Enhanced End Anchorage of Bonded FRP Repairs

by M.J. Chajes, W.W. Finch, Jr., and H.W. Shenton

Synopsis: When strengthening concrete structures using externally bonded composite material plates, the bond between the concrete and plate typically fails well before the plate's tensile capacity is achieved. To enhance the bond performance, using composite fabric between the plate and the concrete was explored. Six tension development specimens were tested to determine the maximum tensile load that could be applied to a CFRP plate before it debonded. Three specimens had a Sika CarboDur strip bonded directly to the concrete, while three others had the CarboDur strip bonded to two plies of Sikawrap Hex 230C fabric material. The fabric was used to distribute the load over a larger bond area. The specimens without fabric failed at an average load of 60.5 kN while the specimens with the CFRP fabric failed at an average load of 92.6 kN. These failure loads represent 18 % and 27.5% of the plate capacity respectively.

Keywords: adhesives; bonding; composite materials; concrete; development length; force transfer

Michael J. Chajes is Professor and Chair of the Department of Civil and Environmental Engineering Department at the University of Delaware. He is a registered professional engineer and is a member of ACI. His research interests include bridge evaluation and rehabilitation including the use of advanced composite materials.

William W. Finch, Jr. is President of Structural Testing Incorporated, a firm that specializes in both bridge testing and also the evaluation of advanced composite material applications. He is a registered professional engineer and is a member of ACI. He is also the owner of WF Construction.

Harry W. Shenton, III is an Associate Professor in the Department of Civil and Environmental Engineering Department at the University of Delaware. His research interests include structural health monitoring and condition assessment, in-service and long-term monitoring of bridges, sensors and instrumentation for civil infrastructure systems, structural dynamics and earthquake engineering.

INTRODUCTION

As a nation's infrastructure ages, the number of deficient structures continues to grow. Because of the prohibitive cost of replacing all of the sub-standard structures, innovative techniques for rehabilitating deteriorating structures are needed.

Numerous researchers have studied strengthening of existing structures, in particular concrete structures, through the use of externally bonded steel and composite material plates.[1-18] With regard to steel plates, the studies have focused on problems found at the concrete-steel interface including interface corrosion and peel stresses.[2-9] Other studies have shown that bonding prestressed and non-prestressed composite-material plates and fabrics to concrete beams can lead to significant increases in flexural and shear capacity.[10-19] Possibly the single most critical aspect in strengthening a concrete structure through externally bonded plates is the bond between the plate and the concrete. Studies such as that by Chajes et al.[1] have evaluated the bond strength and have shown that a composite plate will typically debond well before it reaches its ultimate tensile capacity. Some more recent studies have looked at ways to improve the bond using FRP wraps placed over the bonded plates.[20] This study will investigate the ability to improve bond behavior by placing composite fabric between the bonded plates and the concrete substrate.

RESEARCH SIGNIFICANCE

To more fully utilize the capacity of externally bonded composite plates, improved anchorage is needed. This paper presents research aimed at improving the bond in the anchorage zone so as to more fully utilize the tensile capacity of the bonded plate.

A simple and relatively effective method for improving end anchorage involving the bonding of a CFRP fabric directly to the concrete surface at the anchorage area, and then bonding the composite plate to the fabric has been studied.

SPECIMEN FABRICATION

A total of nine tension development test specimens were fabricated (six to be used for testing, and three to be used as back up specimens in case any problems in the testing procedure were encountered). Six specimens (three for testing and three back-ups) were fabricated as shown in Figure 1 (specimens nos. 1, 3, 4, 5, 6 & 9), and three specimens (all for testing) were fabricated as shown in Figure 2 (specimens nos. 2, 7 & 8). The specimens shown in Figure 1 had a 102 mm wide CarboDur strip[21] bonded directly to the 254 mm by 305 mm by 610 mm concrete block (610 mm bond length), whereas the specimens shown in Figure 2 had the CarboDur bonded directly to two plies of SikaWrap Hex 230C material[22] arranged at a plus/minus 45 degree layout. The purpose of the plus/minus 45 degree carbon fiber sheet was to distribute the load over a wider concrete bond area. Please note that for the specimens with the fabric, the fabric and plate were bonded at the same time, and the fabric extended beyond the width of the 102 mm plate all the way out to the edges of the 305 mm wide block. As such, the bonded fabric area was much greater than the bonded area of just the plate alone. After fabrication, specimens 1, 3, and 9 were set aside as extra samples, and specimens 2, 4, 5, 6, 7 & 8 were instrumented with strain gages as shown in Figure 3 and subsequently tested. The back-up specimens (1, 3, and 9) were not needed and will not be discussed further.

The concrete blocks were cast using 27.6 MPa concrete with a 2% non-chloride accelerator added. In addition to the concrete development specimens, 6 standard concrete cylinders were cast for compression testing. These concrete development specimens were moist-cured for 1-½ weeks and then the carbon fiber materials were applied (once the specimens had dried out. The cylinders were cured under the same conditions at the specimens and were tested at the same time as the development tests were conducted. Ten compression test cubes, 51 mm x 51 mm x 51 mm, were fabricated from the SikaDur 30 epoxy that was used to bond the CarboDur plate to the test specimens. It should be noted that in addition to the strain gages bonded to the CarboDur, strain gages were bonded to each piece of vertical rebar at the mid-height of the specimen. The application of both types of carbon fiber reinforcing systems was performed per the Sika Corporation's recommended procedures.

The 102 mm wide by 1.2 mm thick CFRP CarboDur plates used (Type 2-101) had a tensile modulus of 165 GPa, a strain to failure of 1.69%, and an ultimate tensile strength of 336 kN. The SikaWrap Hex 230C fabric had a weight per square yard of 1.9 N, and carbon fibers having a tensile strength of 3.45 GPa and a tensile modulus of 230 GPa. These are the manufacturer's values.

TEST PROCEDURE

A universal testing machine was used to load the specimens as shown in the photograph in Figure 4, and the schematic in Figure 5. The specimens were placed into the testing machine using an overhead crane. They were tested under displacement control at a slow rate of loading until well beyond debonding of the CarboDur from the concrete specimen. A set of rollers were used to stabilize the specimen and the set-up appeared to work well and not cause a clamping effect. Strains were recorded during testing on a continuous basis using a PC based data acquisition system. Six specimens were tested, three with no fabric (specimens 4, 5, and 6) and three with fabric (2, 7, and 8).

TEST RESULTS

The six concrete compressive test cylinders and the SikaDur 30 epoxy compressive test cubes were tested on the same dates as the tension development specimens. The average compressive failure stress of the cylinders was 34.0 MPa. Ten compressive cubes of SikaDur 30 were tested and the average compressive failure stress of the cubes was 79.6 MPa.

Load versus microstrain plots for all six test specimens are shown in Figures 6 through 11. The first three plots, Figures 6, 7, and 8, are plots of the specimens that were fabricated with the CarboDur plate bonded directly to the concrete. Figures 9, 10, and 11 are plots of the specimens that were fabricated with the CarboDur plate bonded to the SikaWrap Hex 230C carbon fiber fabric that was in turn bonded to the concrete surface. Failure was defined as the load at which the CarboDur starts to debond from the test specimen. This load is indicated by the vertical dashed line in the figures. The average load at which the CarboDur debonded when bonded directly to the concrete surface was 60.5 kN and the average load at which the CarboDur debonded when bonded to the SikaWrap Hex 230C was 92.6 kN.

The test specimens with the CarboDur bonded directly to the concrete failed in the concrete with a thin layer of concrete bonded to the complete surface of the CarboDur plate. The test specimens with the CarboDur bonded to the SikaWrap carbon fabric failed between the SikaDur 30 adhesive and CarboDur plate through either a debonding of the adhesive to the plate or a surface failure of the CarboDur plate. This explains the higher failure load because the weaker concrete surface bond no longer governs.

The failure loads represented approximately 18% of the ultimate strength of the CarboDur strip being developed when bonded directly to the concrete surface and 27.5% of the CarboDur strip ultimate tensile strength being developed when bonded to the Hex 230C carbon fabric. In the plots one can see that after the bond breaks, the plate was carrying the entire load. Prior to failure, the interior gages on the plate showed a reduced tension because some of the force has transferred into the concrete specimen (now being carried by the rebar).

Figure 12 shows a comparison of the strain distribution along the bonded plates (both with and without fabric) at a load just before failure. One can easily see that the plate with the fabric beneath it (specimen 8) carries significantly more load (i.e. has more strain at all points along the length) than the plate that is bonded directly to the concrete (specimen 6). Figures 13 (specimen 6) and 14 (specimen 8) show plots of the strain distribution along the length of the CarboDur plate at 70%, 90% and 100% of the ultimate load that causes debonding of the CarboDur plate. The zero point on the x-axis is the starting point of the bonded CarboDur plate and 610 mm on the x-axis is the end of the bonded length of the CarboDur plate. These figures illustrate the transfer of the force in the CarboDur plate to the concrete specimen. Figure 13 (the CarboDur bonded directly to the concrete) shows that only approximately 100 to 125 mm of bond length are utilized to transfer the force into the concrete. Figure 14 shows that improved development length was achieved when the CarboDur plate was bonded to the SikaWrap Hex 230C carbon fiber material. The Hex 230C material effectively distributed the load to a wider area of concrete.

CONCLUSIONS

A simple method for improving the bond of CFRP plates to concrete has been presented. The application of CFRP fabric between the plate and the concrete in which the fabric extends beyond the footprint of the plate has shown to improve the force transfer and increase the ultimate bond strength. For the six tension development test specimens tested, the three specimens without the fabric failed at an approximate average failure load of 60.5 kN while the three specimens with the CFRP fabric failed at an average load of 92.6 kN. This represents a 53% increase in ultimate load. Furthermore, the failure load increased from approximately 18 % of the ultimate strength of the CFRP plate to 27.5% of the plate's ultimate strength. The results are based on tests of single lap specimens. Future work involving full-scale beams that simulate realistic field applications, as well as analytical modeling of the bond behavior, would be very useful.

ACKNOWLEDGMENTS

The authors would like to thank the Sika Corporation for helping to support this research. We would like to thank Doug Baker and Michael Davidson for their assistance with test equipment and fixtures.

REFERENCES

1. Chajes, M.J., Finch, W.W., Januszka, T.F., and Thomson, T.A. "Bond and Force Transfer of Composite-Material Plates Adhered to Concrete," *Structural Journal*, ACI, 93(2), 1996, 208-217.

2. Swamy, R.N., Jones, R., and Bloxham, J.W. "Crack Control of Reinforced Concrete Beams Through Epoxy Bonded Steel Plates." *Adhesion Between Polymers and Concrete*, RILEM 86, 1986, pp. 542-555.

3. Jones, R., Swamy, R.N., and Ang, T.H. "Under- and Over-reinforced Concrete Beams With Glued Steel Plates." *The International Journal of Cement Composite and Lightweight Concrete*, 1(1), 1982, pp. 19-32.

4. Johnson, R.P., and Tait, C.J. "The Strength in Combined Bending and Tension of Concrete Beams With Externally Bonded Reinforcing Plates." *Building and Environment*, 16(4), 1981, pp. 287-299.

5. Macdonald, M.D., and Calder, A.J.J. "Bonded Steel Plating for Strengthening Concrete Structures." *International Journal of Adhesion and Adhesives*, (4), April 1982, pp. 119-127.

6. Solomon, S.K., Smith, D.W., and Cusens, A.R. "Flexural Tests of Steel-Concrete-Steel Sandwiches." *Magazine of Concrete Research,* 28(94), March 1976, pp. 12-20.

7. Hamoush, S.A., and Ahmad, S.H. "Debonding of Steel Plate-Strengthened Concrete Beams." *Journal of Structural Engineering*, 116(2), February 1990, pp. 356-371.

8. Oehlers, D.J., and Moran, J.P. "Premature Failure of Externally Plated Reinforced Concrete Beams." *Journal of Structural Engineering*, 116(4), April 1990, pp. 978-995.

9. Jones, R., Swamy, R.N., and Charif, A. "Plate Separation and Anchorage of Reinforced Concrete Beams Strengthened by Epoxy-Bonded Steel Plates." *The Structural Engineer Part A*, 66(12), June 1988, pp. 85-94.

10. Chajes, M.J., Thomson, T.A., Finch, W.W., and Januszka, T.F. "Flexural Strengthening of Concrete Beams Using Externally Bonded Composite Materials," *Construction and Building Materials*, 8(3), 1994, pp. 191-201.

11. Ritchie, P.A, Thomas, D.A., Lu, L.W., and Connelly, G.M. "External Reinforcement of Concrete Beams Using Fiber Reinforced Plastics." *ACI Structural Journal*, 88(4), July-August 1991, pp. 490-500.

12. Saadatmanesh, H., and Ehsani, M.R. "RC Beams Strengthened With GFRP Plates. 1: Experimental Study." *Journal of Structural Engineering*, 117(11), November 1991, pp. 3417-3433.

13. Meier, U., Deuring, M., Meier, H., and Schwegler, G. "Strengthening of Structures With CFRP Laminates: Research and Applications in Switzerland." *Advanced Composite Materials in Bridges and Structures*, CSCE, Sherbrooke, Canada, 1992, pp. 243-251.

14. Karam, G.N. "Optimal Design For Prestressing With FRP Sheets in Structural Members." *Advanced Composite Materials in Bridges and Structures*, CSCE, Sherbrooke, Canada, 1992, pp. 277-285.

15. Triantafillou, T.C., and Plevris, N. "Post-Strengthening of R/C Beams With Epoxy-Bonded Fiber Composite Materials." *Advanced Composites Materials in Civil Engineering Structures*, ASCE, Las Vegas, Nevada, 1991, pp. 245-256.

16. Triantafillou, T.C., and Meier, U. "Innovative Design of FRP Combined With Concrete." *Advanced Composite Materials in Bridges and Structures*, CSCE, Sherbrooke, Canada, 1992, pp. 491-500.

17. Triantafillou, T.C., Deskovic, N., and Deuring, M. "Strengthening of Concrete Structures With Prestressed Fiber Reinforced Plastic Sheets." *ACI Structural Journal*, 89(3), May-June 1992, pp. 235-244.

18. Triantafillou, T.C., and Deskovic, N. "Innovative Prestressing with FRP Sheets: Mechanics of Short-Term Behavior." *Journal of Engineering Mechanics*, 117(7), July 1991, pp. 1652-1672.

19. Chajes, M.J., Januszka, T.F., Mertz, D.R., Thomson, T.A., and Finch, W.W. "Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics," *ACI Structural Journal,* ACI. 92(3), 1995, 295-303.

20. Hamad, B., Soudki, K, Harajli, M., and Rteil, A. "Experimental and Analytical Evaluation of Bond Strength of Reinforcement in Fiber-Reinforced Polymer-

Wrapped High-Strength Concrete Beams." *ACI Structural Journal,* ACI. 101(6), 2004, 747-754.

21. Sika CarboDur, Product Data Sheet, Edition 9.2003, ID No. 332, Sika Corporation, Lyndhurst, NJ, 07071.

22. SikaWrap Hex 230C, Product Data Sheet, Edition 7.2003, ID No. H33230, Sika Corporation, Lyndhurst, NJ, 07071.

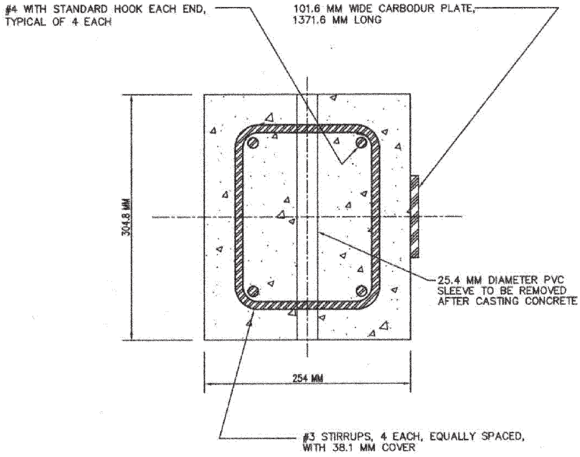

Figure 1 — Typical Section of CarboDur Test Specimen with SikaWrap and No Fabric

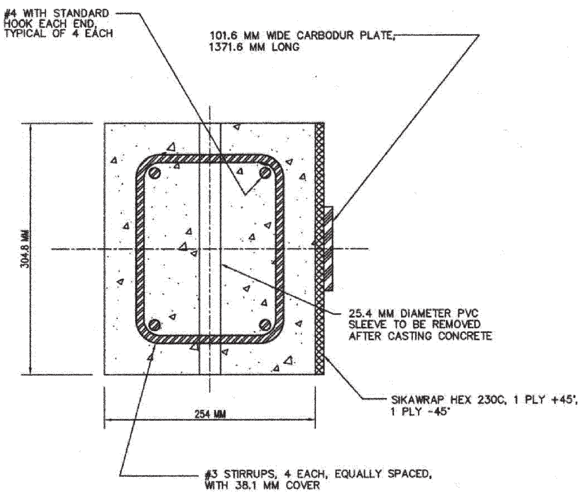

Figure 2 — Typical Section of CarboDur Test Specimen with SikaWrap Fabric

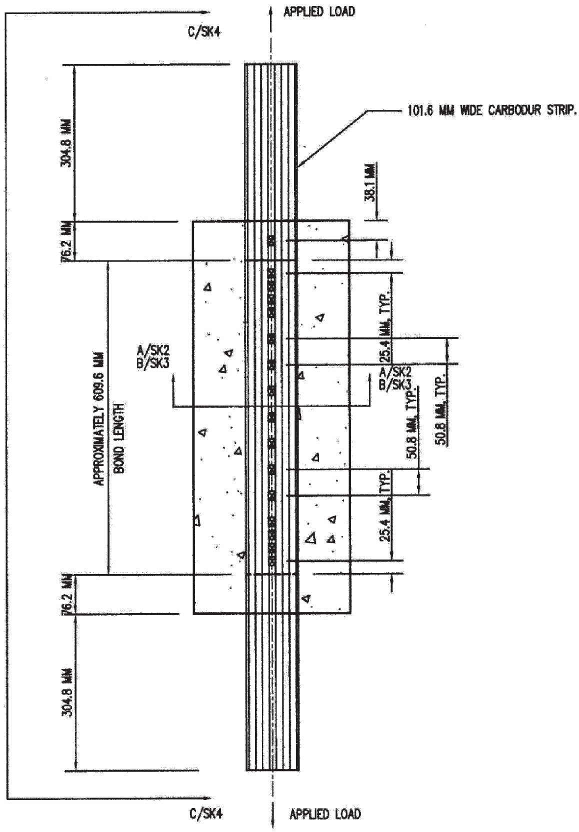

Figure 3 — Elevation View of Instrumented of Test Specimen

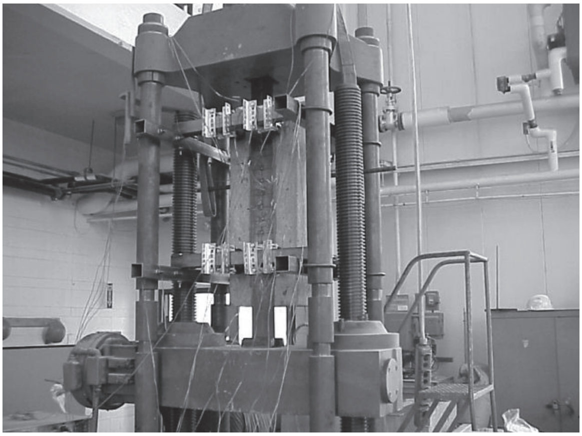

Figure 4 — Photograph of Specimen During Testing

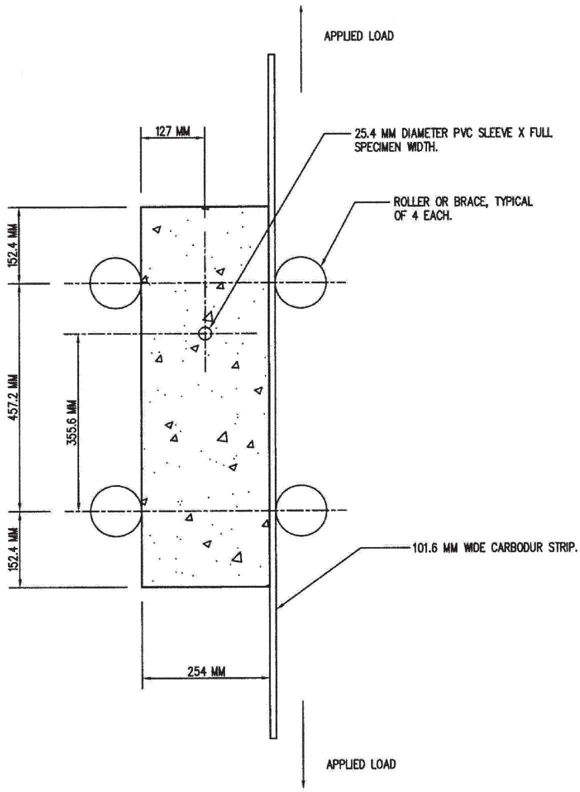

Figure 5 — Schematic of Specimen in Braced Test Fixture

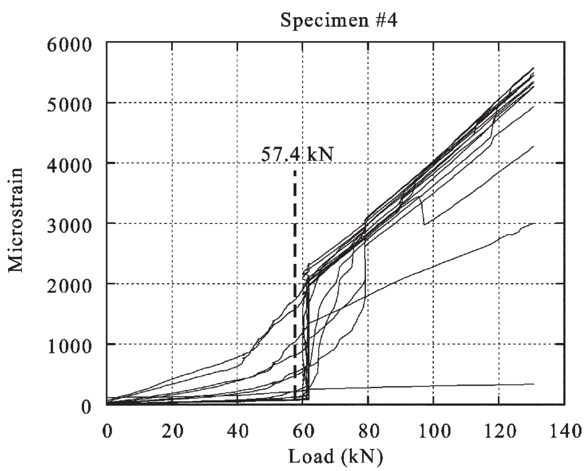

Figure 6 — Load versus Strain Plot for Specimen 4 (No Fabric)

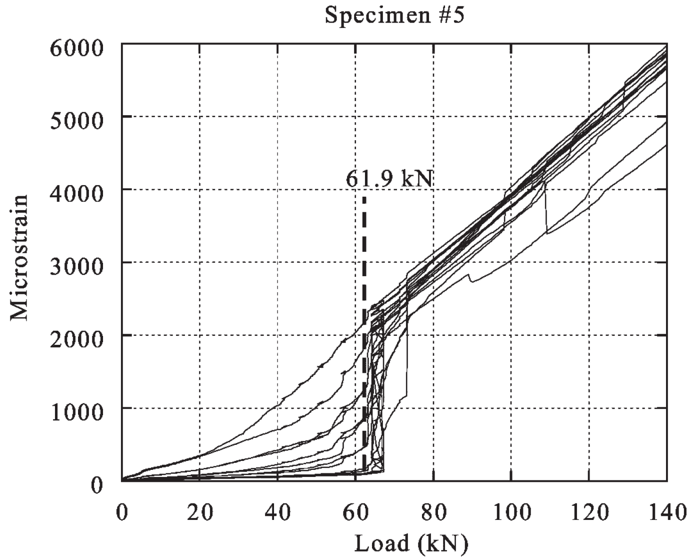

Figure 7 — Load versus Strain Plot for Specimen 5 (No Fabric)

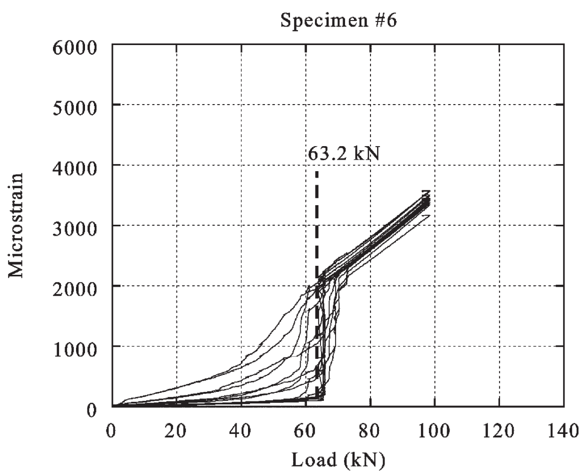

Figure 8 — Load versus Strain Plot for Specimen 6 (No Fabric)

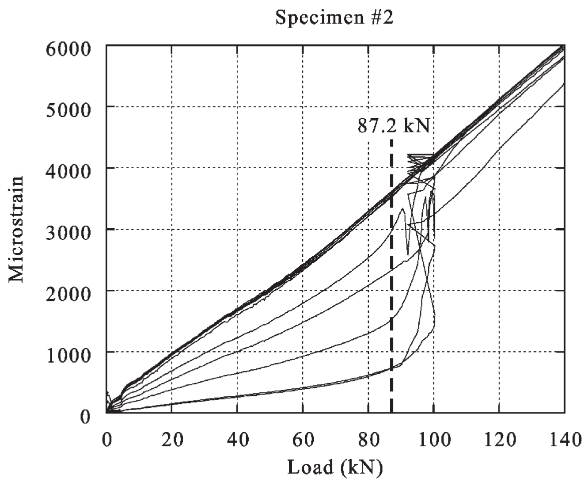

Figure 9 — Load versus Strain Plot for Specimen 2 (With Fabric)

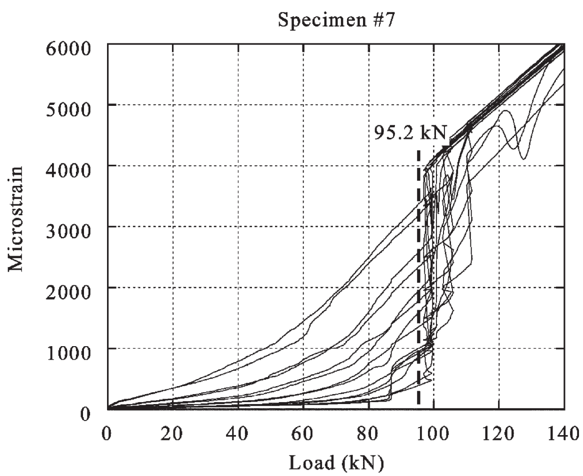

Figure 10 — Load versus Strain Plot for Specimen 7 (With Fabric)

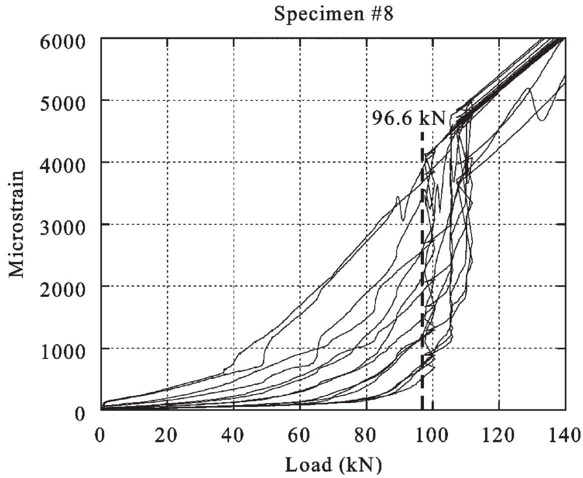

Figure 11 — Load versus Strain Plot for Specimen 8 (With Fabric)

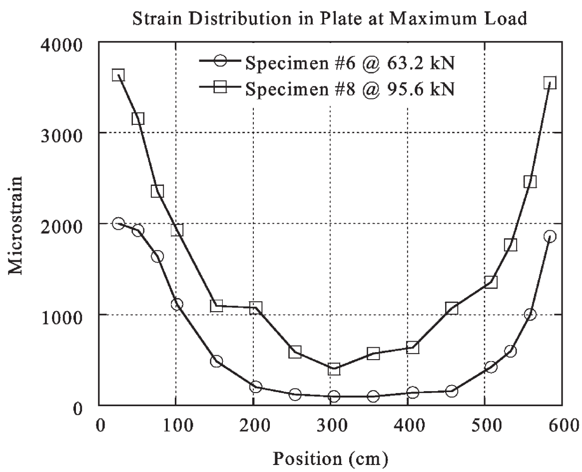

Figure 12 — Comparison of Strain Distribution at Ultimate Load

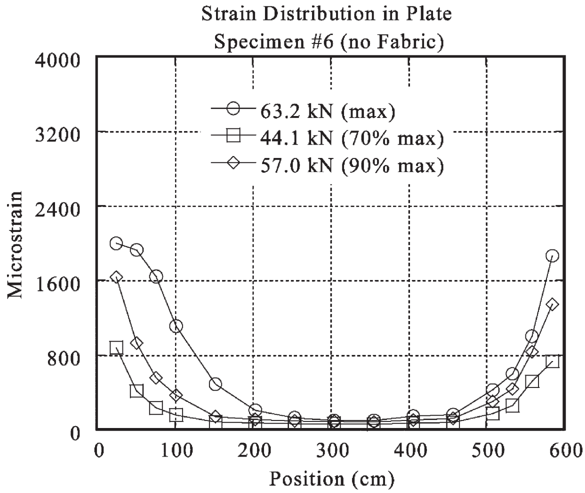

Figure 13 — Strain Distribution for No Fabric Specimen at 70, 90, and 100 % of Load

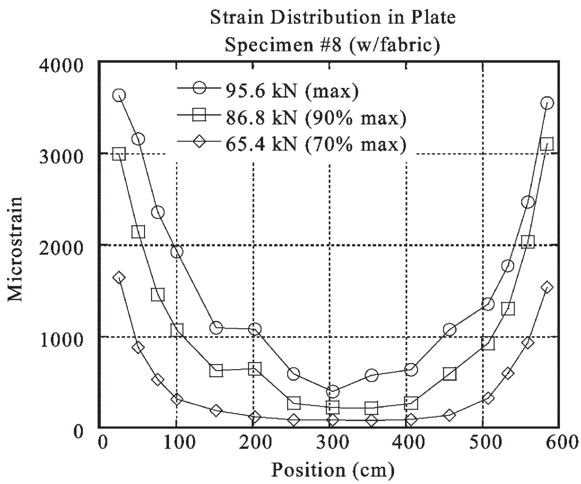

Figure 14 — Strain Distribution for Fabric Specimen at 70, 90, and 100 % of Load