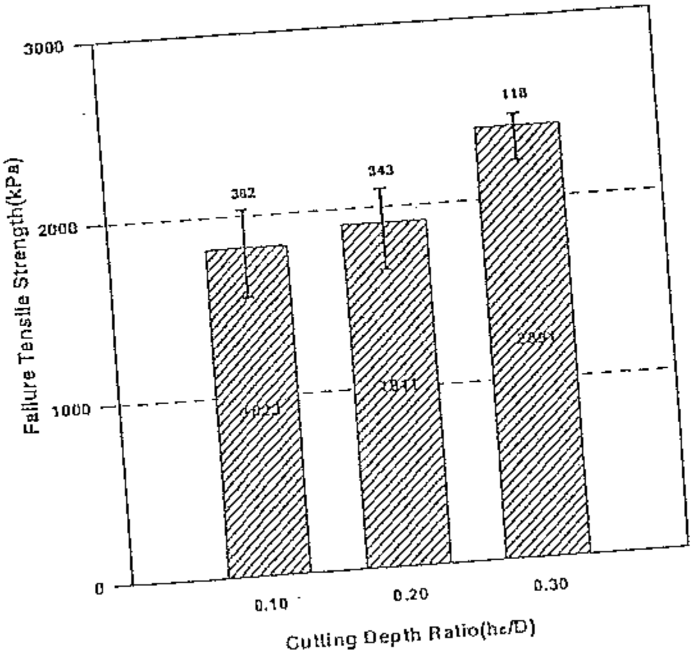


(b) on Failure Tensile Strength

FIGURE 12 Experimental Effect of Cutting Diameter.



(a) D75



(b) D100

FIGURE 13 Experimental Effect of Cutting Depth with Cutting Diameters.