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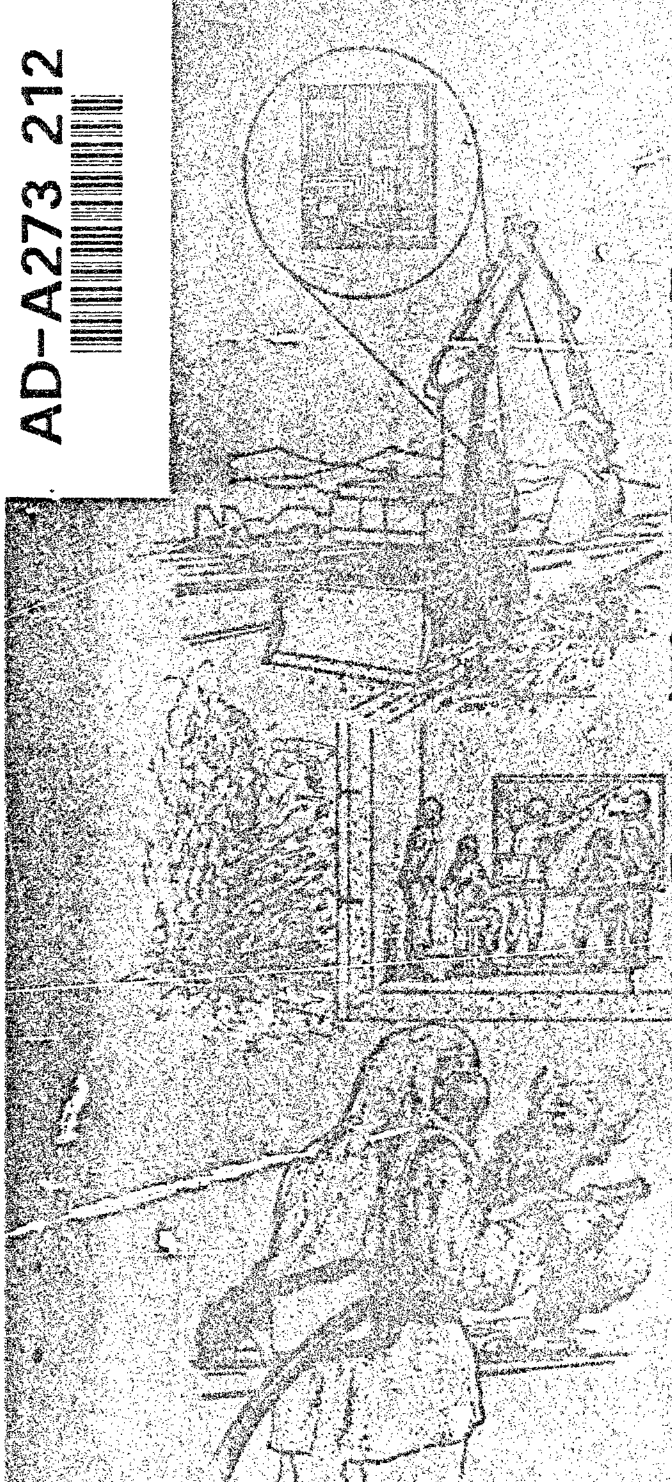

FIBER-REINFORCED CONCRETE FOR HARDENED SHELTER CONSTRUCTION

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FINAL REPORT

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ENGINEERING RESEARCH DIVISION
Air Force Civil Engineering Support Agency
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A test program was conducted to develop a fiber- and rebar-reinforced beam design(s) using lightweight, high-strength concrete. The goal of the testing program was to develop a beam design(s) that provides superior performance at a reduced cost and weight versus the symmetrically rebar reinforced beam design using normal-weight, standard-strength concrete currently used by the U.S. Air Force in hardened structure construction. Beams of various designs, including a baseline symmetrically reinforced beam designed using current hardened structure criteria, were fabricated and tested on a load-frame under deflection control and flexural third-point loading to generate load-deflection curves. From these curves, the ductility, energy absorption characteristics, and overall material toughness of each beam design were determined.

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EXECUTIVE SUMMARY

A. OBJECTIVE

This technical report documents a preliminary research and testing effort undertaken by the Air Force Civil Engineering Support Agency (AFCESA), Engineering Research Division's Airbase Survivability Branch (RACS) to develop a fiber-reinforced concrete beam design(s) that can be used in the construction of hardened structures to increase their survivability, while possibly reducing their cost and weight. Emphasis is placed on modular construction using prefabricated fiber- and rebar-reinforced concrete structural members to allow fiber content, concrete strength, and quality to be controlled, while minimizing construction time and cost. Consequently, field constructability and quality control issues were not considered critical when developing beam designs.

The objective of this technical effort was twofold. First, a literature review was conducted to determine the current state of fiber-reinforced concrete Research and Development (R&D). Emphasis was placed on the current state of R&D on fiber-reinforced concrete structural applications, material compositions, structural/engineering properties, fabrication/mixing, and design methods. Second, a testing program was conducted to develop and evaluate various fiber-reinforced beam designs, with and without standard rebar reinforcement, under static flexural third-point loading. Based on results from the testing program, the best beam candidates for use in hardened structure construction were identified for future research efforts.

B. BACKGROUND

Typically, hardened airbase structures house mission-critical assets, such as command, control, and communication (C^3) centers, personnel, aircraft, munitions, critical equipment and supplies, etc. The current vulnerability of hardened structures at Forward Operating Bases (FOBs), aptly demonstrated during operation Desert Storm, and the possible lack of them at bare bases when force projection is required jeopardizes the ability of either type of airbase to fulfill its mission of sortie generation after attack. To address the problem of ensuring that an airbase fulfills its mission in wartime, the U. S. Air Force developed the Airbase Operability (ABO) concept. ABO consists of five phases: (1) defense, (2) survival, (3) recovery, (4) aircraft sortie generation, and (5) sortie support. As part of the survival phase of ABO, AFCESA/RACS is investigating the use of such methods as deflection grids, burster slabs, reactive armor, and fiber-reinforced concrete in the construction of hardened airbase structures, to improve hardened structure survivability, while at the same time reducing their cost and weight.

C. SCOPE

This report first summarizes results from the literature review. Information from the literature review on the current state of R&D on fiber-reinforced concrete, with respect to major sources of information and associated findings important to this research effort are presented, and areas where current research is lacking are described. Secondly, a testing program investigating fiber-reinforced concrete for use in hardened structure construction is described and results presented. Finally, conclusions and recommendations arising from this technical effort are presented. Conclusions emphasize the benefits fiber reinforcement would provide to hardened structures, while recommendations deal with future testing required to eventually field fiber-reinforced concrete hardened structures.

D. RESULTS

1. Literature Review

On the basis of the results from the literature review, three major areas where fiber-reinforced concrete can provide a benefit to hardened structure construction have been identified. Each of these areas is briefly discussed below.

a. Rebar Reinforcement Replacement

Standard hardened structure construction uses symmetrically, doubly-reinforced concrete members. Use of fiber reinforcement may minimize, or possibly eliminate, the need for compression and shear reinforcement in such members, without degrading their performance. However, the literature indicates that it is doubtful that fiber reinforcement will allow the elimination of any tension rebar reinforcement. Partial or total replacement of compression and shear reinforcement provides two primary benefits to hardened structure construction. The first is a weight saving in concrete structural members. The second area is a cost saving, which is always an issue with hardened structure construction.

b. Toughness

Another possible benefit of using fiber reinforcement for hardened structures is an increase in toughness of the concrete used in the structure. Throughout the reviewed literature, it is indicated that including fibers in concrete beams, both with and without standard rebar reinforcement, increases the area under the beam's load-deflection curve. By various methods, the area under a load-deflection curve is used to measure a beam's material toughness. By increasing the toughness of structural members in a hardened structure, the structure becomes better able to withstand large deformations caused by blast effects and/or dynamic impacts, without catastrophic failure. Obviously this is a critical consideration in the design of hardened structures.

c. Spalling

The final benefit using fiber-reinforced concrete provides to hardened structures is the minimization of spalling. Use of fiber reinforcement significantly reduces the chance of spalling when concrete is subjected to dynamic impact or blast effects. Spalling of the inside walls of a hardened structure from blast and/or dynamic impacts poses a significant hazard to personnel and equipment within the structure. Minimizing spalling is another critical consideration in the design of hardened structures.

2. Testing Program

The testing program consisted of two phases. In the first phase, the performance of fiber-only reinforced beams was compared against the performance of symmetrically reinforced beams designed to current hardened structure criteria. The goal of this phase was to determine if fiber-only reinforced beams are a practical option for hardened structure construction. Comparisons were based on load-deflection curves generated under static flexural third-point loading for each beam type. Specifically, the area under the curves at several points were calculated, allowing relative comparisons of material toughness to be made. The larger the area under a curve the better a beam's performance. Results from this test phase show that beams reinforced with fibers only are not a viable concept for hardened structure construction.

The second phase of the testing program involved and an iterative process that sought out the best fiber and rebar combination to enhance a beams performance under static flexural third-point loading. In this test phase, load-deflection curves were again generated for each beam type. Then using these curves, ductility indices and energy ratios were generated for each beam type allowing relative comparisons to be made with regard to material ductility and energy absorption. This in turn allowed the overall toughness of each beam type to be assessed. In addition, test beams were compared to a baseline beam. The baseline beam was a standard weight beam designed to current hardened construction standards, i.e., symmetrically reinforced. Results from this test phase show several types of beams that provide far superior performance, based on material ductility and energy absorption, versus the baseline beam. Additionally, all but a few beam types showed some improvement in performance versus the baseline beam.

E. CONCLUSIONS

Use of fiber reinforcement in combination with standard rebar reinforcement in hardened structures can provide a significant performance enhancement over currently fielded hardened structures. The major benefits are threefold. First, the ductility and energy absorption characteristics, i.e., material toughness, of fiber- and rebar-reinforced structural members are clearly superior to the symmetrically reinforced structural members currently used in hardened structures by the U.S. Air Force. Second, using fibers would eliminate the need for compression, and in all probability shear, reinforcement in concrete structural members without degrading their performance. In fact, test results indicate the performance of the structural members would be enhanced by using fibers. Third, inclusion of fibers would minimize, or possibly eliminate, spalling of the interior walls of hardened structures from blast loadings or projectile impacts.

Increased material toughness in concrete structural members at a lower weight and reduced cost, is especially beneficial for prefabricated, modular hardened structures designed for bare base and force projection situations. This especially holds true for prefabricated, modular airmobile hardened structures.

B. RECOMMENDATIONS

It is recommended that a large-scale, two-phase testing program be undertaken by the U.S. Air Force to investigate the most promising fiber- and rebar-reinforced beam types identified in this study. The first phase should consist of laboratory tests of most promising beam types, but using beam sizes closer to that actually used in hardened structure construction. Enough beams should be tested, so statistically significant conclusions can be made. The second phase of the testing program should consist of field tests of scaled hardened structures constructed using fiber- and rebar-reinforced structural members. These structures, which should be instrumented with accelerometers, pressure gauges, etc., should be subjected to blast loadings and dynamic impacts from conventional weapons such as bombs and rockets. Successful completion of this two phase testing program could lead to the eventual incorporation of fiber- and rebar-reinforced concrete structural members into U.S. Air Force hardened structure designs.

PREFACE

This report was prepared by Applied Research Associates, Inc. (ARA), under contract F08635-88-C-0067 for the Air Force Civil Engineering Support Agency (AFCESA), Civil Engineering Laboratory, Tyndall Air Force Base, Florida.

This report summarizes work accomplished between 1 October 1991 and 30 November 1992. Major Jacob Gheriani (IAF) and Maj. Dan Shenbach (IAF) were the HQ AFCESA/RACS Project Officers during this effort.

This report has been reviewed by the Public Affairs Office, and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the public, including foreign nations.

This report has been reviewed and is approved for publication.

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Project Officer

Felix T. Uhlik III
Felix T. Uhlik III, Lt. Col., USAF
Chief, Air Base Systems Branch

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William S. Strickland
Chief, Airbase Survivability Section

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SECTION I

INTRODUCTION

A. OBJECTIVE

This technical report documents a preliminary research and testing effort undertaken by the Air Force Civil Engineering Support Agency (AFCESA), Engineering Research Division's Airbase Survivability Branch (RACS) to develop a fiber- and rebar-reinforced concrete beam design(s) that can be used in the construction of hardened structures to increase their survivability, while reducing their cost and weight. In particular, this work will benefit bare base and airmobile modular, prefabricated hardened structures where weight saving and increased material toughness, i.e., energy absorption as a function of material weight, are critical issues. In addition, using prefabricated fiber- and rebar-reinforced concrete structural members will allow fiber content, concrete strength, and quality to be controlled, while minimizing construction time and cost. Because prefabricated construction is envisioned for fiber-reinforced hardened structures, such issues as field constructability and field quality control management were not considered critical when developing beam designs during this research effort. However, use of fibers in conjunction with standard reinforcement does not preclude field pouring and construction of hardened structures.

The objective of this technical effort was twofold. First, a literature review was conducted to determine the state of fiber-reinforced concrete Research and Development (R&D). Emphasis was placed on the current state of R&D on fiber-reinforced concrete structural applications, material compositions, structural and engineering properties, fabrication and mixing, and design methods. On the basis of this literature review, areas where research is currently lacking were determined. In addition, results from this review were used to determine the possible benefits of using fiber reinforcement in combination with standard rebar reinforcement in the construction of hardened structures. Specifically, will the use of fibers increase the survivability of hardened structures, while at the same time reducing their cost and weight? Finally, a testing program was proposed in the literature review to develop and evaluate fiber- and rebar-reinforced beam designs.

The second objective of this effort was to conduct a testing program to develop, test, and evaluate a wide range of fiber-reinforced beam designs with and without standard rebar reinforcement. On the basis of results from the literature review, the testing program was structured to investigate areas were fiber-reinforced concrete R&D is currently lacking. Finally, the best beam candidates for possible use in hardened structure construction were identified for future research efforts.

B. BACKGROUND

As was shown in operation Desert Storm, hardened structures housing mission-critical assets are susceptible to severe damage or total destruction from "smart" conventional weapons. In addition, significant damage can occur to hardened structures from near misses by standard conventional weapons or a direct hit, i.e., the golden BB. Also, during operation Desert Storm, many, if not most, U.S. military mission-critical assets were deployed to bases where hardened structures were in limited supply or not available. Without the protection of hardened structures, mission-critical assets are extremely vulnerable to damage from attack by conventional weapons (bombs, artillery, rockets, small-arms, etc.).

Typically, airbase hardened structures house mission-critical assets, such as command, control, and communications (C^3) centers, personnel, aircraft, munitions, critical equipment and supplies, etc. The current vulnerability of hardened structures at Forward Operating Bases (FOBs), and the possible lack of them at bare bases when force projection is required jeopardizes the ability of either type of airbase to fulfill its mission after an attack. To address the problem of ensuring that an airbase fulfills its mission in wartime, the U. S. Air Force developed the Airbase Operability (ABO) concept. ABO consists of five phases: (1) defense, (2) survival, (3) recovery, (4) aircraft sortie generation, and (5) sortie support.

As part of the survival phase of ABO, the U.S. Air Force is constantly searching for ways to improve the performance, i.e., survivability, of hardened structures, while at the same time, if possible, reducing their construction cost and weight. In addition, to address the possible lack of hardened structures at bare bases, the U.S. Air Force is developing prefabricated, modular, rapidly erectable hardened structures. Some of these prefabricated, modular hardened structures will be air transportable, i.e., airmobile. As part of these research efforts, AFCESA/RACS is investigating the use of such methods as deflection grids, burster slabs, reactive armor, and fiber-reinforced concrete in the construction of hardened airbase structures.

C. SCOPE

In Section II of this report, results from the literature review on fiber-reinforced concrete are summarized. Information from the literature review on the current state of fiber-reinforced concrete R&D, with respect to major sources of information and findings important to this research effort are presented. Additionally, areas where current fiber-reinforced concrete R&D is lacking are described. In Section III, results from the fiber- and rebar-reinforced concrete beam testing program are presented. In Section IV, conclusions dealing with the feasibility and benefits of using fiber- and rebar-reinforced concrete structural members in hardened structures are given. Additionally, recommendations on future R&D needed to eventually field fiber-reinforced concrete hardened structures are presented.

SECTION II

LITERATURE REVIEW SUMMARY

A. MAJOR SOURCES OF INFORMATION

Thousands of technical articles, papers, reports, manuals, and books have been generated on fiber-reinforced concrete since it first began being used in engineering applications in the early 1960s. The literature review of fiber-reinforced concrete, which is contained in Appendix A of this report, identified several key sources of information, which are summarized below.

1. Books And Other Publications

Beaudoin, J.J., Editor, Handbook of Fiber-Reinforced Concrete - Principles, Properties, Development and Applications, Noyes Publications, Park Ridge, New Jersey, 1990.

Fiber-Reinforced Concrete, Portland Cement Association Publication SP039.01T, Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois, 1991.

Balaguru, P.N., and Shah, S.P., Fiber-Reinforced Cement Composites, McGraw-Hill, Inc., New York, New York, 1992.

2. Collected Papers

Shah, S.P., and Batson, G.B., Editors, Fiber-Reinforced Concrete Properties and Applications, American Concrete Institute (ACI) SP-105, American Concrete Institute Publication, P.O. Box 19150, Redford Station, Detroit, Michigan, 1987.

Swamy, R.N., and Barr, B., Editors, Fiber-Reinforced Cements And Concretes - Recent Developments, Elsevier Science Publishers Co., Inc., 655 Avenue of the Americas, New York, NY, 1989.

Hoff, G.C., Editor, Fiber-Reinforced Concrete - International Symposium, ACI SP-81, American Concrete Institute Publication, P.O. Box 19150, Redford Station, Detroit, Michigan, 1984.

Craig, R.J. Editor, Design with Fiber-Reinforced Concrete, ACI SCM-10(85), American Concrete Institute Publication, P.O. Box 19150, Redford Station, Detroit, Michigan, 1985.

3. Magazines

Civil Engineering (Engineered Design And Construction), The Magazine Of The American Society of Civil Engineers (ASCE), 345 East 47th Street, New York, NY, monthly.

Concrete International, The Magazine Of The American Concrete Institute (ACI), P.O. Box 19150, Redford Station, Detroit, Michigan, Monthly.

4. Technical Journals

American Concrete Institute Journal (Prior to 1987), P.O. Box 19150, Redford Station, Detroit, Michigan, bimonthly.

American Concrete Institute Structural Journal (from 1987), P.O. Box 19150, Redford Station, Detroit, Michigan, bimonthly.

American Concrete Institute Materials Journal (from 1987), P.O. Box 19150, Redford Station, Detroit, Michigan, bimonthly.

American Society of Civil Engineers Structural Engineering Journal, 345 East 47th Street, New York, NY, monthly.

American Society of Civil Engineers Engineering Mechanics Journal, 345 East 47th Street, New York, NY, monthly.

B. CURRENT STATE OF RESEARCH

1. Overview

Research on fiber-reinforced concrete has been rapidly expanding in the past 10 years. Hundreds of articles and papers have been published recently. In the last 30 years, literally thousands of papers and articles have been published. Consequently, before an efficient literature review could be conducted, its scope had to be defined to limit the amount of data that had to be reviewed to a reasonable level. The main thrust of this research effort was to develop fiber-reinforced concrete structural members for use in hardened structure construction that save weight and cost, versus the currently used symmetrically reinforced concrete members, while at the same time maintaining or possibly improving the performance of the members. Consequently, it was decided to concentrate the literature review on fiber-reinforced concrete structural and design issues. Particular emphasis was placed on the use of fibers in combination with standard rebar reinforcement in concrete. Additionally, the literature review, while not disregarding older research, concentrated on articles, papers, and books published in the last 10 years.

2. Major Findings And Research Shortfalls

a. Major Findings

On the basis of the literature review, three major areas were identified in which fiber-reinforced concrete can provide a benefit to hardened structures. Each of these areas is discussed below.

(1) Rebar Reinforcement Replacement

Standard hardened structure construction uses symmetrically reinforced concrete members. Reference 1 indicates that using fiber reinforcement may eliminate the need for compression and shear reinforcement in concrete members without sacrificing performance. However, based on reviewed literature, it is doubtful that fiber reinforcement will allow the elimination of tension rebar reinforcement. Still, fiber-only beams were investigated in the test program.

Partial or total replacement of compression and shear reinforcement provides two primary benefits to hardened structures. The first is a weight saving in concrete structural members. Weight reduction is critical for prefabricated, modular hardened structures because members will probably have to be lifted and maneuvered into position with cranes, front-end-loaders, or similar equipment during construction. For obvious reasons, weight saving in concrete structural members is even more critical for airmobile, prefabricated, modular hardened structures. The second area is cost saving, which is always an issue with hardened structures regardless of type, especially today in light of reduced DOD spending levels.

(2) Toughness

The second benefit fiber-reinforced concrete provides to hardened structure construction is increased material toughness, i.e., energy absorption. The reviewed literature, for example References 1, 2, 3, and 4, indicates that inclusion of fibers in concrete, with or without standard rebar reinforcement, increases the area under a beam's load-deflection curve under flexural loading. By various methods, the area under a beam's load-deflection curve is used to measure the beam material's toughness. A method proposed in Reference 5 was used in the testing program described in Section III of this report to determine a beam's toughness using ductility indices and energy ratios.

By increasing the material toughness of the structural members used in the construction of a hardened structure, the structure is more likely to withstand large deformations caused by blast effects and/or dynamic impacts without catastrophic failure. This is a critical consideration in the design of hardened structures.

(3) Spalling

The final benefit provided by using fiber-reinforced concrete in hardened structure construction is the minimization of spalling. Inclusion of fiber reinforcement in concrete significantly reduces the chance of spalling when the concrete is subjected to dynamic impacts or blast effects (References 6 and 7). Spalling of the inside walls of a hardened structure from blast and/or dynamic impacts poses a significant hazard to personnel and equipment within the structure. Fibers help keep the pieces of concrete that try to breakoff due to blast loadings and/or impact impacts attached to the inside walls of a structure. In some cases, pieces of concrete may even be hanging loose from a wall, solely attached by several fibers (Reference 6). Minimizing spalling of the interior walls of a hardened structure is another critical design consideration.

b. Research Shortfalls

Throughout the reviewed literature, there were two areas identified where fiber-reinforced concrete R&D was lacking. The first area is the use of fiber reinforcement in high compressive strength concrete ($f_c' \geq 8{,}000$ psi). Concrete compressive strength in the reviewed literature ranged from a low of 3,000 psi to slightly over 7,000 psi. This is the compressive strength range typically found in commercial construction. No information at higher compressive strengths was found during the literature review.

The second area where fiber-reinforced concrete R&D is lacking is in the use of fibers in lightweight structural concrete. Some work has been done on using fibers in lightweight, non-structural concrete to control cracking, such as in decorative concrete building adornments. However, the weight of structural concrete in all the reviewed literature fell within the standard range of 140 to 160 pounds per cubic foot (pcf). This is well outside the 115 to 140 pcf weight range typical of lightweight structural concrete.

Except for the two major areas mentioned above, research efforts on the engineering properties, applications, design, etc., of fiber-reinforced concrete have been very thorough and are ongoing by various universities, companies, institutes, and associations.

3. Fiber-Reinforced Concrete Design Method Overview

A brief overview of the flexural design of concrete members using standard reinforcement in combination with fiber reinforcement is given below. For much more detailed discussions of this subject see References 1, 8, and 9.

Numerous design methods have been proposed for combined fiber- and rebar-reinforced concrete structural members. Some of these include the Williamson method, the Henager and Doherty method, and Swamy and Al-Ta'an method. All of these methods are based on ACI ultimate strength design concepts. The methods differ somewhat in assumptions with regard to the strain diagram, stress block shape and depth, maximum usable strain, etc. However, each basically modifies the force diagram to account for the contribution of the fibers in the tension zone of the concrete. The ultimate moment is then the sum of the couples involving the fibers in the concrete tension zone and the reinforcing bars.

Comparison of the different methods shows that they produce similar results (see Reference 1). However, comparison of the results from each method with experimental data shows they are about 15-percent conservative. This difference is mainly attributable to the methods not taking into account the strain hardening ($\varepsilon_{steel} > \varepsilon_y$) occurring in the reinforcing steel (fibers and rebar).

In conclusion, the basic design of fiber- and rebar-reinforced concrete members does not differ significantly in method or complexity from the design of standard reinforced concrete members. Adequate methods are currently available, which while conservative, provide reasonable accuracy. Additionally, design methods are steadily being improved.

C. TESTING PROGRAM

On the basis of results from the literature review, a fiber-reinforced concrete beam testing program was developed and carried out as part of this technical effort. The testing program focused on lightweight ($\approx$120-140 pcf), high-strength ($f_c' \geq$ 8,000 psi) concrete with various combinations of fiber (types, volumes, and lengths) and/or rebar (steel and fiberglass) reinforcement. Several test methods and specimen sizes were used. The goal of the testing program was to develop a fiber- and tension rebar-reinforced beam design that provides, at a minimum, the same level of strength and toughness as the symmetrically reinforced concrete beam design currently used in hardened structures. See Section III for a detailed discussion of the beam testing program.

D. CONCLUSIONS AND RECOMMENDATIONS

Reviewed literature indicates that the use of fiber reinforcement in commercial construction applications will become common practice within the next 10 years. The reasons for this are many, with decreased cost due to stronger, smaller structural members, cracking control, and increased life span of structures and pavements due to increased material toughness and fatigue resistance being just a few. Additionally, the commercial uses of fiber-reinforced concrete are continuing to increase as practical and validated design methods become more available and better known. Research continues to develop such design methods. In large part, these methods are based on ACI ultimate strength design methods, with appropriate modifications to account for the increased strength of the concrete in the tensile zone caused by fibers bridging and resisting cracking.

The literature review uncovered two areas where research is lacking. The investigation of lightweight (115 to 140 pcf) concrete with fiber reinforcement is one area. The other area is the use of fiber reinforcement in high compressive strength ($f_c' \geq 8{,}000$ psi) concrete. Both of these areas appear to hold promise for hardened structures and were investigated in the testing program.

In summary, the use fiber reinforcement, combined with standard rebar reinforcement in a concrete structural member, holds great promise to dramatically increase the concrete member's material toughness, while at the same time reducing its weight. This possibility, when combined with the ongoing development of design methods for concrete members using fibers in combination standard reinforcement, indicates the use of such members in hardened structures could enhance the survivability of the structures.

SECTION III

TEST PROGRAM DESCRIPTION AND RESULTS

A. TEST PROGRAM STRUCTURE AND OVERVIEW

The testing program described here originally consisted of three phases. In the first phase, the performance of fiber-only reinforced beams was compared to the performance of symmetrically reinforced beams designed to current hardened structure criteria. The goal of this test phase was to determine if fiber-only reinforced beams are a practical option for hardened structure construction. Comparisons were based on load-deflection curves generated under static, flexural, third-point loading for each beam type. Specifically, areas under the curves at several points were calculated, allowing relative comparisons of material toughness between the beams to be made. A beam with more area under its load-deflection curve absorbed more energy, thus exhibiting more material toughness and better performance. See Subsection III-D for a description of Test Phase I.

During execution of the final two phases of the testing program, the phases were merged into a single phase involving an iterative process that sought out the best fiber and rebar combination to enhance a beam's performance under flexural third-point loading. In this combined Test Phase II, static flexural third-point loading load-deflection curves were again generated for each beam type. Then using these curves, ductility indices and energy ratios were generated for each beam type allowing relative comparisons to be made with regard to material ductility and energy absorption characteristics. This in turn allowed the overall toughness of each beam type to be assessed. In addition, test beams were compared to a baseline beam type. The baseline beam type was a standard weight beam designed to current hardened construction standards, i.e., symmetrically reinforced. See Subsection III-E for a description of Test Phase II.

B. TEST SPECIMENS

1. Beams and Cylinders

All beams used in the testing program are summarized below in Table 1 with a corresponding Beam ID. Also included in the table are binder type, average compressive strength, maximum compressive concrete strain, amount of tension reinforcement, amount of compression reinforcement, reinforcing fiber type, percentage of fibers by volume, and average unit weight. Three beams were poured for each beam type. All beams were 40 inches long, 8 inches deep, and 4 inches wide. Beam types F1, F2, and SR1 were used in the first phase of the testing program. All remaining beam types were used in the second phase of the test program.

Average compressive strengths shown in Table 1 come from compressive tests of 6-inch diameter, 12-inch long cylinders (1 to 3 per beam type). Maximum concrete compressive strains come from the same cylinder test data. Average unit weight is based on the average weight of all three beam specimens for a particular type, including fibers and rebar as applicable.

TABLE 1. TEST BEAMS DESCRIPTIONS AND PROPERTIES.

Beam ID	Binder Type(1)	Avg. Comp. Strength (psi)	Avg. Max. Strain (in/in)	Bars: Tension	Bars: Comp.	Fiber Type(2)	Fiber Vol. (%)	Avg. Unit Wt. (pcf)
F1	LW/HS	9,873	0.00251	None	None	Nylon	0.5	124.78
F2	LW/HS	9,648	0.00273	None	None	Steel-1	2.0	127.05
SR1	LW/HS	8,475	0.00221	2 No. 3 (3)	2 No. 3	None	N/A	128.46
SR2	LW/HS	8,475	0.00221	2 No. 3	None	None	N/A	124.76
SR3	LW/HS	9,494	0.00265	2 No. 3	1 No. 3	None	N/A	126.46
SR4	NW/MS	6,537	0.00186	2 No. 3	2 No. 3	None	N/A	152.85
SR5	LW/HS	8,983	0.00245	2 No. 3	None	Steel-2	2.0	130.78
SR6	LW/HS	9,499	0.00276	2 No. 3	None	Steel-1 Nylon	2.0 0.15	128.61
SR7	NW/MS	6,537	0.00186	2 No. 3	None	Steel-1	2.0	157.15
SR8	LW/HS	9,294	0.00259	2 No. 3	None	Steel-3	4.0	134.64
SR9	LW/HS	9,073	0.00258	2 No. 3	None	Steel-4	1.0	126.68
SR10	LW/HS	9,873	0.00251	2 No. 3	None	Nylon	0.5	125.49
SR11	LW/HS	9,648	0.00273	2 No. 3	None	Steel-1	2.0	130.28
FR1	LW/HS	8,976	0.00259	2 FRG(4)	None	Nylon	0.5	122.97
FR2	LW/HS	9,269	0.00253	2 FRG	2 FRG	None	N/A	123.86
M1	LW/HS	10,459	0.00277	None	None	Steel-1 Mat	2.0 0.65	132.26
M2	LW/HS	10,111	0.00266	2 No. 3	None	Steel-1 Mat	2.0 0.65	135.63

Notes: (1) LW=Light Weight, NW=Normal Weight, HS=High Strength, And MS=Medium Strength
(2) Fiber Types (see Table 2 for fiber details): Steel-1=Glued, Hooked Ends Or Loose, Hooked Ends, Steel-2=Anchorloc, Steel-3=Short And Straight, and Steel-4=Long And Hooked Ends
(3) Standard No. 3 (3/8" Dia.) Steel Rebar, 60ksi (54.5ksi tested)
(4) 3/8" Dia. Fiberglass Rebar, 100ksi

2. Fiber Types

Six different types of fibers were used during the fabrication of beam specimens. Four of the fiber types consist of individual steel fibers of differing lengths and shapes, while a fifth type is composed of individual nylon fibers. The remaining fiber type is composed of steel, but in an interwoven mat matrix as shown below in Figure 1.

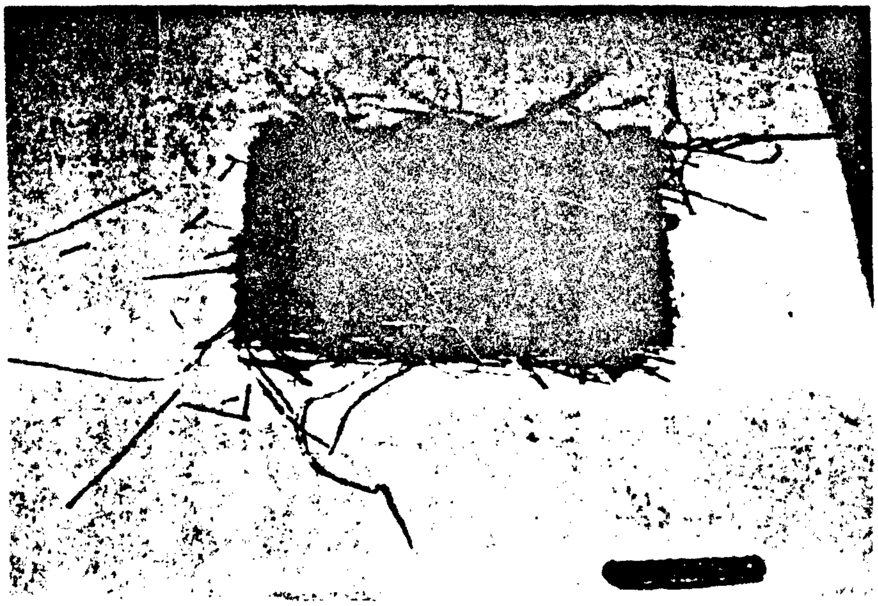

Figure 1. Steel Mat Fiber Matrix Used In Test Beam Types M1 And M2.

The above listed fiber types were selected because they are in the most common use. In addition, they provide good performance at a reasonable cost and are readily available world-wide commercially. Fibers such as carbon and aramid (Kevlar), were not considered due to their high cost and limited availability. Glass fibers were not considered because of long-term durability concerns. Natural fibers were not used because they do not provide enough structural strength. Other fibers such as polyester and polypropylene were not considered because they provide no increase in performance versus steel or nylon. Addionally, polyester and polypropylene fibers are not in as common use as steel or nylon. For a more detailed discussion of commonly used fiber types in fiber-reinforced concrete see the literature review in Appendix A.

Table 2 below summarizes the fiber types used in this testing program. The Fiber ID in Table 2 is the same as used in Table 1. See Table 1 for the fiber volumes used in each beam type.

TABLE 2. FIBER TYPES AND PROPERTIES.

Fiber ID	Description	Length (in)	Diameter (in)	Aspect Ratio (L/D)	Shape	Tensile Yield Strength (ksi)
Steel-1	Bekaert Steel Fibers (Dramix®) Hooked Ends	1.2	0.02	60		170
Steel-2	Anchorloc Steel Fibers By Mitchell Fibercon, Inc. Twisted Shape	1.0	0.10 x 0.044	42		60
Steel-3	Short Steel Fibers By MeH-Tec	0.625	0.020	32.25	—	100
Steel-4	Long Steel Fibers By Bekaert	2.4	0.03	80		170
Nylon	Nylon 6 By NyCon, Inc.	1.0	0.0009	111.11	—	130
Mat	Steel Fiber Mat By Ribbon Technology	N/A	N/A	N/A	See Figure 1	N/A

3. Beam Standard Reinforcing Parameters

Standard Number 3 steel rebar (3/8-inch diameter, 60ksi yield strength, 29,000,000 psi modulus of elasticity, and a unit weight of 0.367 lbs per linear foot) was used in SR beam types. The Number 3 rebar stock used to fabricate the beams was tested, and the rebar's actual yield strength was determined to be 54.5ksi. In beam types FR1 and FR2, FibeRGlass (FRG) rebar was used instead of steel. The FRG rebar was 3/8-inch in diameter, with a 100ksi yield strength. The modulus of elasticity of the FRG material is 7,000,000 psi, with a unit weight of 0.096 lbs per linear foot.

A total of six test beam cross-sections, with and without steel or FRG rebar reinforcement, were used during the test program. These beam cross-sections are shown below in Figure 2. No stirrups were used in the beams, due to limited cross-sectional area of each beam. Using stirrups would have caused constructability problems, and caused the rebar to be too close together (less than 1 inch separation). Additionally, stirrups would have reduced the concrete cover over parts of the rebar below 0.5 inches, which was unacceptable. The locations of standard steel rebar or FRG rebar reinforcement, when used in the beams, are shown on the beam cross-sections in Figure 2. For more information on standard rebar reinforcing parameters see below.

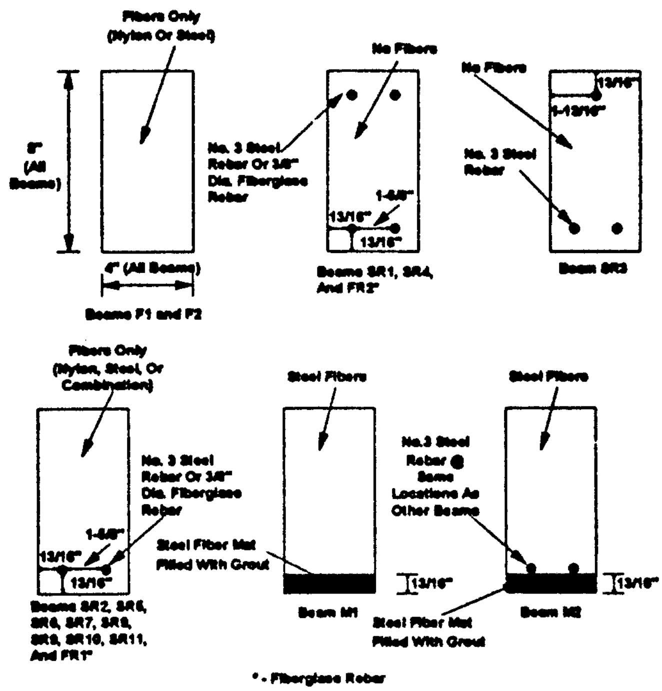

Figure 2. Test Beam Cross-Sections, Test Phases I And II.

a. Fiber-Only Reinforced Beam Types

No rebar reinforcement was used in beam types F1, F2, and M1. Consequently, no standard reinforcement parameters are applicable.

b. Singly Reinforced Beam Types

For the singly reinforced beam types (SR2, SR5 to SR11, FR1, and M2), the balanced reinforcing ratio (ρ_b) was determined using the American Concrete Institute (ACI) equation shown below:

$$\rho_b = \frac{\alpha\varepsilon_c}{(f_y / E_s) + \varepsilon_c} \frac{f_c'}{f_y} \tag{1}$$

Where: ε_c = Maximum concrete compressive strain from compressive cylinder tests

f_y = Steel tensile yield strength (54.5ksi)

E_s = Steel modulus of elasticity (29,000,000 psi)

f_c' = Concrete compressive strength (see Table 1)

α = Average concrete compressive stress in a beam's compression zone divided by f_c' (for f_c' > 8,000 psi α=0.56 and for f_c'=6,000 to 7,000 psi α=0.64)

The values for α given above were developed by the ACI for concrete without fiber reinforcement. However, use of these α values in the design of fiber-reinforced concrete members provides sufficient accuracy according to References 1, 5, 8, and 9. The maximum allowable ACI reinforcing ratio was determined using $\rho_{max} = 0.75\rho_b$. The actual reinforcing ratio for each beam was determined using $\rho = A_s / bd$, where A_s is the reinforcing steel area, b = beam width, and d = depth to the centroid of tension reinforcement. The average reinforcing parameters for all singly reinforced beam types is summarized below in Table 3.

TABLE 3. REINFORCING PARAMETERS - SINGLY REINFORCED BEAM TYPES.

Beam ID	b (in)	d (in)	A_s (in^2)	ρ_b	ρ_{max}	ρ	ρ/ρ_b	ρ/ρ_{max}
SR2	4.0	7.0	0.22	0.0471	0.0353	0.0079	0.1668	0.2226
SR5	4.0	7.0	0.22	0.0522	0.0382	0.0079	0.1505	0.2015
SR6	4.0	7.0	0.22	0.0581	0.0435	0.0079	0.1360	0.1816
SR7	4.0	7.0	0.22	0.0369	0.0277	0.0079	0.2141	0.2852
SR8	4.0	7.0	0.22	0.0551	0.0413	0.0079	0.1434	0.1913
SR9	4.0	7.0	0.22	0.0539	0.0405	0.0079	0.1466	0.1953
SR10	4.0	7.0	0.22	0.0580	0.0435	0.0079	0.1362	0.1816
SR11	4.0	7.0	0.22	0.0587	0.0440	0.0079	0.1346	0.1794
FR1	4.0	7.0	0.22	0.0077	0.0058	0.0079	1.0260	1.3654
M2	4.0	7.0	0.22	0.0609	0.0457	0.0079	0.1297	0.1730

As seen from Table 3, all beam types except the one using FRG rebar (FR1), are significantly under reinforced. This was mainly caused by the small cross-section of the test beams dictated by the limited 50,000-pound capacity of the test equipment used to load the beams to failure (see Subsection III-C). The FR1 beams are moderately over-reinforced. This was caused by the low modulus of elasticity (7,000,000 psi) and relatively high tensile yield strength (100ksi) of the FRG rebar, which lowers the balanced steel ratio determined from Equation (1).

c. Doubly Reinforced Beam Types

For the doubly reinforced beam types (SR1, SR3, SR4, and FR2), the balanced reinforcing ratio (ρ_b) was determined using Equation (1) above. Then, as before, the allowable ACI reinforcing ratio and the actual reinforcing ratio were determined for each beam type using $\rho_{max} = 0.75\rho_b$ and $\rho = A_s / bd$, respectively. According to the ACI , if ρ is equal to or less than

ρ_{max}, a doubly reinforced beam may be designed with acceptable accuracy by ignoring the compression reinforcement and designing the beam as a singly reinforced beam. As seen in Table 4 below, ρ_{max} was greater than ρ for all SR doubly reinforced beam types. Consequently, all SR doubly reinforced beam types were treated as singly reinforced. However, ρ_{max} was less than ρ for the FR2 beam type once again because of the FRG rebar. As a result, FR2 beam reinforcing parameters must be calculated using the ACI equations given below.

$$\rho' = \frac{A'_s}{bd} \tag{2}$$

$$\bar{\rho}_{max} = 0.75\rho_b + \rho' \tag{3}$$

$$\bar{\rho}_{lim} = 0.85\beta_1 \frac{f'_c}{f_y} \frac{d'}{d} \frac{\varepsilon_u}{\varepsilon_u - \varepsilon_y} + \rho' \tag{4}$$

Where: A'_s = Compression steel area

β_1 = 0.65 for $f'_c \geq 8{,}000$ psi

d' = Depth to centroid of compression reinforcing steel

ε_u = 0.00253 (see Table 1)

ε_y = 0.0143 (f_y/E_s, i.e., 100 ksi / 7,000 ksi)

ρ' = Compression steel reinforcing ratio

$\bar{\rho}_{max}$ = Maximum allowable reinforcing ratio

$\bar{\rho}_{lim}$ = Mininium tensile steel reinforcing ratio

Using Equations (2), (3), and (4) with A'_s = 0.22 in^2 and d' = 1.0 inch, the following reinforcing ratio values were determined: ρ' = 0.0079, ρ_{max} = 0.0138, and ρ_{lim} = 0.0063. Since the actual ρ of 0.0079 is between these limits, failure should be initiated by tensile yielding and the compression rebar will have yielded at failure. This assumes FRG rebar exhibits behavior similar to steel rebar. However, FR2 beams exhibited explosive failures during testing, indicating the FRG rebar is more brittle, i.e, less ductile, than steel rebar.

TABLE 4. REINFORCING PARAMETERS - DOUBLY REINFORCED BEAM TYPES.

Beam ID	b (in)	d (in)	d' (in)	A_s (in^2)	A'_s (in^2)	ρ_b	ρ_{max}	ρ	ρ/ρ_b	ρ/ρ_{max}
SR1	4.0	7.0	1.0	0.22	0.22	0.0471	0.0353	0.0079	0.1668	0.2226
SR3	4.0	7.0	1.0	0.22	0.11	0.0571	0.0428	0.0079	0.1376	0.1836
SR4	4.0	7.0	1.0	0.22	0.22	0.0369	0.0277	0.0079	0.2129	0.2837
FR2	4.0	7.0	1.0	0.22	0.22	0.0078	0.0059	0.0079	1.0073	1.3317

4. Beam Fabrication And Mixture Properties

Two concrete forms were fabricated out of steel plate. Each form had three individual bays separated by steel plate, allowing three beams to be poured in each form. Holes had been drilled through the steel plate at the ends of each bay allowing rebar, if used, to be preplaced in the forms prior to pouring concrete. Consequently, concrete ties were not required to position the rebar. Holes had been drilled at appropriated locations to obtain the reinforcement dimensions shown in Figure 2. If no rebar was used in the beams, the holes were taped over to prevent spillage.

A portable, rotary, finned mixer was used to mix the concrete. Fibers, if used, were added toward the end of the mixing process. The concrete was mixed in the mixer for approximately 10 minutes, then poured into the forms. A pencil, internal vibrator was used to consolidate the concrete in the forms. After consolidation, the exposed concrete surface was finished with trowels. The forms were then covered with wet burlap for approximately 24 hours. The beams were then removed from the forms, and cured under water for 28 days. At the same time beams were being poured, some of the concrete was poured into 6-inch diameter, 12-inch long concrete cylinder forms. After 24 hours, the cylinders were removed from the forms and water cured for 28 days. The cylinders were used to obtain concrete compressive strength and maximum compressive strain for each concrete mix. Mix designs for the different concretes are given below in Table 5. A Type-1 cement was used in all mixes.

TABLE 5. CONCRETE MIXES FOR TEST BEAM SPECIMENS.

Beam ID	Fibers(1)	Cement (lbs)	Fine Agg. (lbs)	Coarse Agg. (lbs)	Solite (lbs)(2)	F-10K (lbs)(3)	Water (lbs)	WRDA-79 (oz)(4)	WRDA-19 (oz)(5)
F1	1.11 lbs (N)	104	135	N/A	94	24	23.5	5.64	6.35
F2	21 lbs (S1)	104	135	N/A	94	N/A	23.5	5.64	N/A
SR1	None	104	135	N/A	94	24	23.5	5.64	N/A
SR2	None	104	135	N/A	94	24	23.5	5.64	N/A
SR3	None	104	135	N/A	94	24	23.5	5.64	N/A
SR4	None	83.5	108	200	N/A	9.5	32	N/A	N/A
SR5	21 lbs (S2)	104	135	N/A	94	24	24	5.64	N/A
SR6	21 lbs (S1) 0.33 lbs (N)	104	135	N/A	94	N/A	24	5.64	N/A
SR7	29.4 lbs (S1)	83.5	108	200	N/A	9.5	32	N/A	N/A
SR8	42 lbs (S3)	104	135	N/A	94	24	23.5	5.64	N/A
SR9	10.5 lbs (S4)	104	135	N/A	94	24	23.5	5.64	N/A

TABLE 5. CONCRETE MIXES FOR TEST BEAM SPECIMENS (CONCLUDED).

SR10	1.11 lbs (N)	104	135	N/A	94	24	23.5	5.64	6.35
SR11	21 lbs (S1)	104	135	N/A	94	N/A	23.5	5.64	N/A
FR1	1.11 lbs (N)	104	135	N/A	94	24	23.5	5.64	6.35
FR2	1.11 lbs (N)	104	135	N/A	94	24	23.5	5.64	6.35
M1	21 (S1) Plus Mat	104	135	N/A	94	24	23.5	5.64	N/A
M2	21 (S1) Plus Mat	104	135	N/A	94	24	23.5	5.64	N/A

Notes: (1) N=Nylon, S1=Steel-1, S2= Steel-2, S3= Steel-3, S4=Steel-4
(2) Lightweight aggregate
(3) Force-10K liquid silica flume by W. R. Grace, Co.
(4) Water reducer by W. R. Grace, Co.
(5) Super plasticizer by W. R. Grace, Co.

In addition to the concrete mixes described in Table 4, a slurry mixture consisting of 23.7 pounds of Type-3 cement, 5.9 pounds of fly-ash class "C", 10.4 pounds of water, and 105 grams of Cormix Super 2000-C plasticizer was used for test beam types M1 and M2. The slurry was used to infiltrate the steel fiber mat matrix. The steel-fiber mat matrix was preplaced in the bottom of the concrete forms prior to infiltration. After slurry infiltration, concrete was poured over the infiltrated steel mat to complete the beams.

C. TEST EQUIPMENT

1. Flexural Loading Beam Testing

A 50,000-pound capacity Material Testing System (MTS) load-frame and data acquisition system were used to conducted third-point flexural loading of test beams under deflection control to failure or a maximum mid-span deflection of 2 inches, which ever occurred first. In general, test procedures from ASTM C 78-84, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)" and ATSM C 1018-89, "Standard Test Method for Flexural Toughness and First Crack Strength of Fiber-Reinforced Concrete (Using Simple Beam with Third-Point Loading)" were used to conduct the tests and obtain load-deflection curves for each beam. The MTS machine with a test beam in place is shown below in Figure 3.

In Figure 3, a safety cage around the test beam is not shown on the MTS machine. During beam testing in Test Phase II, some very explosive beam failures occurred when beam deflections reached 1.50 inches or greater. During initial testing in Test Phase II, a safety cage was not used on the MTS machine, and these failures caused pieces of concrete to go flying

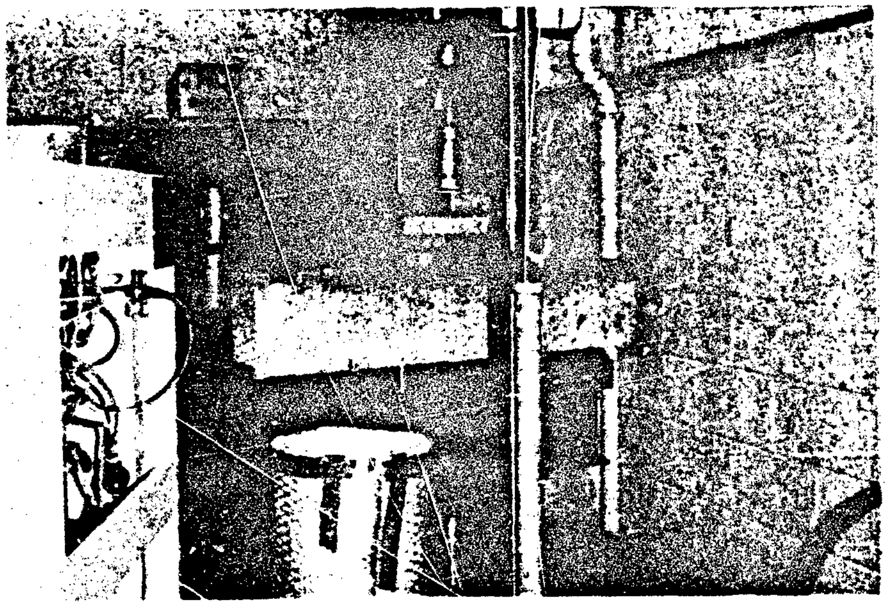

Figure 3. MTS Machine Used To Conduct Flexural Beam Tests.

around the room. These pieces of flying concrete posed a safety hazard to test personnel. To overcome this problem, a safety cage consisting of wire mesh attached to a steel tubular frame was fabricated. The openings in the wire mesh were too small to allow pieces of concrete to pass through. The frame could be attached to or removed from the MTS machine in a few seconds. The cage surrounded the beam on three sides, with the open side facing a masonry block wall on the back side of the MTS machine.

As previously indicated, flexural loading of beams was done using the third-point loading method. In both Test Phases I and II of this program, a load span length to depth (L/D) ratio of 4 was used for all beams. Since the depth of all test beams was 8 inches, the load span length was set at 32 inches. The actual beam loading configuration used on the MTS machine is shown below in Figure 4.

2. Compressive Cylinder Tests

Compressive tests of 6-inch diameter, 12-inch long concrete cylinders poured at the same time individual beams were poured were done using a 500,000-pound capacity Forney load-frame under load control. Compressive stress-strain curves for all beam types from these compressive cylinder tests are contained in Appendix B.

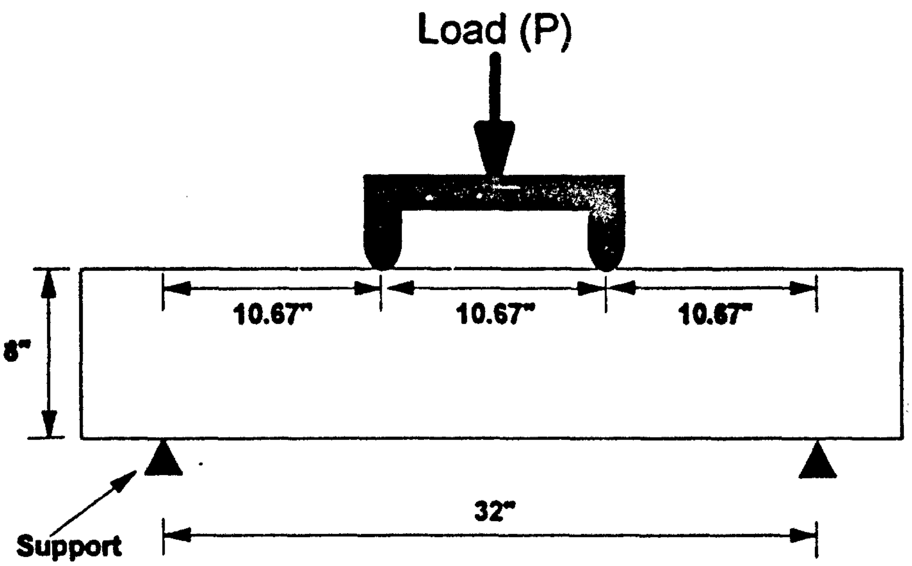

Figure 4. Test Beam Configuration Used On The MTS Machine.

Cylinder stress-strain curves for beam types F1, F2, and SR7 in Appendix B appear to exhibited strain softening. However, under-load controlled testing strain softening can not occur. A possible reason why these cylinders appear to show strain softening behavior is the load rate of 20 to 50 psi per second specified in ASTM C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" was not used for these beam types. A much lower rate of 1 to 2 psi per second was used for these cylinders. As a result, once failure of a cylinder occurred, the pullout strength of the fibers was not instantly exceeded due to the slower loading rate. Thus, the cylinder was held together by the fibers and was slowly crushed. With the faster load rate, when failure occurred, the pullout strength of the fibers was instantly exceeded and the cylinder broke explosively.

Because the accuracy of the compressive cylinder stress-strain curves for beam types F1, F2, and SR7 is very questionable, average compressive strength and average maximum compressive strain given in Table 1 for these beam types was taken from cylinder tests of different beam types that used the same mix design (see Table 4). For beam type F1, cylinder test data from beam type SR10 was used. For beam type F2, cylinder test data from beam type SR11 was used. Finally, for beam type SR7, cylinder test data from beam type SR4 was used.

The same mix designs, including fiber type, were used for F1 and SR10 cylinders and F2 and SR11 cylinders, respectively. Consequently, there is little chance of a significant error as far as concrete compressive strength and maximum strain reported in Table 1 are concerned. While the same basic mix design was used for SR4 and SR7 cylinders, steel fibers were used in SR7 cylinders while none were used in SR4 cylinders. This could introduce an error in the compressive strength and maximum compressive strain values reported in Table 1 for beam type SR7. However, the chance of a large error is unlikely because reviewed literature indicates (see Reference 1, 8, and 9) that fibers do not significantly influence concrete compressive strength or maximum compressive strain.

D. TEST PHASE I

In Test Phase I, three types of beams were tested (beam types F1, F2, and SR1 in Table 1). F1 beams were reinforced with nylon fibers only, while F2 beams were reinforced with steel fibers only. The SR1 beams had no fiber reinforcement, and were symmetrically reinforced with Number 3 rebar as shown in Figure 2. There were three beams of each type. The beams were tested on the MTS machine following the procedures described in ASTM C 1018-79 and ASTM C 78-84 to develop load-deflection curves for each beam. Typical generated total load versus mid-span deflection curves of each beam type are shown below in Figure 5. As seen, the symmetrically reinforced SR1 beam without fibers is clearly superior, with the area under its curve much greater than either of the F1 or F2 beams. As also can be seen, the steel fiber-reinforced beam (F2) provides superior performance versus the nylon fiber reinforced beam (F1).

The clear superiority of beam type SR1 over beam types F1 and F2 is further demonstrated in Table 6 below. In this table, the maximum mid-span deflection for each beam, the average maximum mid-span deflection for each beam type, the maximum total load for each beam, the average maximum total load for each beam type, the Japanese area (described in Reference 10) for each beam, the average Japanese area for each beam type, the total (ultimate) area under the total load versus mid-span deflection curve for each beam, and the average total area for each beam type are presented.

The Japanese Area Method, which is used for fiber-only reinforced beams, calculates the area under a load-deflection curve up to a deflection equaling the beam's load span length divided by 150. For the beams used in this test program, this deflection point equals 0.21333 inches (32 inches divided by 150). This method was also applied to the standard reinforced SR1 beams in Table 6 for comparison purposes and completeness.

All generated load-deflection curves from this test phase are contained in Appendix C.

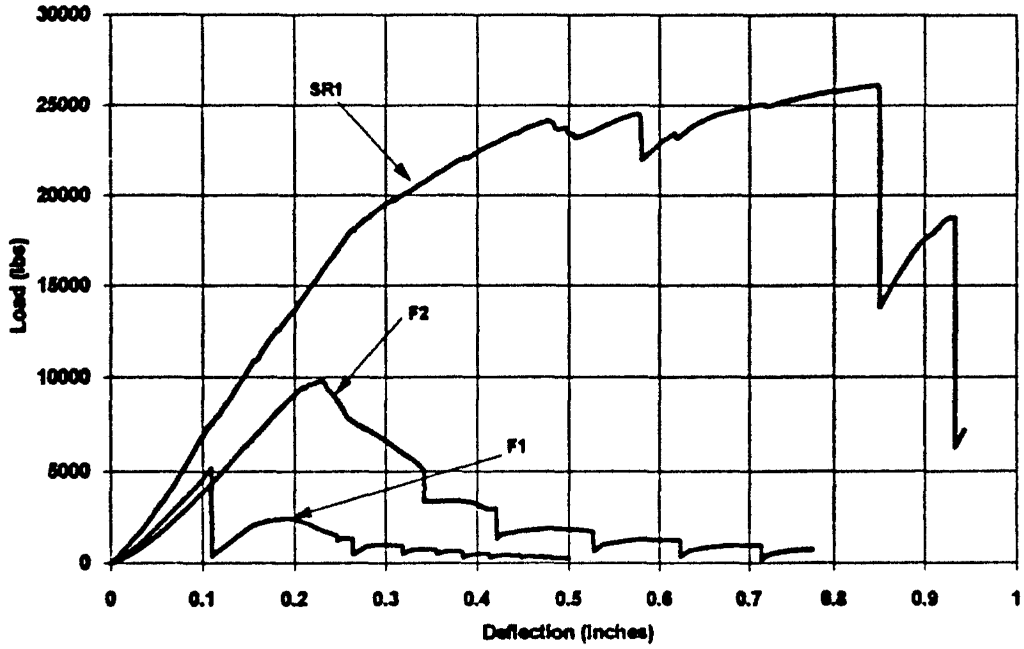

Figure 5. Typical Load-Deflection Curves Of Beam Types F1, F2, SR1.

TABLE 6. COMPARISON BETWEEN BEAM TYPES F1, F2, AND SR1.

Beam ID	Beam No.	Max. Deflec. (in)	Avg. Max. Deflec. (in)	Max. Load (lbs)	Avg. Max. Load (lbs)	Japanese Area (in.lbs)	Avg. Japanese Area (in.lbs)	Ultimate Area (in.lbs)	Avg. Ultimate Area (in.lbs)
F1	1	0.3337		5,146		323.5		437.8	
	2	0.4533	0.3443	3,814	4,181	365.0	318.1	458.3	389.9
	3	0.2460		3,582		265.8		273.5	
F2	1	0.5169		9,784		1,184.1		1,709.7	
	2	0.4600	0.4388	9,742	9,985	1,202.4	1,207.3	1,768.0	1,683.0
	3	0.3394		10,429		1,236.7		1,571.2	
SR1	1	0.9439		26,109		1,530.5		17,551.7	
	2	1.0992	1.0839	23,006	25,105	1,436.2	1,453.5	15,113.6	15,932.4
	3	1.2087		26,199		1,393.8		15,131.9	

As seen from Figure 5 and Table 6, the performance of the fiber-only reinforced beam types is clearly inferior to the standard, symmetrically reinforced, concrete beam type. However, the average compressive strength of 8,745 psi of the SR1 type beams (see Table 1) is greater than the 4,000 to 6,000 psi range normally used in hardened structure construction. Still, even this strength difference would not compensate for the order of magnitude, or greater, difference in ultimate areas between the SR1 baseline beams and the F1 and F2 beams.

Because of the results shown in Figure 5 and Table 6, testing in Phase II of the program primarily concentrated on beams that combined standard reinforcement in combination with fiber reinforcement. The goal of the testing was to eliminate the need for compression rebar, while improving the performance of the beams with respect to the baseline beam. Additionally, reviewed literature indicates using fibers will eliminate the need for shear reinforcement.

E. TEST PHASE II

1. Load-Deflection Curves

A total of 14 beam types were tested (3 per type). SR2 to SR11 beam types were reinforced with steel rebar and usually some type of fiber reinforcement. FR1 and FR2 beam types were reinforced with FRG rebar, with FR1 type beams also containing nylon fibers. M1 type beams were reinforced at the bottom with the slurry-infiltrated steel mat fiber matrix, with steel fiber-reinforced concrete above the mat. M2 type beams were reinforced like M1 type beams, but also had steel rebar in the tension zone.

The beams were tested on the MTS machine following the procedures described in ASTM C 1018-79 and ASTM C 78-84 to develop load-deflection curves for each beam. However, because rebar was used in all beam types except one, with or without fiber reinforcement, the specified mid-span deflection rate in ASTM C 1018-89 of 0.002 to 0.004 inches per minute was changed to 0.1476 inches per minute (0.00246 in/sec) as recommended in Reference 5. This deflection rate change was made in order to get reasonable test times. When the slower rate was used in Test Phase I, test times ranged between 2 to 3 hours for the SR1 type beams which had rebar reinforcement. This problem is caused because ATSM C 1018-89 was designed to test beams reinforced with fibers only. Inclusion of rebar reinforcement, especially in combination with fiber reinforcement, substantially increases the toughness of the beams, thereby dramatically increasing the length of the load-deflection curve before failure occurs. Consequently, the deflection rate was increased to obtain reasonable test times. This problem was not a significant factor in Test Phase I, because only 3 SR1 type beams were tested.

Typical generated total load versus mid-span deflection curves for each beam type are shown in Figures 6 through 9.

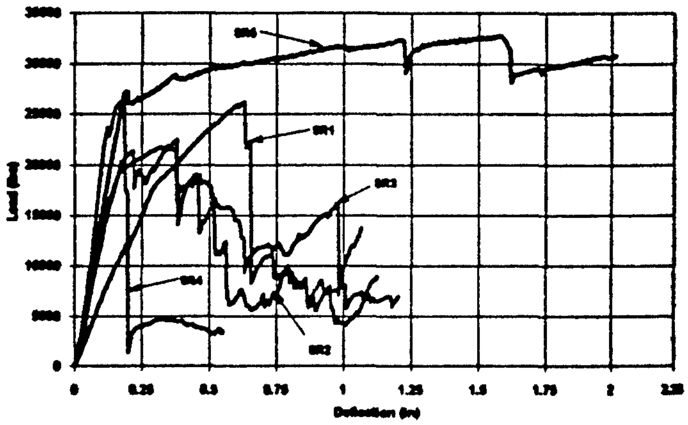

Figure 6. Typical Load-Deflection Curves Of Beam Types SR1 Through SR5.

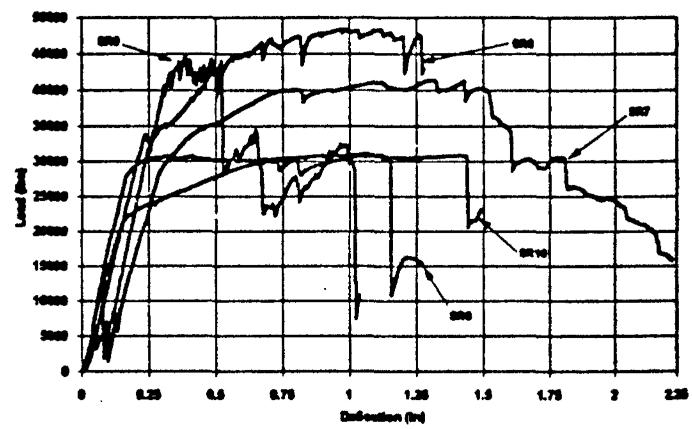

Figure 7. Typical Load-Deflection Curves Of Beam Types SR6 Through SR10.

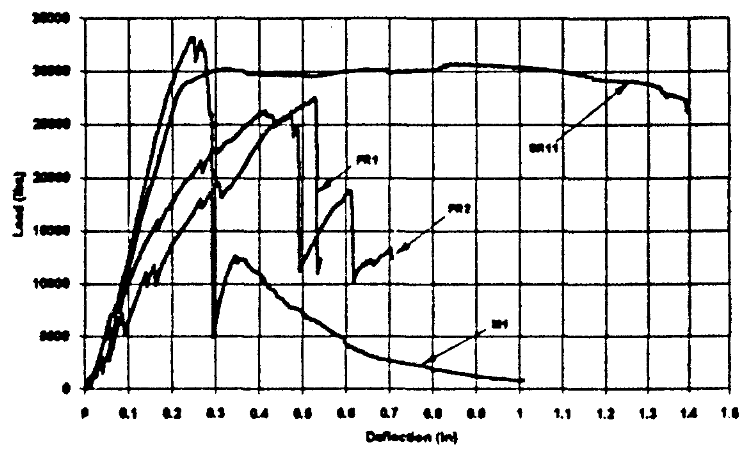

Figure 8. Typical Load-Deflection Curves Of Beam Types SR11, FR1, FR2, And M1.

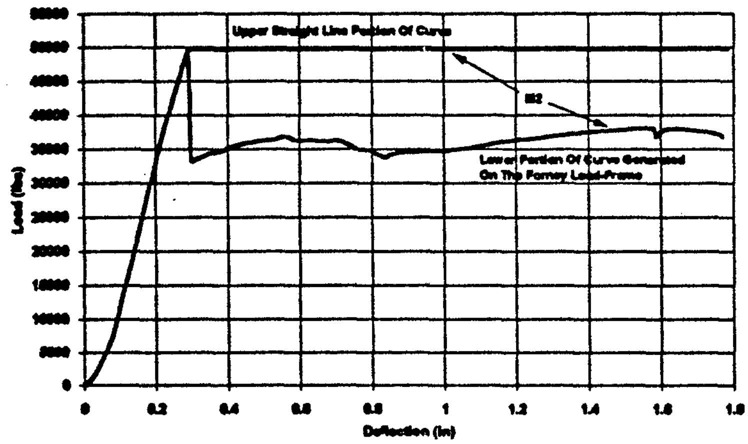

Figure 9. Typical Load-Deflection Curve Of Beam Type M2.

All generated load-deflection curves from this test phase are contained in Appendix C. Beam type SR1 is shown in Figure 6 for completeness, while beam type SR4 in Figure 6 is the baseline, symmetrically reinforced beam.

In Figure 9 above, two different lines are shown for the load-deflection curve after the maximum load was reached. While testing the M2 type beams on the MTS machine, the 50,000-pound capacity of the machine was reach before any significant cracking of the beams occurred and deflection was only 0.292 inches. Beam 1 of the M2 type was tested on the Forney load-frame to determine its ultimate capacity. However, it only reached a maximum load of approximately 37,500-pounds. Beam failure occurred at a maximum deflection of 1.769 inches and a load of 36,870 pounds. The portion of this Forney generated curve from a deflection of 0.299 inches (the closest matching deflection point to the MST curve) is superimposed on the curve from the MTS machine. This is the lower portion of the load-deflection curve shown in Figure 9, running from 0.299 inches to the maximum deflection point of 1.769 inches. In addition to the lower curve, a straight line is also shown on Figure 9 running from the maximum load point of 50,000 pounds to the maximum deflection point of 1.769 inches. Both of these load-deflection curves in Figure 9 were used to calculate the ductility index and energy ratio for beam 1 of the M2 type as described below in Subsections III-E.2 and III-E.3.

2. Ductility Indices And Energy Ratios

The performance of the various beam types tested in this phase was compared using ductility indices and energy ratios. In addition, the average total energy absorbed by a beam type measured in inch-pounds, i.e., the total area under a load-deflection curve, divided by the average weight of the beam type in pounds was also used to compare the beams.

The method used to calculate ductility indices and energy ratios from load-deflection curves is shown below in Figure 10. This method was obtained from Reference 5, where it is described in detail.

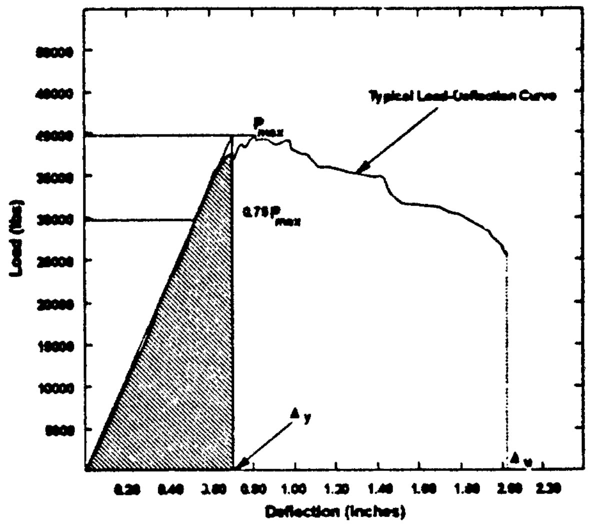

Figure 10. Calculation Of Ductility Index And Energy Ratio From A Load-Deflection Curve.

As shown in Figure 10, the maximum load P_{max} is determined. Then, a straight line is drawn parallel to the deflection axis until it intersects the load axis. Next, a secant is drawn from the origin through the point corresponding to $0.75P_{max}$ on the load-deflection curve, and extended until it intersects the straight line running from P_{max} to the load axis. At this intersection point, a vertical line parallel to the load axis is drawn until it intersects the deflection axis. The point where this line intersects the deflection axis (Δy) is considered the yield deflection for the beam. The energy dissipated at yield (Ey) is defined as the shaded area under the load-deflection curve up to the yield deflection as shown in Figure 10. Next, the ultimate deflection point of the curve (Δu) is determine and the total area under the load-deflection curve up to this point (Eu) calculated. In this test phase, ultimate deflection was limited to 2 inches for calculation of ductility indices and energy ratios. The ductility index is defined as the ultimate deflection divided by the yield deflection ($\Delta u/\Delta y$), while the energy ratio is defined as the ultimate area divided by the yield area (Eu/Ey).

3. Beam Test Results

Using the methods described in Subsection III-E.2., ductility indices, energy ratios, and total absorbed energy per pound were calculated for each beam. A beam's load span length, i.e., 32 inches, was used to calculate beam weight for absorbed energy per pound calculations. Results of all these calculations are given below in Table 7.

TABLE 7. DUCTILITY INDICES, ENERGY RATIOS, AND ABSORBED ENERGY PER POUND FOR TESTED BEAMS.

Beam ID	Beam No.	Yield Deflc. (in)	Max. Deflc. (in)	Duct. Index	Avg. Duct. Index	Yield Area (in.lbs)	Ult. Area (in.lbs)	Energy Ratio	Avg. Energy Ratio	Max. Load (lbs)	Avg. Max. Load (lbs)	Energy (in.lbs) Per lb (1)
	1	0.4033	0.9438	2.34		5,208	17,552	3.37		26,109		
SR1	2	0.3480	1.0991	3.16	2.66	3,769	15,114	4.01	3.23	23,006	25,078	209.3
	3	0.4365	1.2087	2.48		6,526	15,132	2.32		26,119		
	1(2)	—	—	—		—	—	—		—		
SR2	2	0.1797	1.1265	6.27	6.27	1,895	12,566	6.63	6.63	22,521	22,521	170.0
	3(2)	—	—	—		—	—	—		—		
	1(2)	—	—	—		—	—	—		—		
SR3	2(2)	—	—	—	6.02	—	—	—	8.22	—	21,793	210.4
	3	0.1770	1.0650	6.02		1,919	15,768	8.22		21,793		
	1	0.1737	0.4378	2.52		2,568	8,634	3.36		30,877		
SR4	2	0.1342	0.5509	4.11	3.66	1,650	4,569	2.77	4.23	26,500	29,006	108.3
(3)	3	0.1866	0.8117	4.35		2,470	16,227	6.57		29,641		
	1	0.2258	2.0147	8.92		3,426	58,101	16.96		32,713		
SR5	2(2)	—	—	—	8.92	—	—	—	16.96	—	32,713	749.7
	3(2)	—	—	—		—	—	—		—		
	1	0.1903	1.1958	6.28		2,826	32,951	11.66		30,913		
SR6	2	0.1965	1.8181	9.25	7.54	3,298	55,921	16.96	13.71	34,171	32,063	538.2
	3	0.1792	1.2713	7.09		2,732	34,176	12.51		31,104		
	1	0.2395	1.9976	8.34		4,562	45,703	10.02		38,328		
SR7	2	0.2491	1.9977	8.02	6.91	4,584	46,731	10.19	9.19	38,125	39,292	562.3
	3	0.4587	1.9999	4.36		8,780	64,665	7.37		41,423		
	1	0.3079	1.5102	4.90		7,051	56,945	8.08		49,544		
SR8	2	0.4752	1.2791	2.69	3.96	12,522	49,743	3.97	6.54	49,743	49,708	666.3
	3	0.2990	1.2791	4.28		6,982	52,797	7.56		49,838		
	1	0.3052	1.5328	5.02		6,899	53,941	7.82		48,003		
SR9	2	0.3507	1.0378	2.96	3.85	7,040	28,781	4.09	5.63	44,573	47,284	524.4
	3	0.3116	1.1141	3.58		7,088	35,374	4.99		49,275		
	1	0.2101	1.8672	8.89		2,813	34,739	12.35		26,950		
SR10	2	0.2758	1.4935	5.42	6.94	4,529	39,720	8.77	9.93	30,847	28,473	493.1
	3	0.2788	1.8131	6.50		4,097	35,547	8.68		27,622		
	1	0.4677	1.6055	3.43		7,401	41,759	5.64		33,087		
SR11	2	0.2064	1.1188	5.42	4.92	3,245	30,198	9.31	8.80	33,442	32,423	473.8
	3	0.2360	1.3946	5.91		3,297	37,774	11.46		30,740		

TABLE 7. DUCTILITY INDICES, ENERGY RATIOS, AND ABSORBED ENERGY PER POUND FOR TESTED BEAMS (CONCLUDED).

Beam ID	Beam No.	Yield Deflc. (in)	Max. Deflc. (in)	Duct. Index	Avg. Duct. Index	Yield Area (in.lbs)	Ult. Area (in.lbs)	Energy Ratio	Avg. Energy Ratio	Max. Load (lbs)	Avg. Max. Load (lbs)	Energy (in.lbs) Per lb (1)
	1	0.3647	0.5117	1.40		4,393	7,384	1.68		24,638		
FR1	2	0.3346	0.5409	1.62	1.48	4,748	9,942	2.09	1.84	27,486	27,076	125.2
	3	0.3804	0.5410	1.42		5,760	10,055	1.75		29,105		
	1	0.4066	0.7084	1.74		5,259	10,452	1.99		26,192		
FR2	2	0.3532	1.1310	3.20	2.64	4,532	15,778	3.48	2.29	25,768	24,208	140.8
	3	0.3346	0.9975	2.98		3,429	4,768	1.39		20,663		
	1	0.2266	1.0109	4.46		3,480	8,947	2.57		33,140		
M1	2	0.2098	0.8682	4.14	4.59	3,137	7,209	2.30	2.58	32,644	33,128	104.0
	3	0.1767	0.9149	5.18		2,894	8,292	2.87		33,601		
M2	1	0.2948	1.7690	6.00	6.00	6,679	61,025	9.14	10.55	>50K	>50K	876.9
(4)		—	—	—		—	79,938	11.97	(5)			(6)

Notes: (1) Average ultimate area (in.lbs) divided by beam weight in pounds, i.e., ((span x depth x width)/1,728) x unit weight
(2) Bad data due to equipment problems
(3) Baseline beam
(4) Ultimate area values were derived from the two curves shown in Figure 9 (lower values from the lower curve, higher values from the higher curve)
(5) Average of the two energy ratios for the two different curves (this value is probably very conservative)
(6) Determined from the average of the 2 ultimate areas (61,025 and 79,938) divided by average beam weight in pounds (this value is probably very conservative)

On the basis of the results shown in Table 7, each beam type was ranked by average ductility index, energy ratio, maximum load, and energy absorption per pound. This information is presented below in Table 8. On the basis of these rankings, the beam types providing the best overall performance can be quickly determined and outstanding performance by a beam type in any particular easily identified.

In addition, to the results presented in Table 8, average ductility index, energy ratio, and energy absorption per pound were normalized with respect to the baseline beam type SR4. This information is presented below in Table 9. This information allows the beam types providing the best overall performance versus what is currently used in hardened structure construction to be readily identified.

As shown in Table 8, several beam types show good results. Beam type SR5 appears in the top five in ductility index (1), energy ratio (1), and energy absorption (2). Beam type SR6 appears in ductility index (2), energy ratio (2), and energy absorption (5). Beam type SR7 appears in the top five in all four categories. Specifically it appears in ductility index (4), energy ratio (5), maximum load (4), and energy absorption (4). Beam type M2 appears in the top five in

TABLE 8. BEAM TYPE RANKINGS.

Avg. Ductility Index	Avg. Energy Ratio	Avg. Max. Load (lbs)	Energy Absorption Per Pound
SR5 - 8.92	SR5 - 16.96	M2 - >50,000	M2 - 876.9
SR6 - 7.54	SR6 - 13.71	SR8 - 49,708	SR5 - 749.7
SR10 - 6.94	M2 - 10.55	SR9 - 47,284	SR8 - 666.3
SR7 - 6.91	SR10 - 9.93	SR7 - 39,292	SR7 - 562.3
SR2 - 6.27	SR7 - 9.19	M1 - 33,128	SR6 - 538.2
SR3 - 6.02	SR11 - 8.80	SR5 - 32,713	SR9 - 524.4
M2 - 6.00	SR3 - 8.22	SR11 - 32,423	SR10 - 493.1
SR11 - 4.92	SR2 - 6.63	SR6 - 32,063	SR11 - 473.8
M1 - 4.59	SR8 - 6.54	SR4 - 29,006	SR3 - 210.4
SR8 - 3.96	SR9 - 5.63	SR10 - 28,473	SR1 - 209.3
SR9 - 3.85	SR4 - 4.23	FR1 - 27,076	SR2 - 170.0
SR4 - 3.66	SR1 - 3.23	SR1 - 25,078	FR2 - 140.8
SR1 - 2.66	M1 - 2.58	FR2 - 24,208	FR1 - 125.2
FR2 - 2.64	FR2 - 2.29	SR2 - 22,521	SR4 - 108.3
FR1 - 1.48	FR1 - 1.84	SR3 - 21,793	M1 - 104.0
Avg: 5.09	Avg: 7.36	Avg: 32,984	Avg: 396.8

TABLE 9. NORMALIZED BEAM TYPE RANKINGS.

Beam ID	Avg. Ductility Index	Avg. Energy Ratio	Energy Absorption Per Pound
SR1	0.73	0.76	1.93
SR2	1.71	1.57	1.57
SR3	1.64	1.94	1.94
SR4	1.00	1.00	1.00
SR5	2.44	4.01	6.92
SR6	2.06	3.24	4.97
SR7	1.89	2.17	5.19
SR8	1.08	1.55	6.15
SR9	1.05	1.33	4.84
SR10	1.90	2.35	4.55
SR11	1.34	2.08	4.37
FR1	0.40	0.43	1.16
FR2	0.72	0.54	1.30
M1	1.25	0.61	0.96
M2	1.64	2.49	8.10

energy ratio (3), maximum load (1), and energy absorption (1). For the three beam types mentioned above that fall outside the top five in 1 of 4 categories, all but beam type SR6 are still above the average for that category. Beam type SR6 falls slightly below the average maximum load (32,063 lbs versus the 32,984 lbs average).

For prefabricated, modular hardened structures, where overall energy absorption, especially as a function of weight, is critical, beam types SR5 and M2 appear to offer the best performance. Maximizing energy absorption as a function of weight is even more critical for prefabricated, modular, airmobile hardened structure. Beam type M2 also provides the highest maximum load (>50,000 pounds), while beam type SR5 provides the highest ductility ratio. The good performance of the M2 type beams with regard to average energy ratio and energy absorption as a function of weight is especially praiseworthy when, as indicated in Notes 4 and 5 in Table 6, these values are probably very conservative for this beam type. It also should be noted, that other beam types cited in the preceding paragraph also show promise for hardened structure applications.

Table 9 presents two facts. First, the beam types that show good performance, based on Table 8, also show good performance when normalized against the baseline beam type SR4. Second, only three beam types fail to provide ductility indices, energy ratios, or energy absorption values superior to the baseline beam currently used for hardened structure construction.

Specifically, beam types FR1 and FR2 provide inferior ductility indices and energy ratios compared to the baseline beam, while beam type M1 provides inferior energy ratio and energy absorption values. This strongly indicates the use of some type of fiber reinforcement in combination with standard reinforcement in the structural members used in hardened structures would greatly improve the structure's performance. In this case, a structure's performance being defined as its ability to sustain blast and dynamic impact loadings through increased ductility and energy absorption characteristics, i.e., a structure's ability to withstand large permanent deformations without allowing penetration or catastrophic failure.

On the basis of test results, fiber-reinforcement appears to eliminate the need for compression rebar reinforcement. Beam types that used tension and compression rebar reinforcement and no fibers, i.e., beam types SR1, SR3, and SR4, did not perform as well as beam types that used tension rebar and fiber reinforcement, but no compression rebar reinforcement. Additionally, the literature review in Appendix A indicates that fiber reinforcement also minimizes, or possibly eliminates, the need for shear reinforcement in beams. Elimination of compression and shear reinforcement will save weight and cost in hardened structure construction.

4. Best Beam Types

On the basis of the discussion presented in Subsection III-E.3. above, four beam types show the greatest promise for enhancing the performance of hardened structures. Specifically, these beam types are:

- Beam Type SR5: lightweight, high-strength concrete with tension rebar reinforcement in combination with deformed Anchorloc steel fiber reinforcement (Fiber Type Steel-2 in Table 2).
- Beam Type SR6: lightweight, high-strength concrete with tension rebar reinforcement in with combination nylon and hooked end steel fibers (Fiber Types Nylon and Steel-1 in Table 2).
- Beam Type SR7: normal weight, medium strength concrete with tension rebar reinforcement in combination with hooked end steel fibers (Fiber Type Steel-1 in Table 2).
- Beam Type M2: lightweight, high-strength concrete with tension rebar reinforcement in combination with hooked end steel fibers and mat fiber matrix in the bottom of the beam (Fiber Types Steel-1 and Mat in Table 2).

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Use of fiber reinforcement in combination with standard reinforcement in hardened structures would provide a significant performance enhancement over currently fielded hardened structures. The major benefits are threefold. First, the ductility and energy absorption characteristics, i.e., material toughness, of fiber- and rebar-reinforced structural members are clearly superior to the symmetrically reinforced structural members currently used by the U.S. Air Force. Second, using fibers would eliminate the need for compression, and possibly shear, reinforcement in the structural members without degrading their performance. Additionally, elimination of compression and shear reinforcement would reduce the cost and weight of the structural members. Third, inclusion of fibers would minimize, or possibly eliminate, spalling of the interior walls of a hardened structure from blast loadings or projectile impacts.

Increasing concrete's material toughness by using fibers, while at the same time lowering the concrete's weight and cost, is especially beneficial for prefabricated, modular hardened structures designed for bare base, force projection situations. By incorporating fiber- and rebar-reinforced concrete structural members into the design of a hardened structure, the same level of protection can be obtain at a much lower weight and cost than possible using current design methods. Conversely, for the same weight and slightly lower cost a hardened structure could be designed using fiber- and rebar-reinforced structural members that is far more resistance to blast loading and dynamic impacts than currently available designs.

B. RECOMMENDATIONS

While literature review and test results presented in this report indicate fiber-reinforced concrete would provide significant benefits if incorporated into hardened structure designs, a definitive conclusion on this issue can not be made at this time. The inability to make a definitive conclusion is primarily caused by four reasons. First, the test results from the small size test beams used in this study might not necessarily scale upward to the full-size beams that would be used in hardened structures. Second, not enough beams were tested to be statistically significant. Third, beams were fabricated and tested under laboratory conditions. Even if beams are prefabricated in a batch mixing plant before assembly into a modular structure, their overall quality might not equal that obtained in the laboratory, thus degrading their performance. Finally, tested beams were not subjected to actual blast loadings and dynamic impacts. Consequently, even though their material toughness appears superior to current hardened structure beam designs, their actual performance when subjected to blast loadings and dynamic impacts is unknown at this time.

For the reasons given in the preceding paragraph, it is recommend that a large-scale, two-phase testing program be under taken by the U.S. Air Force. The first phase of the program should consist of laboratory tests of the most promising beam types identified in this study, but using beam sizes closer to that actually used in the construction of hardened structures. Enough beams should be tested, so that statistically significant conclusions can be made. The second phase of the testing program should consist of field tests of scaled hardened structures constructed using fiber- and rebar-reinforced structural members. These structures, which should be instrumented with accelerometers, pressure gauges, etc., should be subjected to blast loadings and dynamic impacts from conventional weapons such as bombs and rockets. Successful completion of this two-phase testing program could lead to the eventual incorporation of fiber- and rebar-reinforced concrete structural members into U.S. Air Force hardened structure designs.

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APPENDIX-A

LITERATURE REVIEW: FIBER-REINFORCED CONCRETE

LITERATURE REVIEW: FIBER-REINFORCED CONCRETE

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SECTION I

INTRODUCTION

A. OBJECTIVE

The literature review presented here is the initial part of a research effort undertaken by the Air Force Civil Engineering Support Agency (AFCESA), Engineering Research Division's Airbase Survivability Branch (RACS) to determine the feasibility of using fiber-reinforced concrete in the construction of hardened structures to increase their survivability, while possibly reducing their cost and weight. Emphasis is placed on modular construction using prefabricated fiber and rebar reinforced concrete structural members to allow fiber content, concrete strength, and quality to be controlled, while minimizing construction time and cost.

The objective of this literature review was to determine the current state of fiber-reinforced concrete research. Emphasis was placed on the current state of research and development on fiber-reinforced concrete structural applications, material compositions, structural/engineering properties, fabrication/mixing, and design methods. The types of fibers investigated in this literature review for use in fiber-reinforced concrete include, but are not limited to, steel, nylon, polypropylene, carbon, glass, and steel fiber-mat matrices.

Based on this literature review, areas where research is currently lacking were determined. In addition, results from this review were used to determine whether it may be practical to use fiber reinforcement in conjunction with standard rebar reinforcement in the construction of hardened structures to increase their survivability, while at the same time reducing their cost and weight.

B. BACKGROUND

As was shown in operation Desert Storm, hardened structures housing mission-critical assets are susceptible to severe damage or total destruction from "smart" conventional weapons. In addition, significant damage can occur to the structures from near misses by standard conventional weapons or the occasional direct hit, i.e., the golden BB. Also, during operation Desert Storm, many if not most U.S. military mission-critical assets were deployed to bases where hardened structures were not available. Without the protection of hardened structures, mission-critical assets are extremely vulnerable to damage from attack by conventional weapons (bombs, artillery, rockets, small-arms, etc.).

Typically, airbase hardened structures house mission-critical assets, such as command, control, and communications (C^3) centers, personnel, aircraft, munitions, critical equipment and supplies, etc.. The current vulnerability of hardened structures at Forward Operating Bases (FOBs), and the possible lack of them at bare bases when force projection is required jeopardize the ability of either type of airbase to fulfill its mission of sortie generation after attack. To address the problem of ensuring that an airbase fulfills its mission in wartime, and other similar problems, such as the expedient repair of damaged structures housing mission-critical assets, the U. S. Air Force developed the Airbase Operability (ABO) concept. ABO consists of five phases: (1) defense, (2) survival, (3) recovery, (4) aircraft sortie generation, and (5) sortie support.

As part of the survival phase of ABO, the U.S. Air Force is constantly searching for ways to improve the performance, i.e. survivability of hardened structures, while at the same time, if possible, reducing their construction cost. In addition, to address the possible lack of hardened structures at bare bases, the U.S. Air Force is investigating rapidly erectable, modular hardened structures, which in some cases may be airmobile. As part of these research efforts, AFCESA/RACS is investigating the use of such methods as deflection grids, burster slabs, reactive armor, and fiber-reinforced concrete in the construction of hardened airbase structures to improve their survivability, while at the same time reducing their cost and weight.

C. SCOPE

This report includes a brief general discussion of the background of, major fiber types in, and fabrication of fiber-reinforced concrete. Additionally, the structural behavior of fiber-reinforced concrete is briefly described. Information from the literature review on the current state of research on fiber-reinforced concrete, with respect to major sources of information and associated findings important to this research effort are presented, and areas where current research is lacking are identified. This information allows possible applications of fiber-reinforced concrete to hardened structure construction to be addressed. Additionally, based on literature review results, a testing program is proposed to investigate fiber-reinforced concrete for use in hardened structure construction. Finally, conclusions and recommendations arising from the literature review are presented.

D. OVERVIEW - MAJOR SOURCES OF INFORMATION

Thousands of technical articles, papers, reports, manuals, and books have been generated on fiber-reinforced concrete since it first began being used in engineering applications in the early

1960s. As the literature review of fiber-reinforced concrete progressed, several key sources of information were identified, which are summarized below.

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SECTION II

LITERATURE REVIEW: FIBER-REINFORCED CONCRETE OVERVIEW

A. HISTORY AND BACKGROUND

Straw fibers were used in biblical times to reinforce brittle construction materials, such as mud-based mortars (Reference A-1). Additionally, horse hairs have been used for centuries to reinforce plaster (Reference A-2). However, portland cement-based systems using steel fibers as reinforcement were not investigated until the beginning of this century, and it has not been until the last 40 years (especially the last 10 years) that detailed investigations of fiber-reinforced concrete behavior and engineering properties have been undertaken (References A-1 and A-2).

In the 1950s and early 1960s research reported in References A-3 and A-4 looked at the use of closely spaced wires and random fibers in portland cement concrete to arrest cracking and increase concrete tensile strength. Additionally, the Portland Cement Association (PCA) investigated fiber reinforcement in the late 1950s (Reference A-5) as a way to enhance the engineering properties of concrete. Some additional early research on fiber-reinforced concrete is reported in References A-6 to A-12.

Numerous fiber types have been investigated (especially in the last 10 years), including, but not limited to, steel, glass, polypropylene, natural and mineral, carbon, polyvinyl alcohol, polyamide, polyethylene, alumina, and various polymers (References A-1 and A-2). Results from these investigations of fiber-reinforced concrete have allowed the development of analytical design tools and methods for engineers. As these design tools and methods have become more available, the use of fiber-reinforced concrete in construction has greatly increased, especially in applications where toughness and crack resistance are critical (Reference A-2).

To enhance the development of analytical tools for predicting fiber-reinforced concrete behavior, research in the last 10 years has focused on the microstructural behavior of fiber-reinforced concrete. Great emphasis has been placed on the behavior of the interface zone between the reinforcement and the cement/concrete matrix, and how it controls the fundamental properties, behavior, and performance of fiber-reinforced cement/concrete (References A-1 and A-13).

In recent years, researchers have begun to investigate and understand the behavior and engineering properties of fiber-reinforced concrete, incorporating standard tension and compression rebar reinforcement (References A-14 and A-15). As this research yields analytical design methods, the use of fiber reinforcement in combination with standard reinforcement in concrete structural members, such as beams, columns, and slabs, will increase. The literature review described here emphasizes the use of such concrete structural members in hardened construction, where the toughness and impact resistance of fiber/rebar reinforced concrete may be quite beneficial. Use of fiber/rebar reinforced concrete may allow significant cost and weight savings in the construction of hardened structures, while providing the same or possibly a greater level of survivability.

B. STRUCTURAL BEHAVIOR OF FIBER-REINFORCED CONCRETE

The following brief and general discussion of the structural behavior of fiber-reinforced concrete is based primarily on References A-1, A-2, A-13, A-14, and A-16. See these references for more thorough and detailed discussions of the topic.

1. General Behavior

In fiber-reinforced concrete, fibers are embedded in a surrounding concrete matrix. By shear deformation at the fiber/matrix interface, a load is transferred from the matrix to the fibers. Consequently, the fibers contribute to the load carrying ability of the concrete. Principally, the load transfer between the matrix and fibers occurs because of the mismatch between the physical characteristics of the two materials, with the difference in the modulus of elasticity of the two materials having the greatest effect. Some of the other factors affecting the load-carrying ability of the fibers are fiber volume, length, and orientation, and the end conditions of the fibers. If the ends of the fibers are deformed, such as being hooked, the load-carrying ability of the fiber is enhanced. Variations of any of the factors cited above can result in different failure mechanisms of the concrete, for example pull-out of the fibers from the matrix or failure of the matrix around the fibers.

In fiber-reinforced concrete, the fibers are generally discontinuous and randomly distributed throughout the concrete matrix. This differs significantly from continuous, aligned fibers, where the matrix applies little or no load to the fibers, but merely bonds them together, so the load can be directly applied (Reference A-1). One advantage of continuous fibers is that the tensile stress in the fiber is very nearly constant over its entire length, thereby eliminating stress concentrations and allowing the entire fiber to contribute to the load-carrying ability of the concrete matrix. However, the disadvantages of continuous fibers are poor constructibility and the fact that unanticipated loads, causing stresses not parallel to the fibers, could cause catastrophic failure, i.e., the strength of the concrete member is primarily in the direction of the fibers. This is a critical consideration in the design of areospace components using composite materials, where fiber orientation is altered frequently during fabrication to account for changes in the direction of design stresses/strains. Random orientation of fibers minimizes both these problems, but reduces the efficiency factor of the fibers from near 1.0 to between 0.25 to 0.40 in the anticipated direction of tensile/flexural stress, because many fibers will be at an angle to the principal tensile stresses and/or not have the required embedment length (Reference A-16).

2. Critical Parameters And Properties

Below are brief discussions of the critical parameters and properties affecting the behavior and performance of fiber-reinforced concrete.

a. Stress Transfer

Most models of fiber-reinforced concrete are based on aligned, discontinuous fibers, uniformly distributed in the concrete matrix, with both the fibers and matrix behaving elastically (Reference A-1). An example of a rationalized, aligned, discontinuous fiber composite concrete subjected to tension is shown below in Figure A-1.

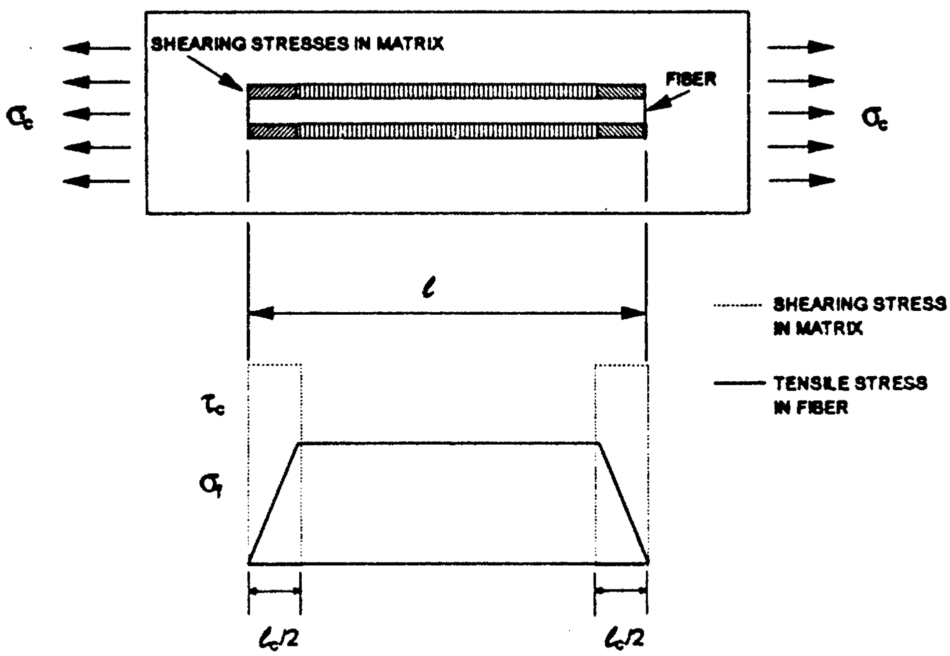

Figure A-1. Typical Fiber-Reinforced Concrete Stress Distribution Model (Reference 1).

As seen, a constant shear stress near the fiber ends causes an increase in the fiber axial tensile stress. Pull-out or sliding of the interface will occur if the fiber is shorter than a certain critical length, ℓ_c, given by the equation below.

$$\ell_c = \frac{d\sigma_f}{2\tau_c} \tag{A.-1}$$

Where d is the fiber diameter, σ_f is the ultimate tensile strength of the fiber, and τ_c is the interfacial shear strength. The transfer length is defined as half the critical length, i.e., $\ell_c/2$.

b. Fiber-Fiber Interaction

The discontinuous ends of fibers cause stress concentrations in the matrix material. These stress concentrations must be taken up by surrounding fibers. This process is called fiber-fiber interaction. This effect causes discontinuous fibers to only be able to contribute a maximum of 6/7 of their strength to the concrete (Reference A-17) or in the case of badly flawed fibers as little as 1/2 of their strength (Reference A-18).

c. Critical Fiber Volume (Reported In Reference A-1)

In fiber-reinforced concrete, the failure strain of the fibers is greater than that of the concrete matrix. Consequently, when the matrix cracks the fibers either carry the additional load or failure occurs. The minimum or critical fiber volume fraction, V_{cr}, required for the fiber-reinforced concrete to sustain the load after matrix fracture occurs is given by:

$$V_{cr}\sigma_{fu} = V_{cr}\sigma'_f + (1 - V_{cr})\sigma_{mu} \tag{A-2a}$$

or

$$V_{cr} = \frac{\sigma_{mu}}{\sigma_{mu} + (\sigma_{fu} - \sigma'_f)} \tag{A-2b}$$

where σ'_f is the stress on the fibers when the matrix fails, and σ_{mu} and σ_{fu} are the ultimate strengths of the matrix and fibers, respectively.

The critical fiber volume in concrete for some of the more common fiber types is calculated to be approximately 0.31-, 0.40-, and 0.75-percent for steel, glass, and polypropylene, respectively.

d. Mixture Rules

Reference A-19 gives simple, two-phase mixture rules as the basis for predicting fiber-reinforced concrete properties. For discontinuous, fiber-reinforced concrete, equations for predicting modulus of elasticity, E_c, and tensile or flexural strength, σ_c, are given in the form of:

$$E_c = \phi_i E_f V_f + E_m V_m \quad \text{(A-3)}$$

$$\sigma_c = \phi_i \sigma_f V_f + \sigma_m V_m \quad \text{(A-4)}$$

where V_f and V_m are the volume fractions of the fibers and the concrete matrix, respectively. The elastic modulus for the fibers and concrete matrix are denoted by E_f and E_m, respectively. While σ_f and σ_m are the corresponding tensile strengths. A composite efficiency factor, φ_i, in the equations accounts for the reduction in fiber-reinforced concrete mechanical property values due to such factors as fiber length, orientation, defects, and fiber-fiber interaction. For continuous, aligned fibers, $\phi_i \equiv 1$, and failure usually occurs by fiber fracture and not fiber pull-out.

e. Failure Modes

The four primary failure modes of fiber-reinforced concrete are: (1) fiber failure in tension, (2) concrete failure in tension, (3) fiber pull-out from the matrix, and (4) failure caused by badly flawed fibers. For fiber pullout to occur, the fibers must be shorter than the critical length given by Equation (A-1). In general, increases in fiber aspect ratio (length/diameter), length, and volume fraction increase the tensile and flexural strength of fiber-reinforced concrete (References A-1 and A-2).

f. Fiber-Matrix Bond

Properties of the fiber and concrete matrix interface have a significant impact on the mechanical behavior of fiber-reinforced concretes. Strength predictions for fiber-reinforced concrete are dependent upon the shear-deformation behavior of a special fiber-matrix interfacial region called a transition zone. To determine the shear strength of this interface zone, pull-out test of fibers from concrete specimens have been used. A detailed discussion on fiber-matrix bonding and the corresponding interface zone, along with empirically derived equations for predicting the interfacial shear strength from pullout experimental data, are given in Reference A-1 (pages 14 to 18).

C. MAJOR FIBER TYPES

Following are brief discussions of the major fiber types used in fiber-reinforced concrete. Fibers other than those discussed below are sometimes used, but not on a large scale commercially. For more detailed discussions of fiber types used in fiber-reinforced concrete see References A-1, A-2, and A-16. A summary of major fiber types and properties is given below in Table A-1.

TABLE A-1. MAJOR FIBER TYPES AND PROPERTIES, REFERENCE A-16.

Fiber Type	Specific Gravity	Young's Modulus, ksi	Diameter (x 0.001 in.)	Tensile Strength, ksi	Strain at Failure, %
Steel					
High Tensile	7.80	29,000	4.0-40.0	50-250	3.5
Stainless	7.80	23,200	0.4-13.0	300	3.0
Glass					
E	2.50	10,400	0.4	500	4.8
Alkali-Resistant	2.70	11,600	0.5	360	3.6
Polymeric					
Polypropylene					
Monofilament	0.90	725	4.0-8.0	65	18
Fibrillated	0.90	500	20.0-160.0	80-110	8
Polyethylene	0.96	725-25,000	1.0-40.0	29-435	3-80
Polyester	1.38	1,450-25,000	0.4-3.0	80-170	10-50
Acrylic	1.18	2,600	0.2-0.7	30-145	28-50
Aramid					
Kevlar® 29	1.44	9,000	0.47	525	3.6
Kevlar® 49	1.44	17,000	0.40	525	2.5
Asbestos					
Crocidolite	3.40	28,400	0.004-0.8	29-260	2-3
Chrysotile	2.60	23,800	0.0008-1.2	500	2-3

TABLE A-1. MAJOR FIBER TYPES AND PROPERTIES, REFERENCE A-16 (CONCLUDED).

Fiber Type	Specific Gravity	Young's Modulus, ksi	Diameter (x 0.001 in.)	Tensile Strength, ksi	Strain at Failure, %
Carbon					
I (High Modulus)	1.90	55,100	0.30	260	0.5-0.7
II (High Strength)	1.90	33,400	0.35	380	1.0-1.5
Natural					
Wood Cellulose	1.50	1,450-5,800	0.8-4.7	44-131	----
Sisal	----	1,890-3,770	<8.0	41-82	3-5
Coir (coconut)	1.12-1.15	2,760-3,770	4.0-16.0	17-29	10-25
Bamboo	1.50	4,790-5,800	2.0-16.0	51-73	----
Jute	1.02-1.04	3,770-4,640	4.0-8.0	36-51	1.5-1.9
Akwara	0.96	76-464	40.0-160.0	----	----
Elephant Grass	-----	716	17.0	26	3.6

1. Steel Fibers

Research reported in References 3 and 4 in the late 1950s and early 1960s began the development of steel fiber-reinforced concrete (SFRC). Early steel fibers were round and smooth, and were obtained by cutting wire. Today, steel fibers have rough surfaces, hooked ends, and/or are crimped or undulated along their length. These characteristics improve their pull-out performance. Most manufactured steel fibers are obtained from drawn steel wire, or in some cases steel sheet material.

Most steel fiber types have equivalent diameters, based on cross-sectional area, ranging from 0.010 to 0.040 inches. Their aspect ratio, defined as fiber length divided by fiber diameter, range from 30 to 100, with fiber length ranging from 0.5 to 3.0 inches.

Normally, carbon steel fibers are used in SFRC, but corrosion-resistant alloy fibers are also available. Use of such alloys depends upon cost factors and environmental or other exposure conditions. For example, stainless steel fibers are used in SFRC for most high temperature applications for increased durability (Reference A-16).

2. Glass Fibers

Initial research on glass fiber-reinforced concrete (GFRC) took place in the late 1950s and early to mid 1960s (References A-20, A-21, and A-22). This work used borosilicate glass fibers (E-glass) and soda-lime-silica glass fibers (A-glass). GFRC using A- or E-glass fibers loses strength rapidly due to the strong alkalinity (pH ≥12.5) of the concrete matrix, making it unsuitable for long-term use. However, continued research resulted in the development of alkali-resistant glass fiber-reinforced concrete (AR-GFRC).

AR-GFRC uses glass fibers containing 16-percent zirconia, and was first marketed in 1971 under the trade name "Cem-FIL". Since then, other alkali-resistant glass fibers have been developed by both Japanese and American companies. Alkali-resistant glass fibers are by far the most widely used to reinforce concrete in a wide range of areas, from large size tanks such as swimming pools to roofing system tiles and shingles.

3. Polymeric Fibers

Numerous polymeric synthetic fibers have been used to reinforce concrete. The major fibers currently in use are: (1) polypropylene, (2) polyethylene, (3) polyester, and (4) acrylic. Other types of plastic fibers, such as nylon, aramid, and high-modulus polyethylene are also coming into commercial use. Brief discussions of major polymeric fiber types are given below.

a. Polypropylene Fibers

As indicated in Reference A-23, adding small quantities of polypropylene fibers to concrete (less than 0.5-percent by volume) results in a significant increase in ductility and impact resistance. Since the mid 1960s, polypropylene fibers have been used as a primary or supplementary concrete reinforcement to enhance its material properties, in particular toughness.

Polypropylene is a manmade hydrocarbon polymer, and the fibers are produced by an extrusion process, in which the material is hot-drawn through a die. The draw ratio, i.e. the measure of extension applied to the fiber during fabrication, determines its physical properties. In most cases, fibers are produced as continuous cylindrical monofilaments that are then chopped to the desired lengths.

Polypropylene fibers have several characteristics that make them desirable as concrete reinforcement. The fibers are chemically inert, lightweight, and cost-effective when compared to other types of fibers. Additionally, the fibers are hydrophobic and thus do not absorb water, and consequently do not affect the concrete mix ratio. Some of the fiber's disadvantages are poor chemical bond with the concrete matrix, low melting point, combustibility, and a low modulus of elasticity.

b. Polyethylene Fibers

The Mitsui Petrochemical Industry Company of Japan first developed polyethylene fibers as a reinforcing material for concrete. This development arose from the promising results obtained by incorporating other polymeric fibers, such as polypropylene and nylon, into concrete.

Like polypropylene, polyethylene is also a man-made hydrocarbon polymer. The first type of polyethylene fiber, "Bonfix," was developed by the Mitsui Petrochemical Industry Company. This fiber is a chopped, high-density monofilament with wartlike deformations along its length. These deformations improve the interfacial mechanical bond between the fiber and concrete. This characteristic is important because the fibers exhibit poor chemical bonding with concrete. These fibers are typically 1.6 inches long and 0.04 inches in diameter.

Improved polyethylene fibers that are far superior to "Bonfix" have been developed. For example "Spectra-900" and "Spectra-1000," developed by the Fibers Division of Allied Corporation, have tensile strengths 13 to 15 times greater than "Bonfix," with a modulus of elasticity 24 to 35 times greater. These fiber types are beginning to replace "Bonfix" fibers in the commercial market.

c. Polyester Fibers

The Fiber-Ad Corporation first developed polyester fibers as a reinforcing material for concrete. Polyester fibers are primarily used as a secondary form of reinforcement. For example, low volumes of the fibers are used instead of wire mesh to minimize shrinkage-induced cracking in concrete slabs. Polyester is a synthetic polymer made primarily of ethyl acetate compounds. The fiber is primarily available in monofilament form in choped lengths of 0.75, 1.5, or 2 inches.

d. Acrylic Fibers

Acrylic fiber-reinforced concrete (AFRC) was primarily developed as a replacement for asbestos cement, due to the health hazards associated with asbestos. AFRC uses high fiber volumes to obtain mechanical properties similar to those of asbestos cement (Reference

A-24). Low fiber contents are also being investigated for such uses as slabs on grade (Reference A-25). Acrylic is a manmade synthetic polymer manufactured by several different companies, such as Mosanto, DuPont, and BASF. Trade names of those fibers are Acrilon, Orlon, and Zefran, respectively.

e. Aramid Fibers

Aramid, which is a high-modulus, manmade polymeric material, was first discovered in 1965. Aramid fibers were first produced for commercial applications in the early 1970s. In the late 1970s, aramid fibers were first used as a reinforcing material in concrete. Aramid fibers have a high tensile strength and tensile modulus. They are 2.5 times as strong as E-glass fibers, and 5 times as strong as most steel fibers (Reference A-26). The fibers are marketed under the trade names of Kevlar® and Technora®. Kevlar® 29 and Kevlar® 49 fibers are produced by DuPont, while Technora® HM-50 fibers are produced by Teijin. Aramid fibers are very strong, with excellent strength retention and dimensional stability at high temperatures. Additionally, they have excellent static and dynamic fatigue resistance (References A-22 and A-27).

4. Asbestos Fibers

Use of asbestos fibers to reinforce cement and concrete began in the early 1900s. However, due to the newly recognized hazardous nature of asbestos, alternative fibers, such as acrylic fibers, are replacing asbestos in commercial use. Asbestos is a naturally occurring, fibrous silicate mineral having several different forms. Chrysotile, amosite, and crocidolite are the most commonly used types of asbestos fibers in cement and concrete.

5. Carbon Fibers

Carbon fibers provide very high strength properties and are light in weight. However, their commercial use has been limited by their high cost. Still, laboratory research is being performed on carbon fiber-reinforced concrete (CFRC) to determine its engineering properties (References A-28 and A-29).

Carbon fibers are inert in the presence of most chemicals, and provide high stiffness and tensile strength. The fibers come in two principal types: Type I has a high modulus of elasticity, while Type II has a high tensile strength. These factors are controlled by their material source and the extent of hot-stretching during fabrication. Conventional Type I and Type II fibers are significantly more expensive then other fiber types, such as steel and glass. Low cost types, which are formed from petroleum and coal pitch, are available. But their strength characteristics and modulus are much lower, thus minimizing their commercial use (Reference A-30).

6. Natural Fibers

Natural fibers have been used as a reinforcing material for centuries. Mud bricks reinforced with straw and mortar reinforced with horse hair are but two examples. Engineering properties of natural fibers are being researched currently (Reference A-31). Research is underway because of the desirability of using natural fibers to reinforce concrete in less-developed, third-world countries. In these poor countries, normal reinforcing fibers may be too expensive or unavailable. Development of suitable natural fibers would, in such cases, provide a significant benefit. Natural fibers are readily available in most third-world countries. Extraction and processing can usually be done at reasonable cost, and do not require technical sophistication. Use of these types of fibers may be applicable in Bare Base force projection situations.

Below are brief discussions of some of the more common natural fibers.

a. Wood Cellulose Fibers

Wood cellulose fiber has good mechanical properties compared to some manmade fibers like polypropylene and polyester. Cellulose fibers from high-quality wood with lignin component removed by a chemical pulping process to enhance its strength can have tensile strengths of up to 290 ksi. Cellulose fibers from poorer quality woods have tensile strengths of roughly 73 ksi.

b. Sisal Fibers

Sisal fiber comes from the leaves of the Agave Sisalana. This fiber has a relatively high strength compared to other natural fibers. However, its principal draw back is poor durability. Sisal fibers tend to break down with time when used to reinforce concrete.

c. Coir Fibers

Coir fibers come from coconut husks. They are easily extracted using water to decompose the soft material of the husk. Coir fibers are very durable, but their low modulus of elasticity and sensitivity to changes in moisture reduce their effectiveness as a reinforcing material in concrete.

d. Bamboo Fibers

Research reported in Reference A-31 shows that bamboo fibers can be used successfully to reinforce concrete, either as discrete fibers or continuous rods. The fibers are relatively strong in tension, with a reasonable modulus of elasticity. However, like coir fibers, they are highly susceptible to changes in moisture content causing large volumetric changes. This in turn adversely affects the bond strength between the fiber and concrete matrix. (Reference A-32).

e. Jute Fibers

Jute fibers are extracted from the fibrous bark of the jute plant. Jute fibers are mainly used to make rope and grain-carrying bags. The fiber is relatively strong compared to other natural fibers, and is fairly durable. Because of their desirable characteristics, research on jute fibers as concrete reinforcing is underway (Reference A-31). However, at this time no definitive conclusion can be made on their suitability for reinforcing concrete.

f. Akwara Fibers

Akwara is a dark brown natural stem fiber. Its cross-section may be circular, rectangular, or elliptical. Akwara fibers are dimensionally stable in water, and durable in an alkaline environment. However, use of the fiber to reinforce concrete is limited by its brittleness and low modulus of elasticity.

g. Elephant Grass Fibers

This fiber comes from the leaves of the elephant plant. It is more durable than most natural fibers, and has good rot and alkali resistance. Additionally, it is dimensionally stable when subjected to moisture variations. Initial research into elephant grass fibers to reinforce concrete shows great promise and is being continued (Reference A-33). However, as with jute fibers, no definitive conclusion on the suitability of elephant grass fibers for reinforcing concrete can be made at this time.

7. Fiber-Mat Matrices

A recent innovation in fiber-reinforced concrete is fiber-mat matrices. These are mats of randomly oriented fibers, typically steel, that can be flooded with a grount or slurry to form a structural member with extremely high fiber contents (8- to 12-percent). These matrices can provide engineering properties similar to Slurry Infiltrated Fiber Concrete (SIFCON), while greatly easing constructability (Reference A-1). Constructability is the major concern with SIFCON, because fibers must be placed by hand in a very time-consuming process in order to obtain the desired fiber content in an evenly-distributed fashion throughout the concrete. See Reference A-34 for a discussion of the engineering properties and constructibility issues of SIFCON.

D. FABRICATION OF FIBER-REINFORCED CONCRETE

1. Mixing

Mixing fiber-reinforced concrete can be accomplished by plant-batching, ready-mixing, or hand-mixing, depending on the size of the job. It is critical, regardless of mixing method, to have a uniform dispersion of fibers in the mix, and to prevent balling of the fibers during mixing. Balling during mixing appears most dependent upon the aspect ratio of the fibers, with other important factors being volume percentage of fibers, coarse aggregate size and amount, overall gradation of aggregate, water-cement (W/C) ratio, and method of mixing. In general, higher aspect ratios, volume percent of fibers, and amount of coarse aggregate increase the likelihood of fiber balling. Balling of fibers can be minimized by taking care in the sequence and rate of fiber addition, or using bundled (glued) fibers. Fiber balling in most field applications can usually be traced to over-mixing, poor mix proportions, and/or too high a percentage of fibers for the aspect ratio involved (Reference A-2).

Compared to conventional concrete, fiber-reinforced concrete mixes tend to have higher cement ratios and fine aggregate content, and smaller sized coarse aggregate. These factors cause conventional mix proportioning methods to not be completely applicable. References A-35 and A-36 suggest fiber-reinforced concrete mix proportioning methods for paving and structural applications, respectively. As an alternative, Table A-2 below shows possible trial mixes based on experience.

TABLE A-2. TRIAL MIXES FOR FIBER-REINFORCED CONCRETE (REFERENCE A-2).

Component	Mortar	3/8-Inch Maximum Sized Aggregate	3/4-Inch Maximum Sized Aggregate
Cement (lb/yd^3 of concrete)	700-1,200	600-1,000	500-900
W/C Ratio	0.30-0.45	0.35-0.45	0.40-0.50
Percent Fine To Coarse Aggregate	100 %	45% to 60%	45% to 55%
Entrained Air Content	7% to 10%	4% to 7%	4% to 6%
Fiber Content (Vol. %)			
Deformed Steel Fibers	0.5 to 1.0	0.4 to 0.9	0.3 to 0.8
Smooth Steel Fibers	1.0 to 2.0	0.9 to 1.8	0.8 to 1.6
Glass Fibers	2.0 to 5.0	0.3 to 1.2	-----

2. Placing

Fiber-reinforced concrete requires more vibration during placement to move and consolidate the mix. If possible, external vibration should be used in preference to internal vibration, to minimize the chance of fiber segregation. Working the mix with shovels and hoes is difficult because of the fibers. Consequently, forks and rakes are preferred. Standard screeding methods can be used. It is important to keep the concrete damp during initial curing, because rapid drying can cause cracking before the concrete bond to the fibers is strong enough to prevent cracking. Such cracking will significantly reduce the long-term effectiveness and durability of the concrete (Reference A-2).

Standard quality control test methods, such as slump, air density, and strength tests, are used for fiber-reinforced concrete. However, slump tests must be used with care. Fibers tend to reduce slump. Consequently, reliance on standard slump tests often causes excessive amounts of water to be added to the mix to increase the slump, without noticeably increasing workability. Experience with placing fiber-reinforced concrete under field conditions is the best cure for this problem.

SECTION III

LITERATURE REVIEW: SUMMARY AND PROPOSED TESTING PROGRAM

A. STATE OF RESEARCH

1. Major Sources

Research on fiber-reinforced concrete has been rapidly expanding in the past 10 years. Hundreds of articles and papers have been published recently. In the last 30 years, literally thousands of papers and articles have been published. Consequently, before an efficient literature review could be conducted, its scope had to be defined to limit the amount of data that had to be reviewed to a reasonable level. Since the main thrust of this research effort is to develop a fiber-reinforced concrete for use in hardened shelter construction that saves weight and cost, versus currently-used doubly-reinforced concrete, while maintaining or possibly improving performance, it was decided to concentrate the literature review on fiber-reinforced concrete structural and design issues. Particular emphasis was placed on the use of fibers along with standard rebar reinforcement in concrete. Additionally, the literature review, while not disregarding older research, concentrated on articles, papers, and books published in the last 10 years.

Based on the review criteria given in the preceding paragraph, the papers, articles, and books listed below were reviewed in detail.

1. Al-Ausi, M.A., et.al., "Effect of Fibers on the Strength of Reinforced Concrete Beams Under Combined Loading," International Conference on Recent Developments in Fiber Reinforced Cements and Concretes, University of Wales College, UK, 18-20 September 1989.

2. Allos, A.E., "Shear Transfer in Fiber Reinforced Concrete," International Conference on Recent Developments in Fiber Reinforced Cements and Concretes, University of Wales College, UK, 18-20 September 1989.

3. Batson, G., Terry, T., and Chang M-S., "Fiber Reinforced Concrete Beams Subjected to Combined Bending and Torsion," ACI SP-81, American Concrete Institute, 1984.

4. Craig, R.J., "Flexural Behavior and Design of Reinforced Fiber Concrete Members," ACI SP-105, American Concrete Institute, 1987.

5. Craig, R.J., et.al, "Torsional Behavior of Reinforced Fibrous Concrete Beams," ACI SP-81, American Concrete Institute, 1984.

6. Craig, R.J, et.al., "Behavior of Reinforced Fibrous Concrete Columns," ACI SP-81, American Concrete Institute, 1984.

7. Craig, R.J., et.al., "Behavior of Joints Using Reinforced Fibrous Concrete," ACI SP-81, American Concrete Institute, 1984.

8. Jindall, R.L., and Sharma, V., "Behavior of Steel Fiber Reinforced Concrete Knee-Type Beam-Column Connections," ACI SP-105, American Concrete Institute, 1987.

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In addition to the sources listed above, many other articles, papers, and books were reviewed. However, the above listed sources provided the most information applicable to this research effort.

2. Major Findings And Research Shortfalls

a. Major Findings

Based on the review of the literature cited above, and other sources, three major areas were identified in which fiber-reinforced concrete can provide a benefit to hardened structure construction. Each of these areas is discussed below.

(1) Rebar Reinforcement Replacement

Standard hardened structural construction uses symmetrically, doubly reinforced concrete members. Reference A-14 indicates that using fiber reinforcement may eliminate the need for compression rebar and shear reinforcement such as stirrups in such members without sacrificing performance. However, based on reviewed literature, it is doubtful that fiber reinforcement will allow the elimination of tension rebar reinforcement.

Partial or total replacement of compression and shear reinforcement provides two primary benefits to hardened structural construction. The first is a weight saving in concrete structural members, which is critical if modular/prefabricated construction is used. Weight saving in structural members is also critical for airmobile hardened structures. The second area is cost saving, which is always an issue with hardened structure construction regardless of type.

(2) Toughness

The second area of benefit pertains to increasing the toughness of the concrete used in the construction of hardened structures. The reviewed literature, for example References A-14, A-37, A-38, and A-39, indicates that inclusion of fibers in concrete, with and without standard rebar reinforcement, increases the area under the concrete's load-deflection curve. By various methods, the area under the curve is used to measure a material's toughness. One such method, developed by the American Society for Testing and Materials, ASTM C-1018-89, "Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)", is shown below in Figure A-2.

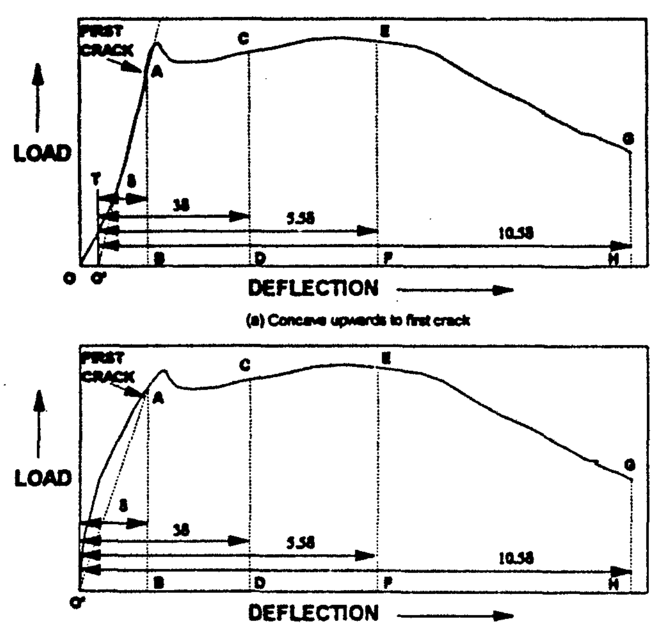

Figure A-2. Calculation Of ASTM C 1018-89 Toughness Indices From Load-Deflection Curves.

The areas under the curves shown in Figure 2, defined by the points "O'AB", "O'ACD", "O'AEF", and "O'AGH", are calculated. Then the area "O'ACD" is divided by the area "O'AB" to obtain toughness index I_5 . This process is continued for the other areas, always dividing by area "O'AB", to obtain toughness indices I_{10} for area "O'AEF" and I_{20} for area "O'AGH", respectively. Additionally, residual strength factors (R) are calculated as: $R_{5,10} = 20(I_{10}-I_5)$ and $R_{10,20} = 10(I_{20}-I_{10})$. These indices and factors can then be used to compare the relative toughness of different concretes. Inclusion of fibers in the concrete tends to increase both the toughness indices and residual strength factors.

By increasing the toughness of the structural members used in the construction of a hardened structure, the structure is more likely to withstand large deformations caused by blast effects and/or dynamic impacts without catastrophic failure. Obviously this is a critical consideration in the design of hardened structures.

(3) Spalling

The final area of benefit in using fiber-reinforced concrete in hardened shelter construction is the minimization of spalling. Inclusion of fiber reinforcement significantly reduces the chance of spalling when concrete is subjected to dynamic impacts or blast effects (References A-40 and A-41). Spalling of the inside wall of a hardened structure from blast and/or dynamic impacts poses a significant hazard to personnel and equipment within the structure. Fibers help keep pieces of concrete that try to breakoff due to blast and/or impact effects attached to the inside wall. In some cases, pieces of concrete may even be hanging loose from the wall, solely attached by several fibers. Minimizing spalling is another critical consideration in the design of hardened structures.

b. Research Shortfalls

Throughout the reviewed literature, there were two areas identified in which research was lacking. The first is the use of fiber reinforcement in high compressive strength concrete ($f'_c \geq 8{,}000$ psi). Concrete strength in the reviewed literature ranged from a low of 3,000 psi to slightly over 7,000 psi. These are the strengths of concrete typically found in commercial construction. No data at higher strengths was found during the literature review.

The second area where research is lacking is the use of fibers in lightweight structural concrete. Some work has been done on using fibers in lightweight, non-structural concrete to control cracking, such as in decorative concrete building adornments. However, the weight of structural concrete in all the reviewed literature fell in the standard range of 140 to 160 pounds per cubic foot (pcf). This is well outside the typical range of lightweight structural concrete of 115 to 140 pcf.

Except for the two major areas mentioned above, research efforts on the engineering properties, applications, design, etc., of fiber-reinforced concrete have been very thorough and are ongoing by various universities, companies, institutes, and associations.

B. Fiber-Reinforced Concrete Design Method Overview

A brief overview of the flexural design of reinforced concrete members using standard reinforcement in combination with fiber reinforcement is given below. For much more detailed discussions of this subject see References A-13, A-14, and A-15.

Numerous design methods have been proposed for a combined fiber and rebar reinforced structural member. Some of these include the Williamson method, the Henager and Doherty method, and Swamy and Al-Ta'an method. In general, all of these methods are based on ACI ultimate strength design concepts. The methods differ somewhat in assumptions with regard to the strain diagram, stress block shape and depth, maximum usable strain, etc. However, each basically modifies the force diagram to account for the contribution of the fibers in the tension zone of the concrete. The ultimate moment is then the sum of the couples involving the fibers in the concrete tension zone and the reinforcing bars.

Comparison of the different methods shows that they produce similar results (see Reference A-14). However, comparison of the results from each method with experimental data shows they are about 15-percent conservative. This difference is mainly attributable to not taking into account strain hardening ($\varepsilon_{steel} > \varepsilon_y$) occurring in the reinforcing steel (fibers and rebar).

In conclusion, the basic design of fiber- and rebar-reinforced concrete members does not differ significantly in method or complexity from the design of standard reinforced concrete members. Adequate methods are currently available, which while conservative, provide reasonable accuracy. Additionally, design methods are steadily being improved.

C. PROPOSED TESTING PROGRAM

1. Emphasis and Goal

The emphasis of the proposed testing program for this research effort is on lightweight ($\approx$ 115-140 pcf), high-strength ($f_c' \geq$ 8,000 psi) concrete with various combinations of fibers (types, volumes, and lengths) and/or rebar (steel and fiberglass) reinforcement. Several test methods and specimen sizes will be used.

The goal of the testing program is to develop a fiber/rebar combination that will allow the reduction or elimination of compression and shear reinforcement, while providing at a minimum the same level of strength and toughness as current hardened construction design methods using doubly reinforced concrete members.

2. Test Program Phases

The proposed testing program consists of three test phases. Each test phase is described below.

a. Test Phase I

(1) Objective

Determine the performance of doubly-reinforced beams (baseline) versus fiber-only reinforced beams. The baseline doubly-reinforced beam will be designed to standard hardened structure criteria.

(2) Fibers

Steel, nylon, and steel-mat-matrix fibers will be used in this testing phase.

(3) Test Method/Method Of Comparison

Load-Deflection curves of the beams will be used to compare the relative performance of the doubly-reinforced baseline beams versus the fiber-only reinforced beams. The MTS machine of AFCESA/RACO will be used to generate the curves. Toughness indices and residual strength factors, as defined by the previously described ASTM C 1018-89, will be calculated for each beam type. Based on these indices and factors, the relative performance of each beam type will be assessed.

(4) Test Beam Size And Configuration

The beam size and configuration for load-deflection curve testing to determine material toughness in this testing phase is shown below in Figure A-3.

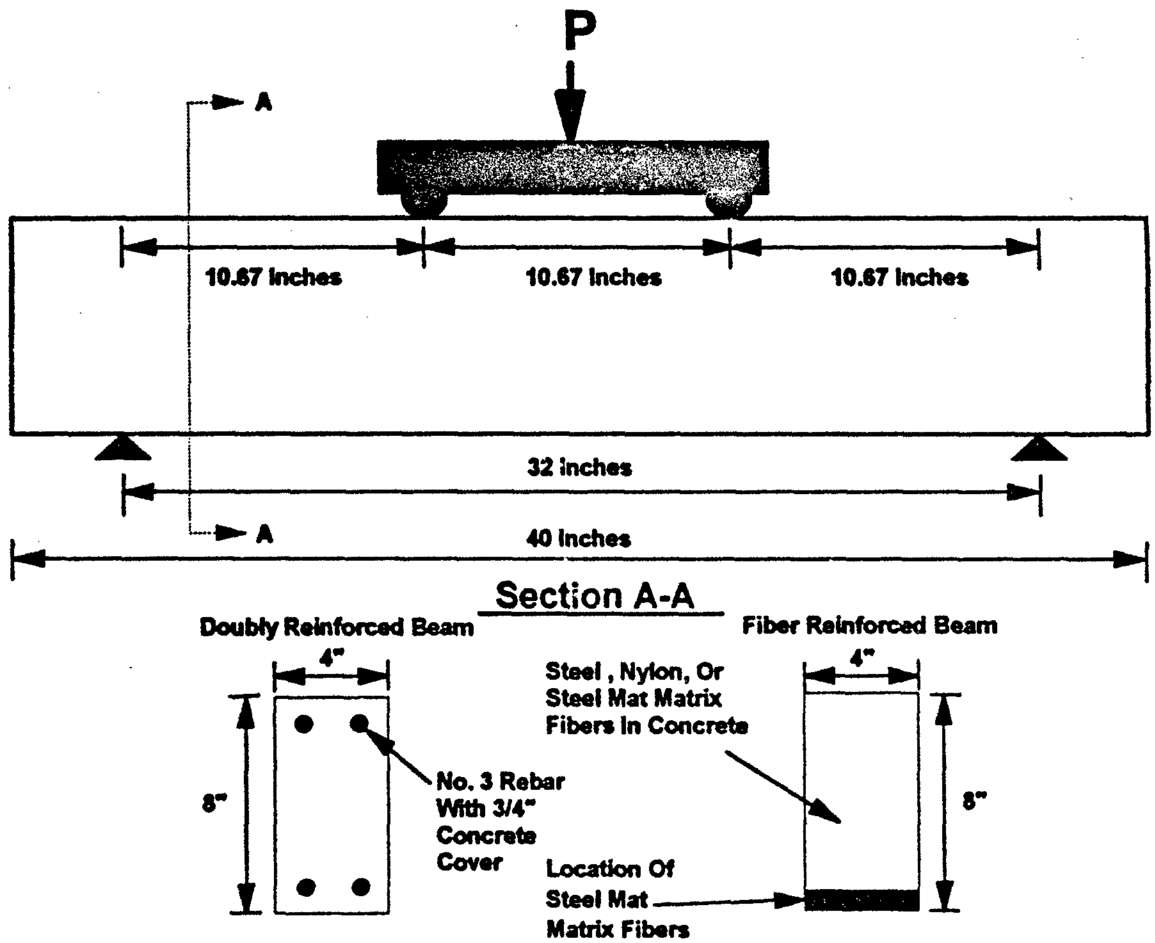

Figure A-3. Beam Size And Configuration, Test Phase I.

As seen in Figure A-3, the test beams are 8 inches deep, 4 inches wide, and 40 inches long. The span-to-depth ratio (L/D) is 4. As previously mentioned, loading to obtain load-deflection curves will be done following ASTM C 1018-89 and other similar standards.

(5) Tests

The following tests will be conducted: (1) three standard, doubly-reinforced beams, (2) three steel fiber-reinforced beams (high fiber content), (3) three nylon fiber-reinforced beams (high fiber content), and (4) three steel-mat-matrix-fiber-reinforced beams.

b. Test Phase II

(1) Objective

Determine several candidate best fiber types for hardened shelter construction, while maximizing fiber content. No rebar reinforcement will be used in test specimens during this phase.

(2) Fibers

Various organic, metallic, inorganic, and hybrid fibers will be investigated.

(3) Test Method/Method Of Comparison

Some or all of the following tests will be accomplished to determine the relative performance of each fiber type: flexural strength by third-point loading, compression strength, splitting-tensile strength, instrumented impact (if equipment is available), compact shear, and split-hopkinson bar. Testing will be accomplished following applicable guidelines and standards.

(4) Test Beam Size And Configuration

For flexural strength and instrumented impact testing, 4- by 4- by 16-inch beams will be used. For compression strength, splitting-tensile strength, and compact shear, 4- by 8-inch cylinders will be used. For split-hopkinson bar testing 2- by 2-inch cylinders will be used.

(5) Tests

Three beams/cylinders of each fiber type will be tested for each utilized test method.

b. Test Phase III

(1) Objective

Using the two best fiber candidates from Test Phase II, determine whether compression and shear steel in a reinforced concrete beam can be replaced by fibers, while at the same time providing the same ultimate strength and toughness of the baseline doubly-reinforced beam from Test Phase I.

(2) Fibers

The two best-performing fibers determined from Test Phase II will be used.

(3) Test Method/Method Of Comparison

Load-Deflection curves of the beams will be used to compare the relative performance of the two fiber types with different combinations/amounts of rebar reinforcement. As previously mentioned, in some cases, fiberglass rebar will be used instead of steel. Toughness indices and residual strength factors will be calculated for each beam type (fiber and rebar combination). Based on these indices and factors, the best performing fiber/rebar combination will be determined. The general testing process is illustrated below in Figure A-4.

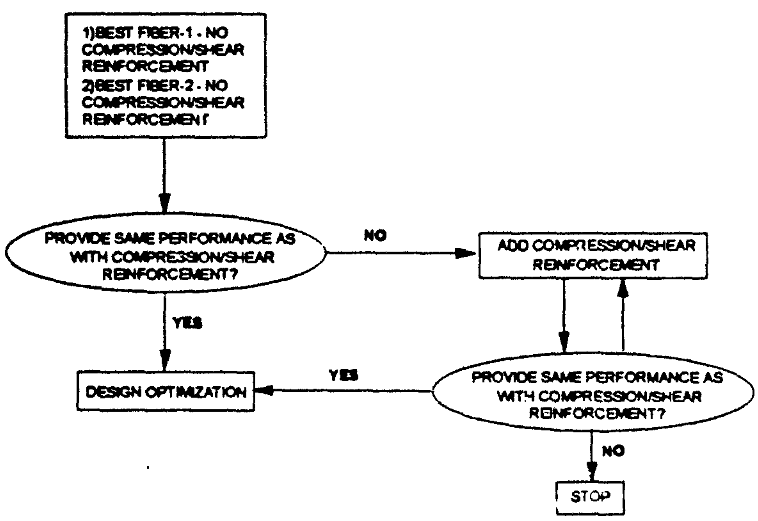

Figure A-4. Test Phase III Beam Optimization Process.

(4) Test Beam Size And Configuration

The beam size and configurations for load-deflection curve testing to determine material toughness in this testing phase are shown below in Figure A-5.

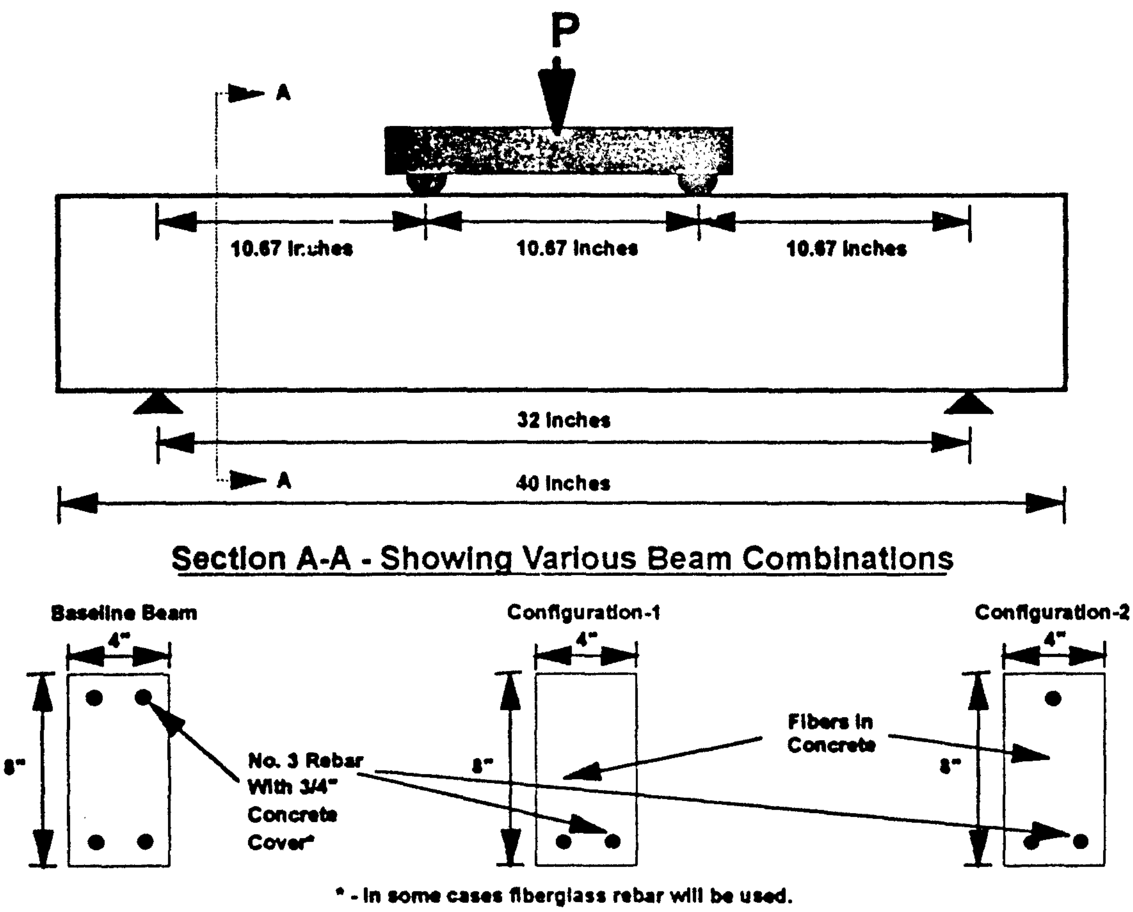

Figure A-5. Beam Size And Configuration, Test Phase III.

As in Test Phase I, the test beams are 8 inches deep, 4 inches wide, and 40 inches long. The span-to-depth ratio (L/D) is 4. The various rebar and fiber configurations to be tested are shown in the figure. Loading to obtain load-deflection curves will once again be done following ASTM C 1018-89 and other similar standards. However, when rebar is used, with or without fiber reinforcement, the specified mid-span deflection rate in ASTM C 1018-89 of 0.002 to 0.004 inches per minute will be changed to 0.1476 inches per minute (0.00246 in/sec) as recommended in Reference A-13. This deflection rate change is made in order to get reasonable test times. If the slower rate is used, test times can range between 2 to 3 hours per beam to obtain a sufficiently long load-deflection curve. This problem is caused because ATSM C 1018-89 was designed principally to test beams reinforced with fibers only. Inclusion of rebar reinforcement in combination with fiber reinforcement substantially increases the toughness of the beams, thereby dramatically increasing the length of the load-deflection curve required to obtain the specified toughness indices. Consequently, the deflection rate must be increased to obtain reasonable test times. This problem is not a significant factor in Test Phase I, because so few beams will be tested. However, in this test phase many more beams will be tested, necessitating the quicker rate.

(5) Tests

Three beams of each fiber/rebar combination will be tested.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

A great deal of research has been done, and is continuing to be done, on fiber-reinforced concrete. Literally thousands of articles, papers, and books have been published in the last 40 years, with the pace of the research increasing dramatically in the last 10 years. The scope of the research is very broad, covering such areas as construction applications, design, fabrication, impact/blast resistance, mechanical/engineering properties, computer modeling, etc.. The scope of the research is continuing to expand. Many different types of fibers, for example steel, polyester, nylon, glass, and natural fibers, are being investigated, along with different types of cement/concrete matrices.

Reviewed literature indicates that the use of fiber reinforcement in commercial construction applications will become common practice within the next 10 years. The reasons for this are many, with decreased cost due to stronger, smaller structural members, cracking control, and increased life span of structures and pavements due to increased material toughness and fatigue resistance being just a few. Additionally, the commercial uses of fiber-reinforced concrete are continuing to increase as practical, validated design methods become more available and better known. Research continues to develop such design concepts. In large part, these methods are based on ACI ultimate strength design methods, with appropriate modifications to account for the increased strength of the concrete in the tensile zone caused by fibers bridging and resisting cracking.

The literature review uncovered two areas where research is lacking. The investigation of lightweight (115 to 135 pcf) concrete with fiber reinforcement is one area . The other area is the the use of fiber reinforcement with high compressive strength ($f_c' \geq 8{,}000$ psi) concrete. Both of these areas appear to hold promise and should be investigated.

In summary, fiber reinforcement, combined with standard reinforcement, holds promise to dramatically increase the material toughness of concrete. This possibility, when combined with the ongoing development of design methods for concrete incorporating fibers with standard reinforcement, indicates the use of fiber reinforcement is a viable option in hardened structure design and construction. Use of fiber reinforcement may allow a reduction in the weight and cost of hardened structures, while maintaining, or possibly improving their performance with respect to blast and impact resistance. Weight reduction of concrete structural members is critical for the development of both modular, rapidly erectable hardened structures and airmobile hardened structures. Cost reduction of hardened structures is always an issue, especially today with decreasing defense budgets.

B. RECOMMENDATIONS

The test program outlined in this report should be conducted to investigate the feasibility of using lightweight, high-strength, fiber-reinforced concrete in hardened shelter construction. Specifically, determine if the amount of compression and shear reinforcement currently used in hardened structures can be reduced, or possibly eliminated, while not reducing performance as measured by material toughness, and at the same time providing less costly, lighter weight concrete structural members.

If fiber-reinforced concrete proves attractive for hardened shelters, a follow-on effort should be undertaken to develop design guidelines and procedures leading to full-scale field testing and eventual fielding.

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APPENDIX-B

STRESS-STRAIN CURVES FROM CONCRETE CYLINDER COMPRESSION TESTS

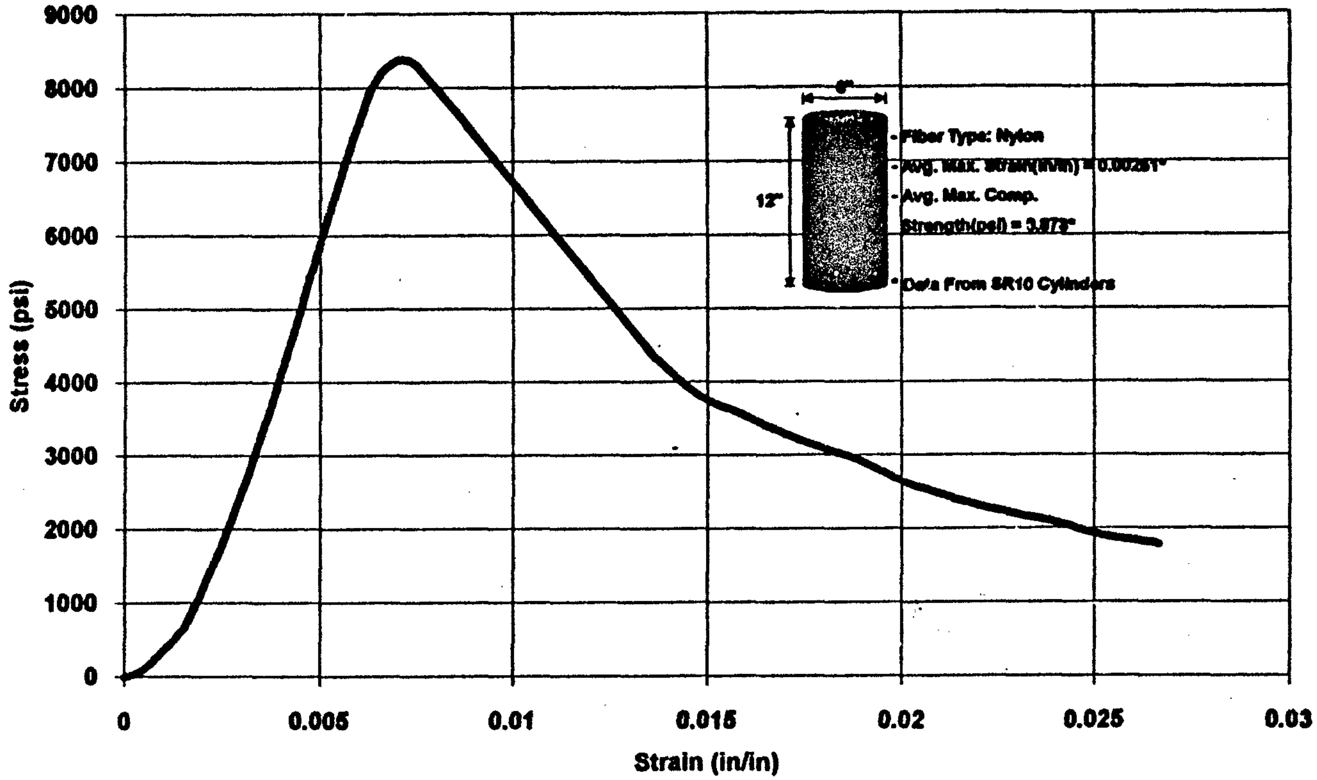

Figure B-1. Cylinder Stress-Strain Curves For Beam Type F1.

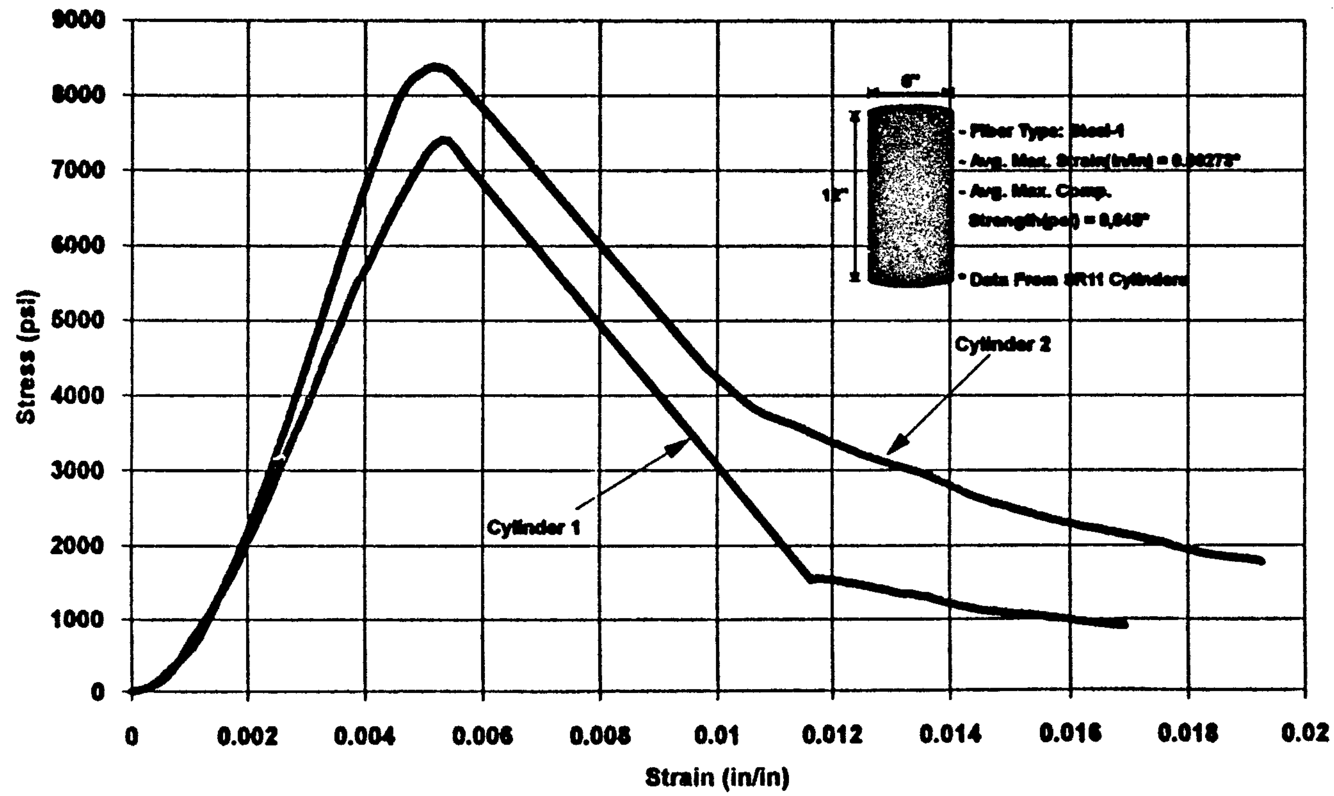

Figure B-2. Cylinder Stress-Strain Curves For Beam Type F2.

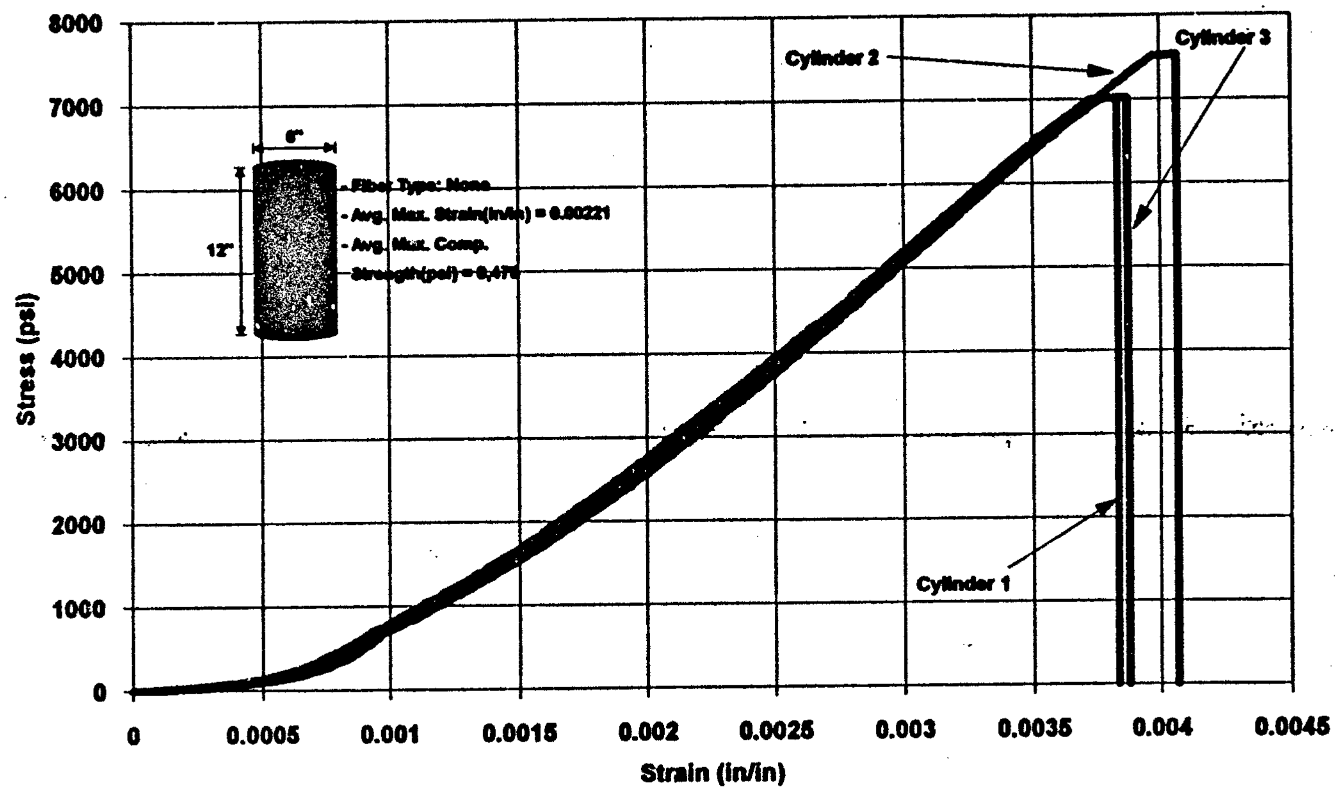

Figure B-3. Cylinder Stress-Strain Curves For Beam Type SR1.

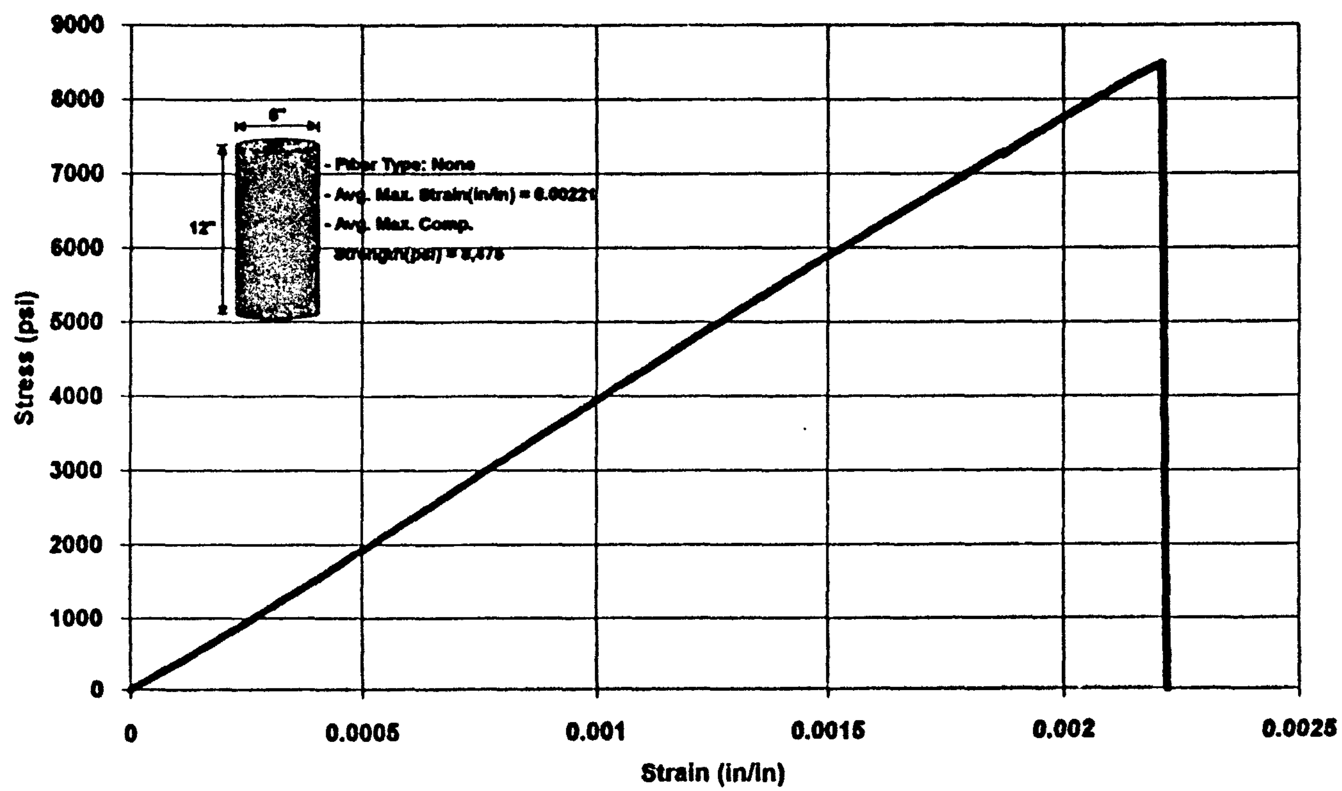

Figure B-4. Cylinder Stress-Strain Curve For Beam Type SR2.

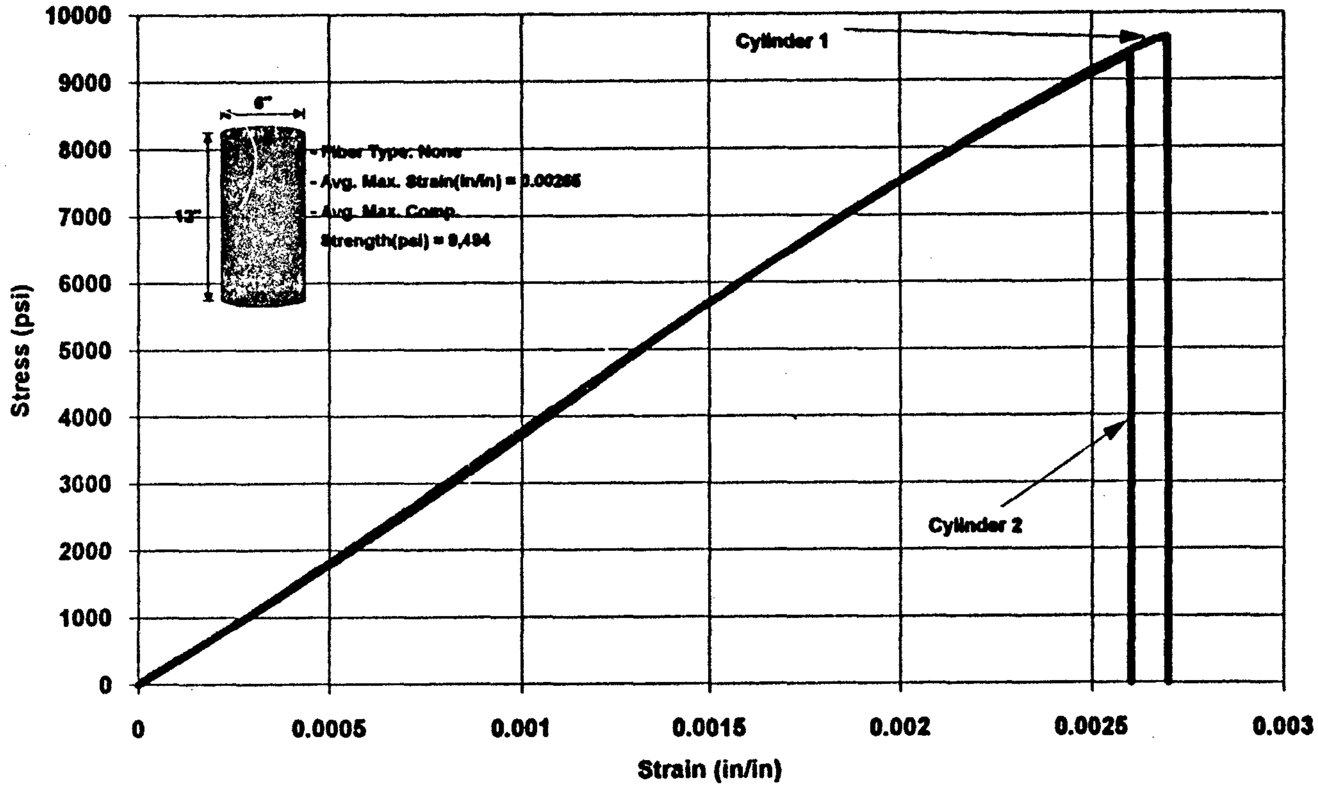

Figure B-5. Cylinder Stress-Strain Curves For Beam Type SR3.

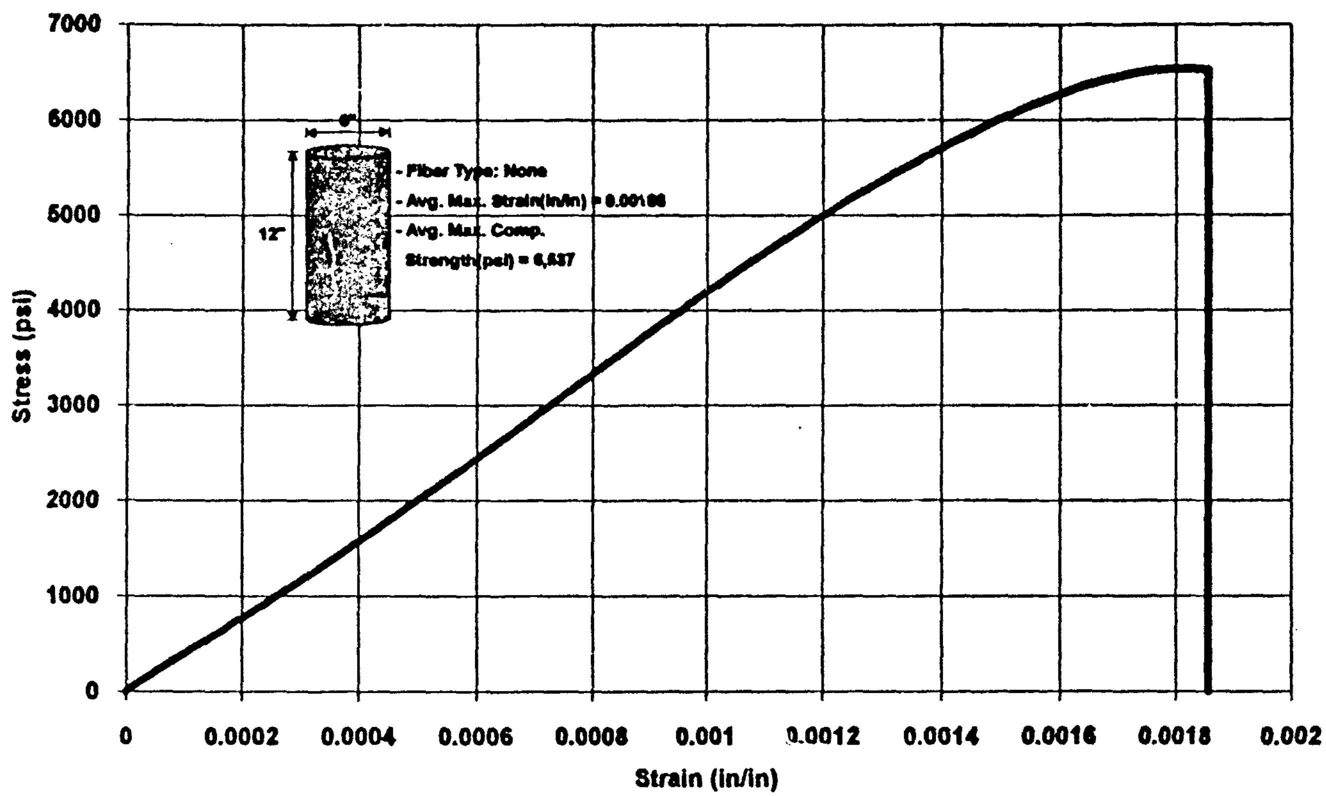

Figure B-6. Cylinder Stress-Strain Curves For Beam Type SR4.

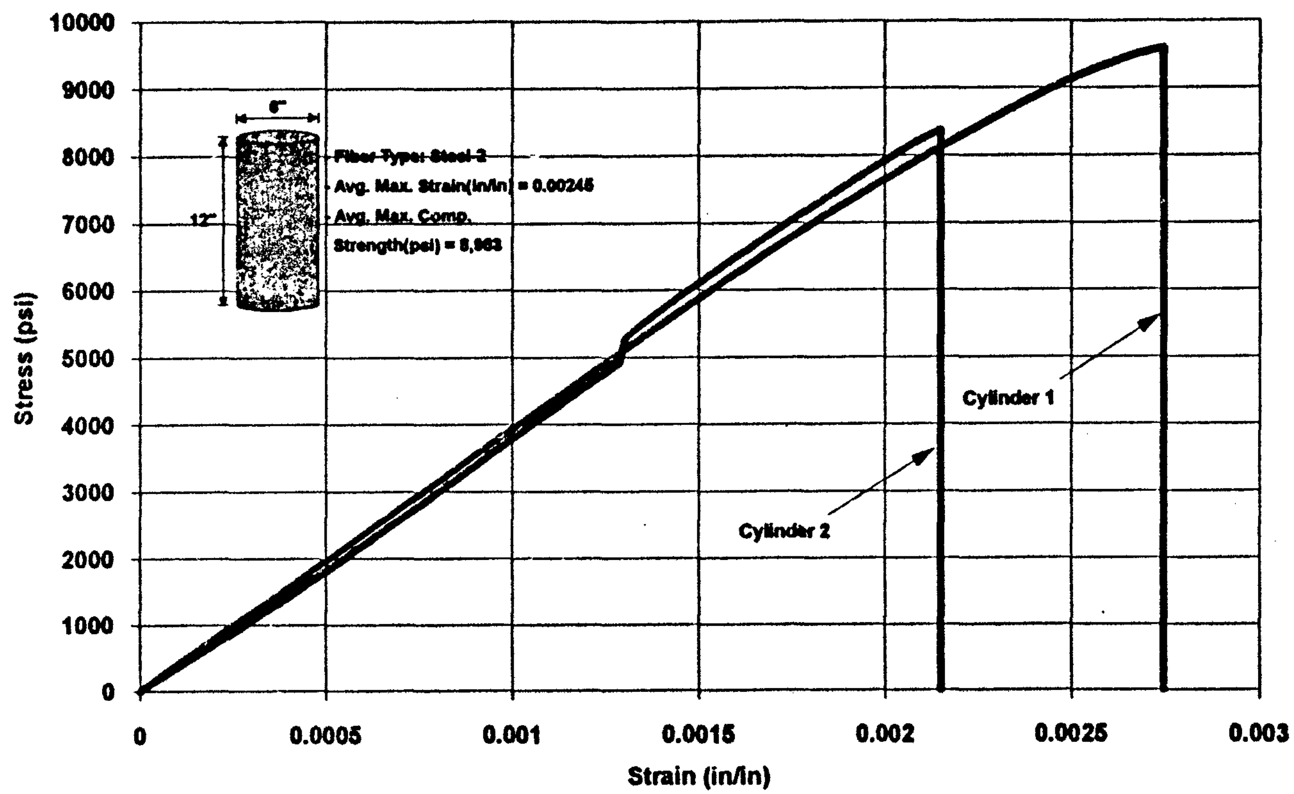

Figure B-7. Cylinder Stress-Strain Curves For Beam Type SR5.

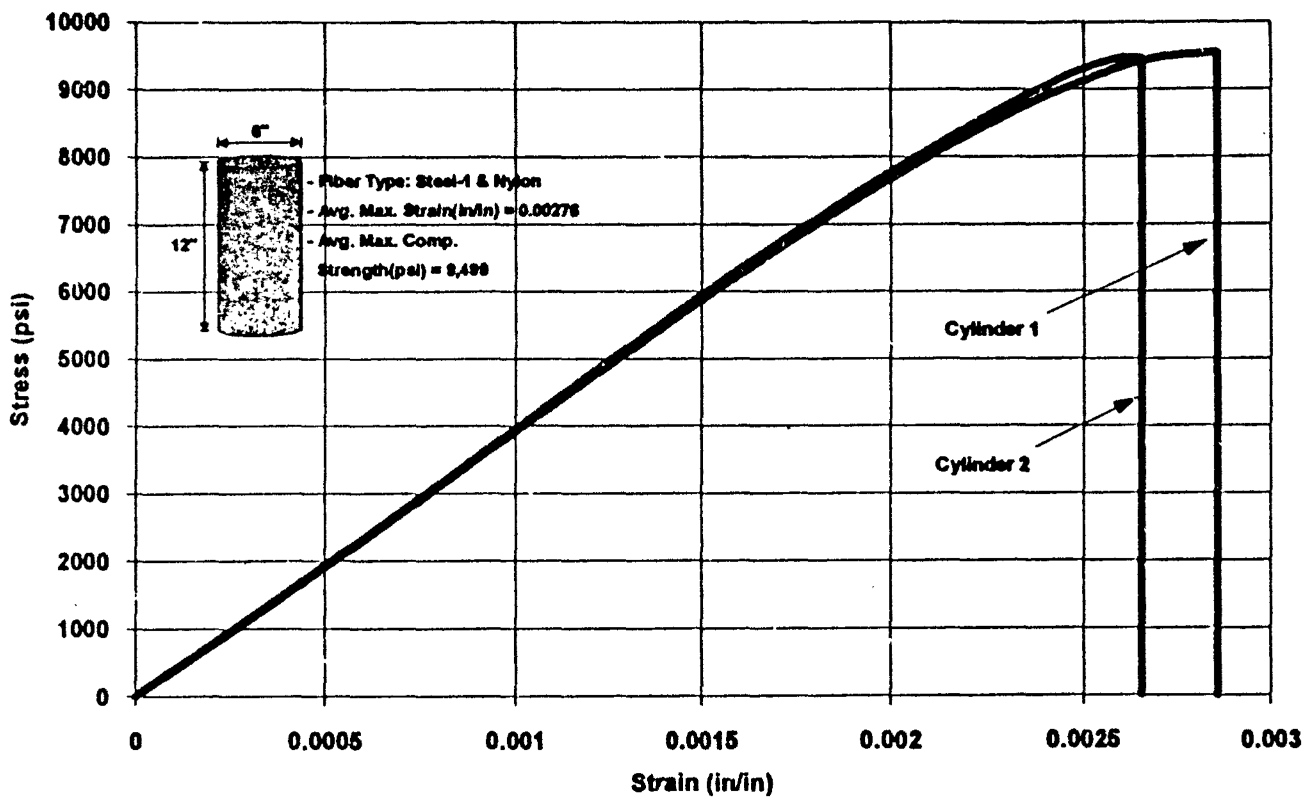

Figure B-8. Cylinder Stress-Strain Curves For Beam Type SR6.

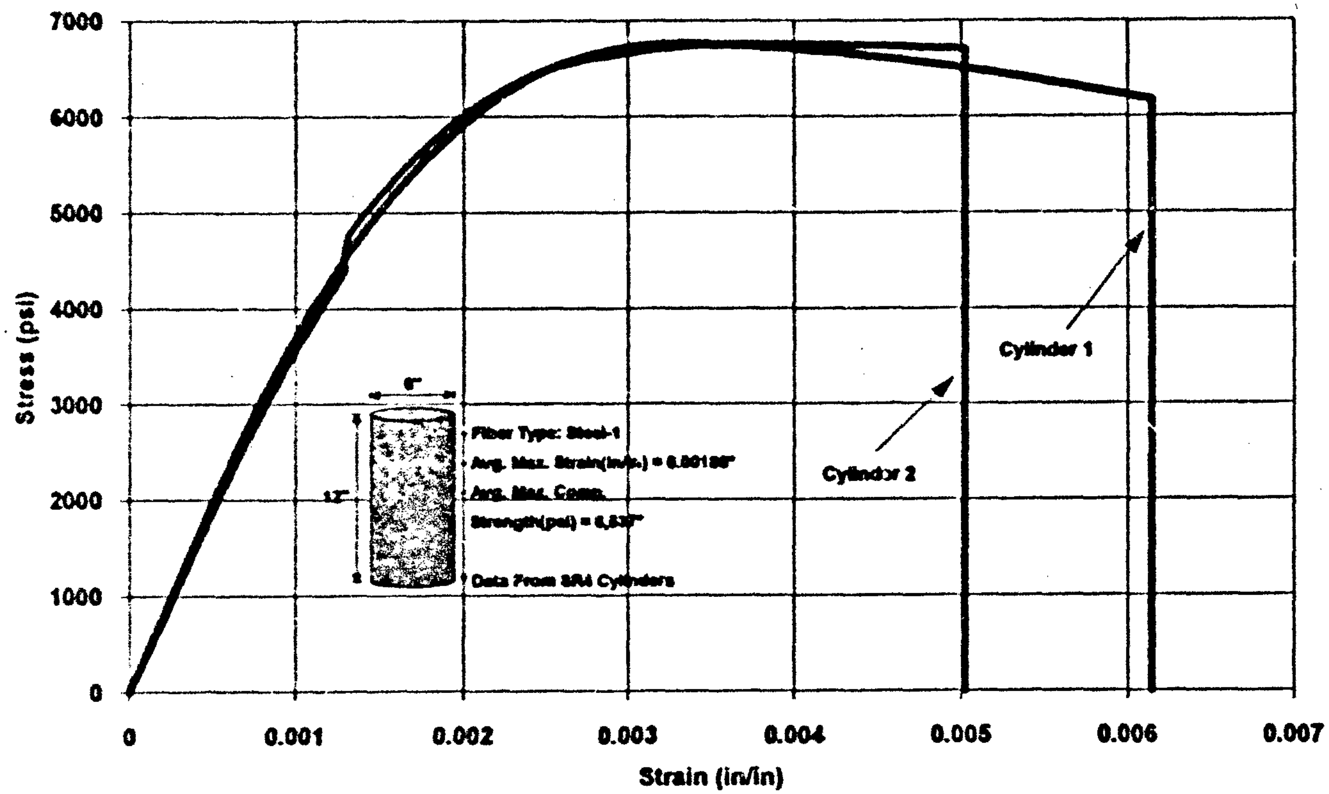

Figure B-9. Cylinder Stress-Strain Curves For Beam Type SR7.

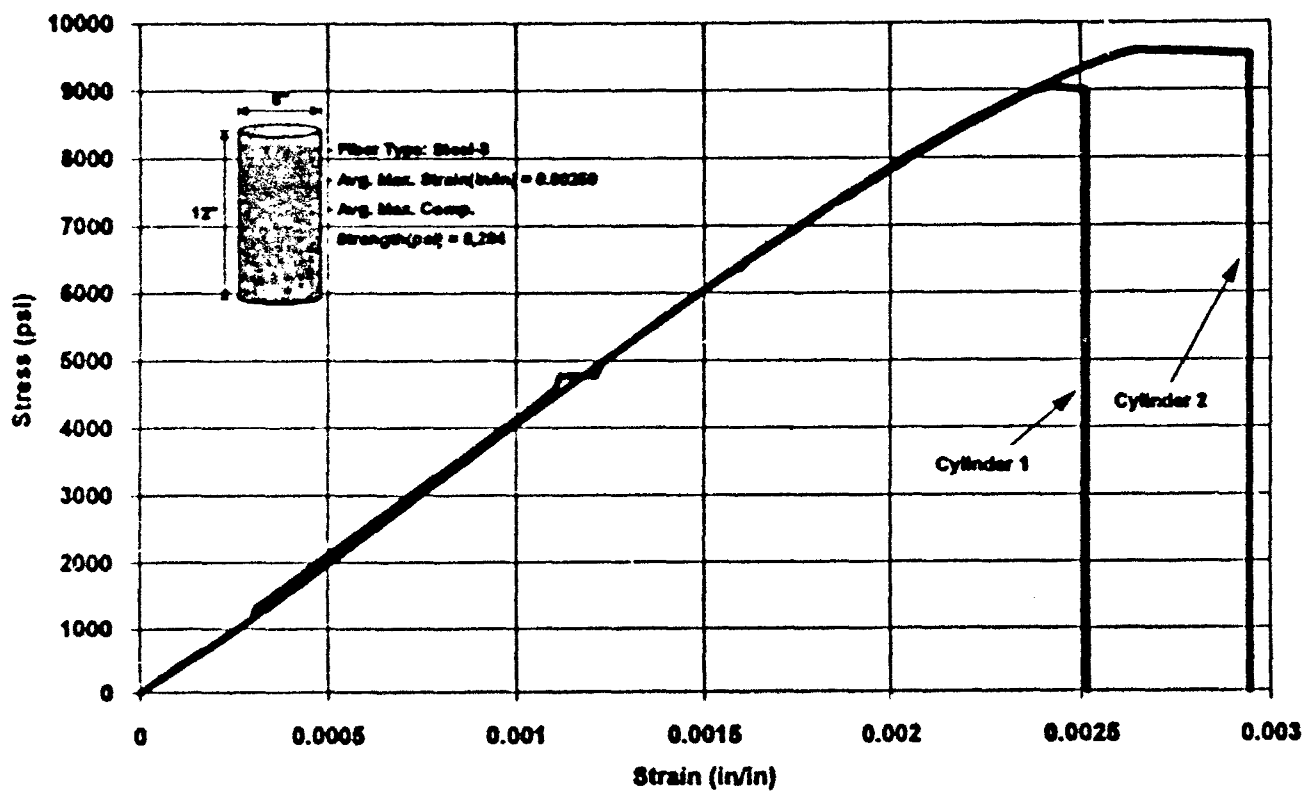

Figure B-10. Cylinder Stress-Strain Curves For Beam Type SR8.

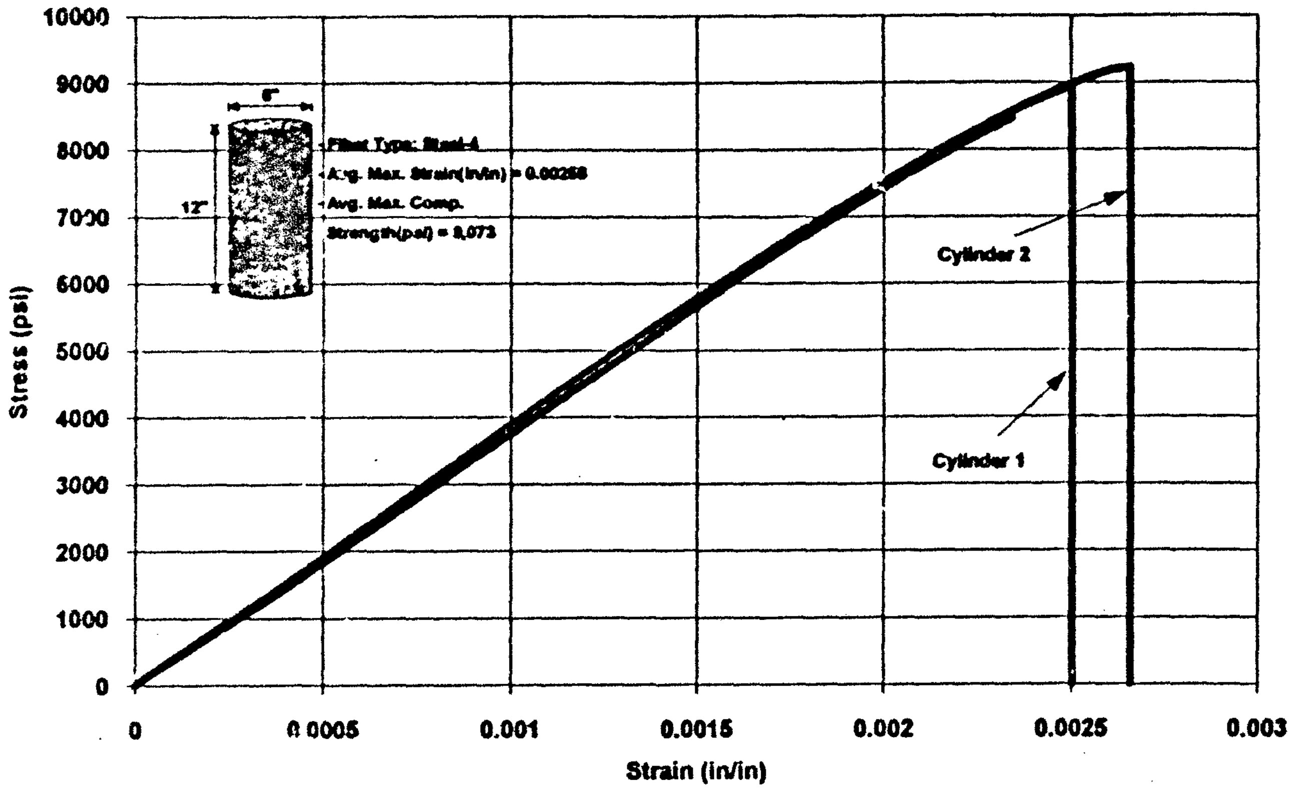

Figure B-11. Cylinder Stress-Strain Curves For Beam Type SR9.

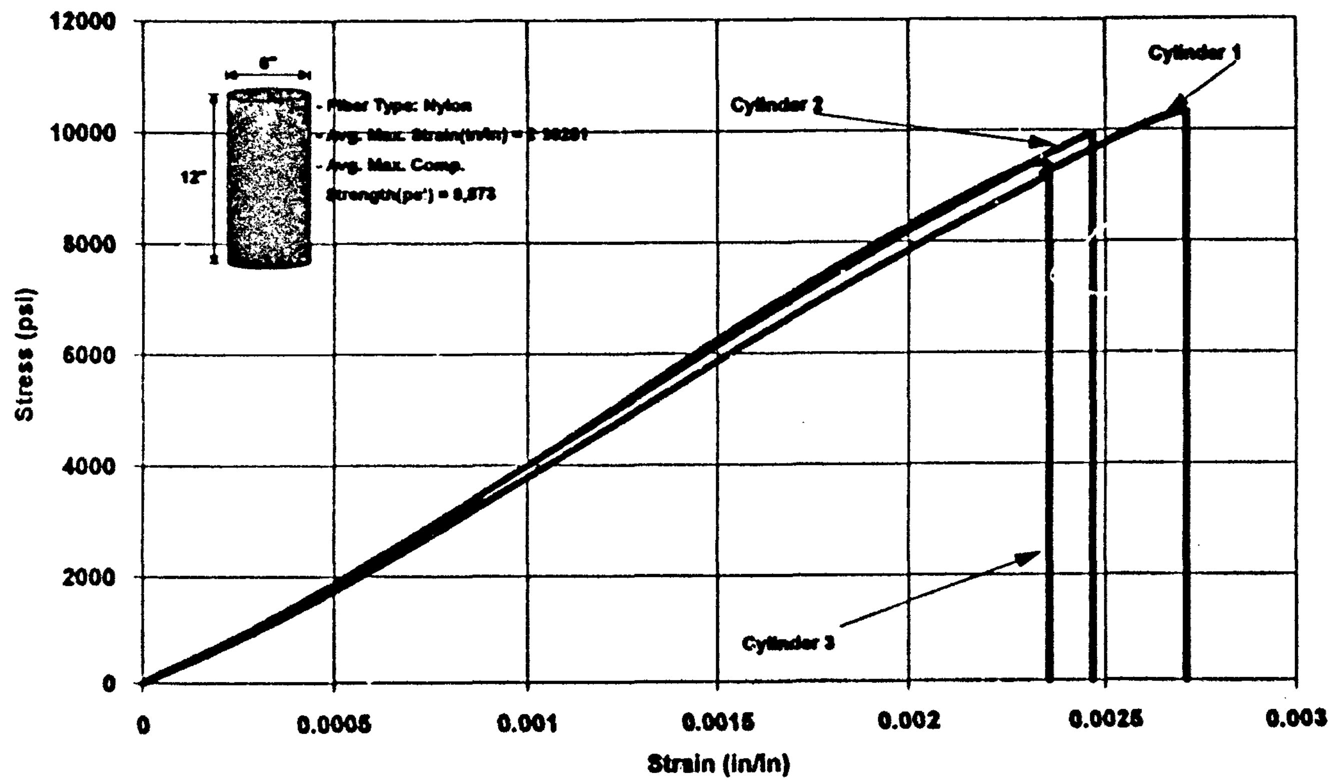

Figure B-12. Cylinder Stress-Strain Curves For Beam Type SR10.

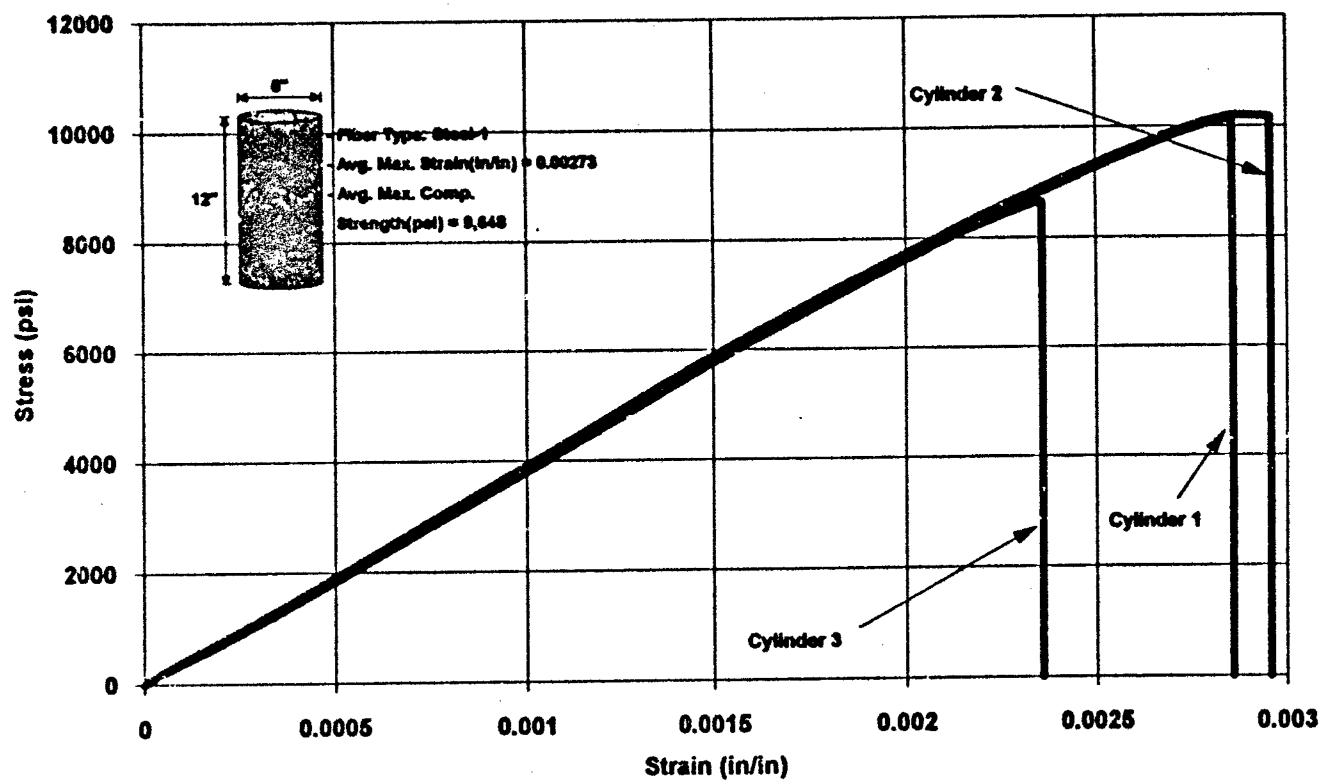

Figure B-13. Cylinder Stress-Strain Curves For Beam Type SR11.

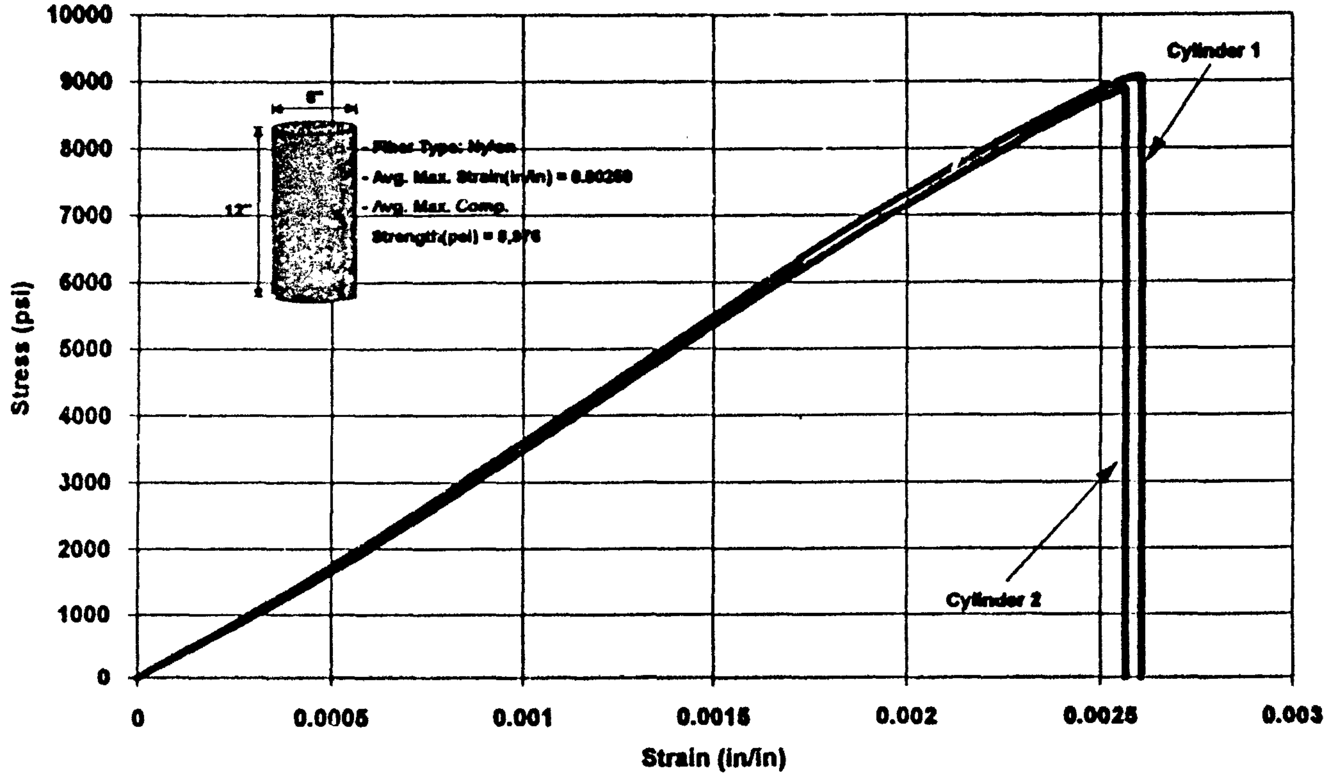

Figure B-14. Cylinder Stress-Strain Curves For Beam Type FR1.

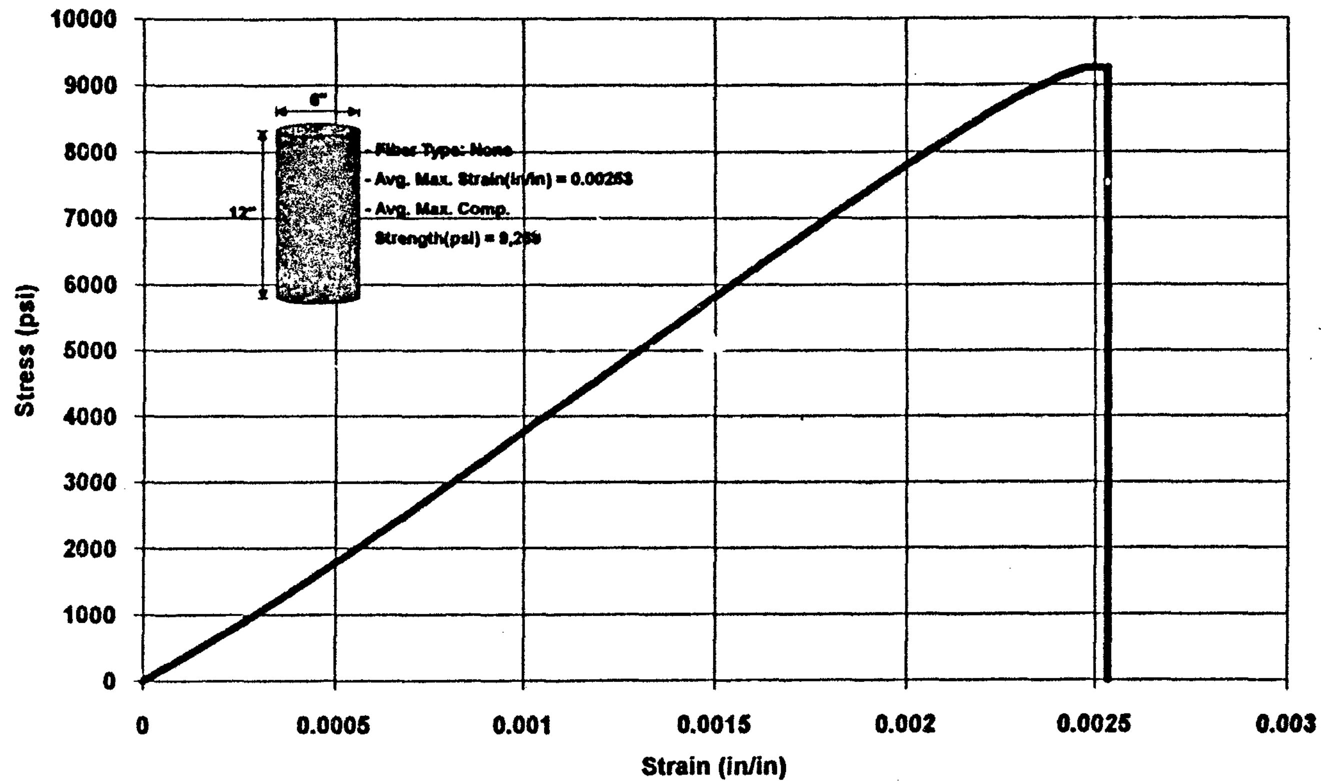

Figure B-15. Cylinder Stress-Strain Curve For Beam Type FR2.

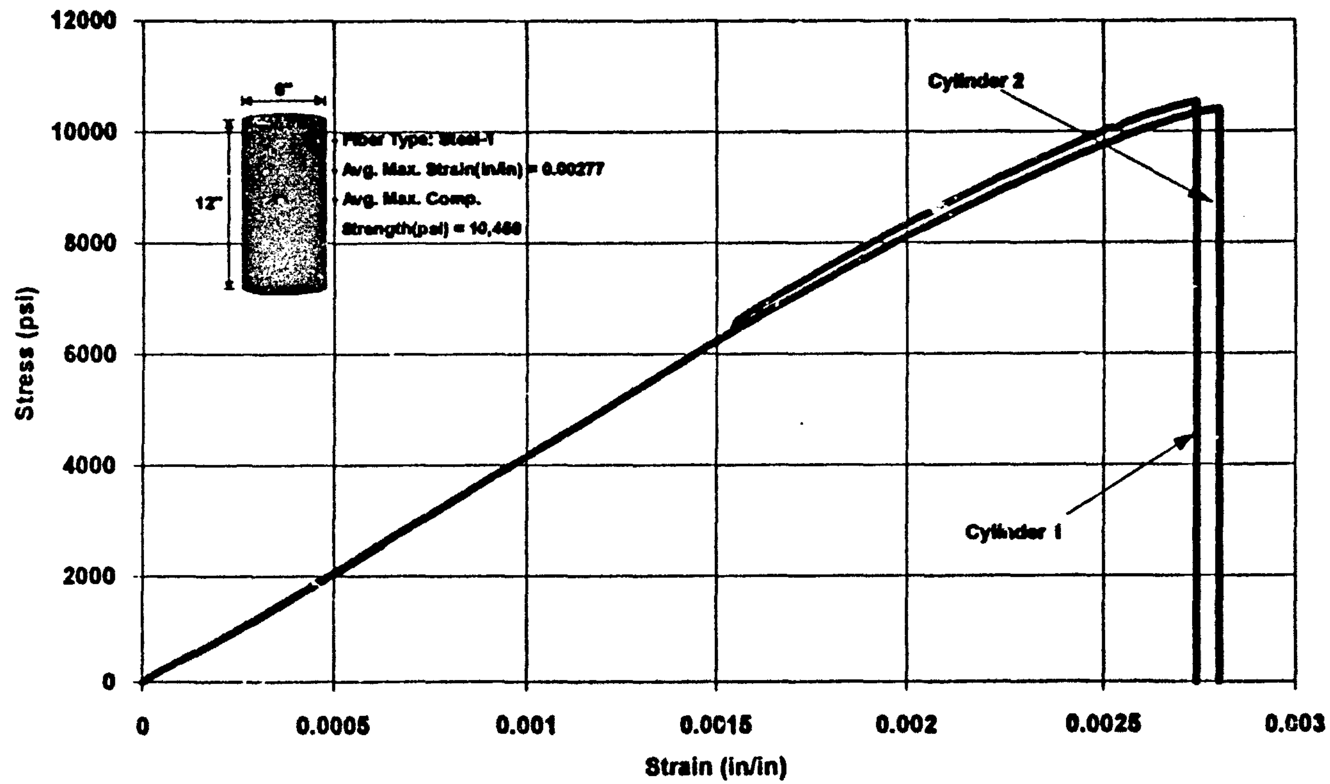

Figure B-16. Cylinder Stress-Strain Curves For Beam Type M1.

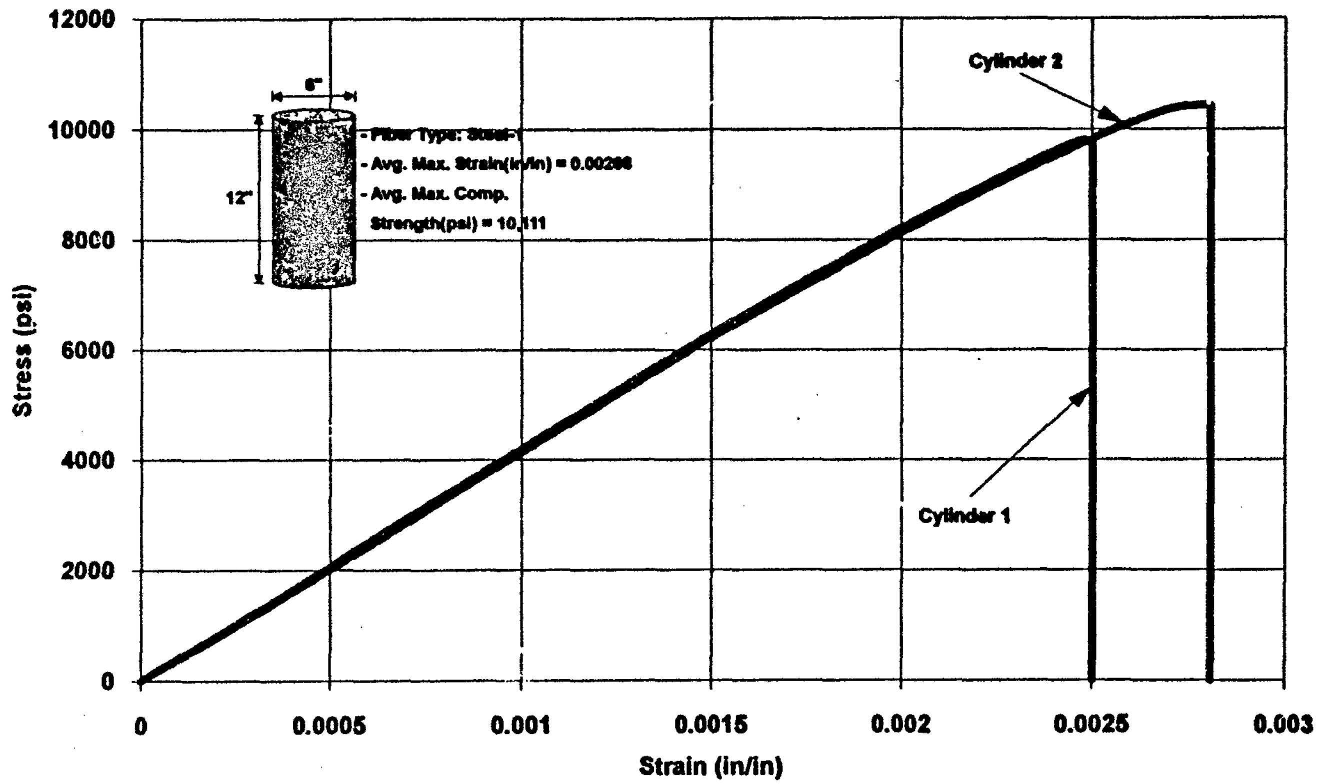

Figure B-17. Cylinder Stress-Strain Curves For Beam Type M2.

APPENDIX C

LOAD-DEFLECTION CURVES FROM FLEXURAL BEAM TESTS

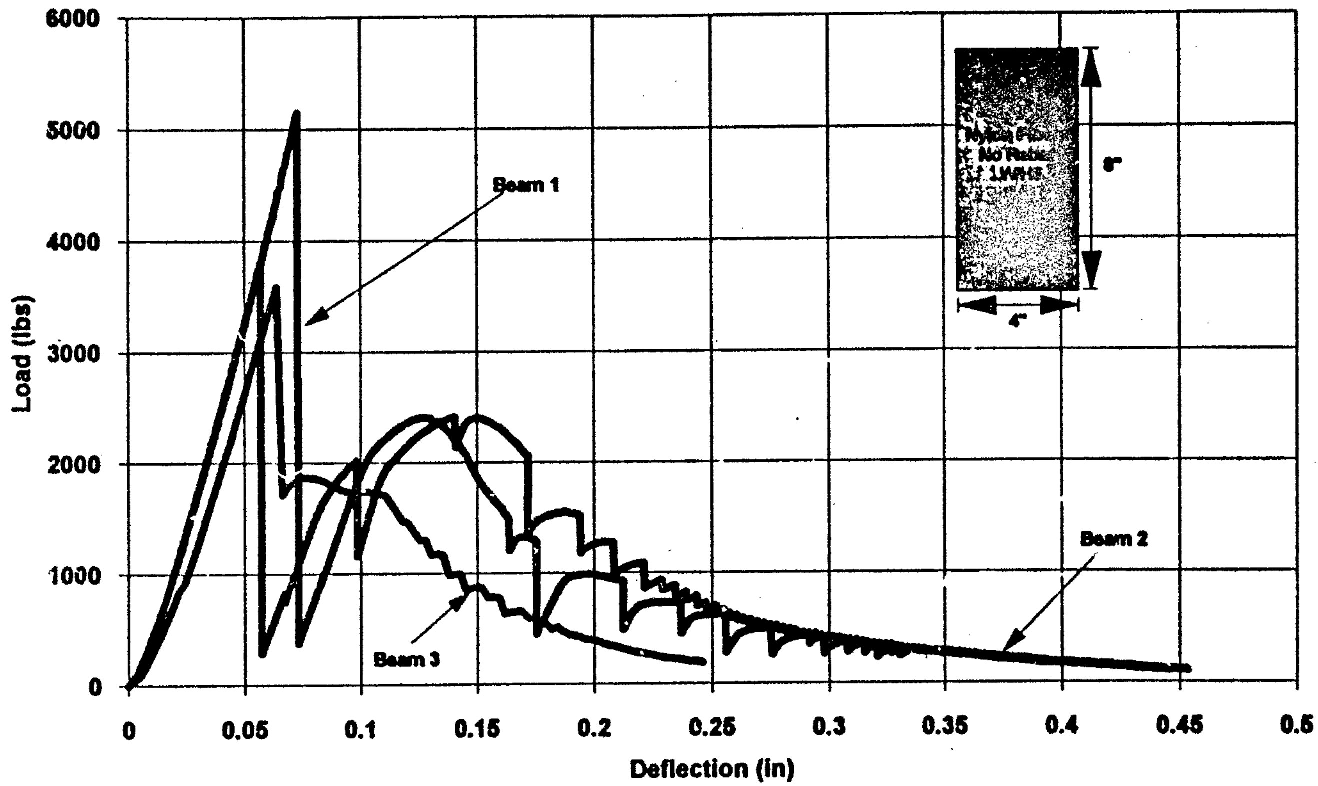

Figure C-1. Load-Deflection Curves For Beam Type F1.

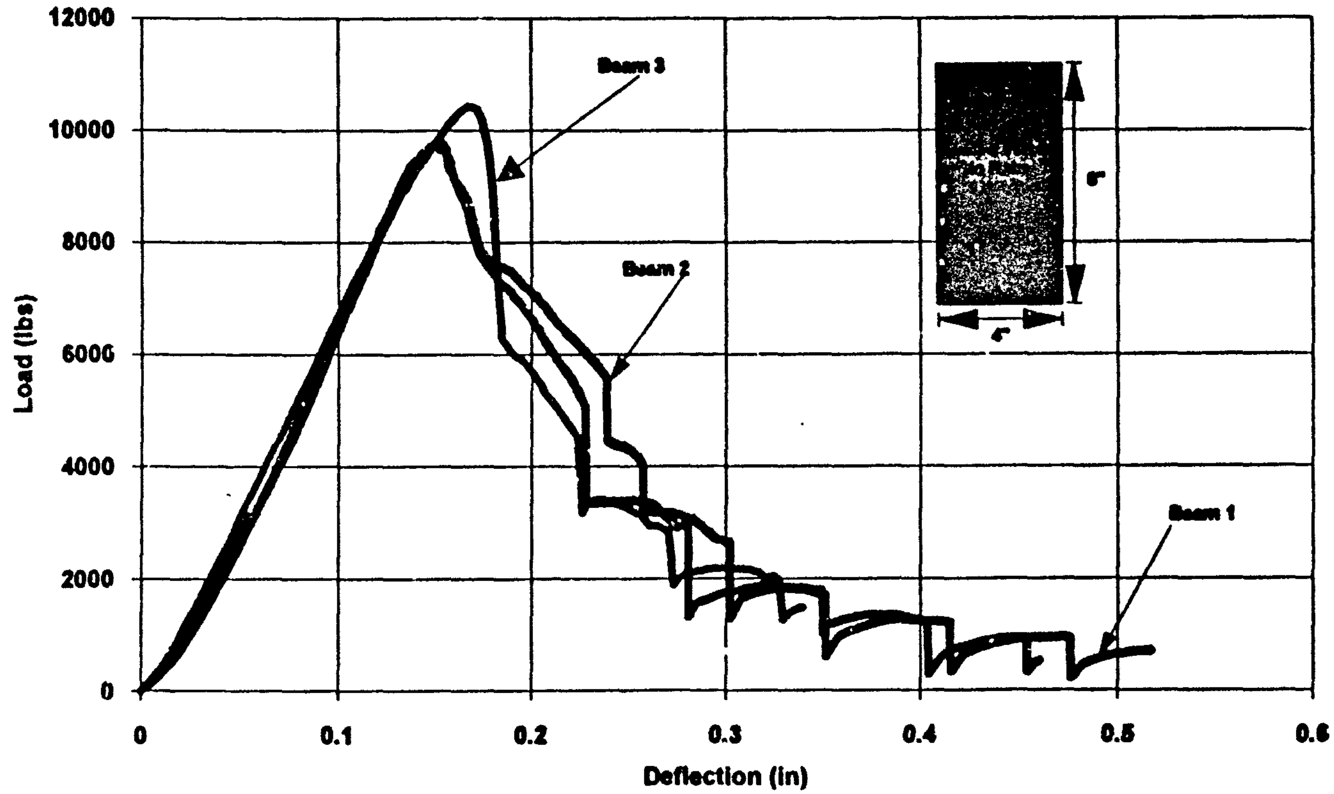

Figure C-2. Load-Deflection Curves For Beam Type F2.

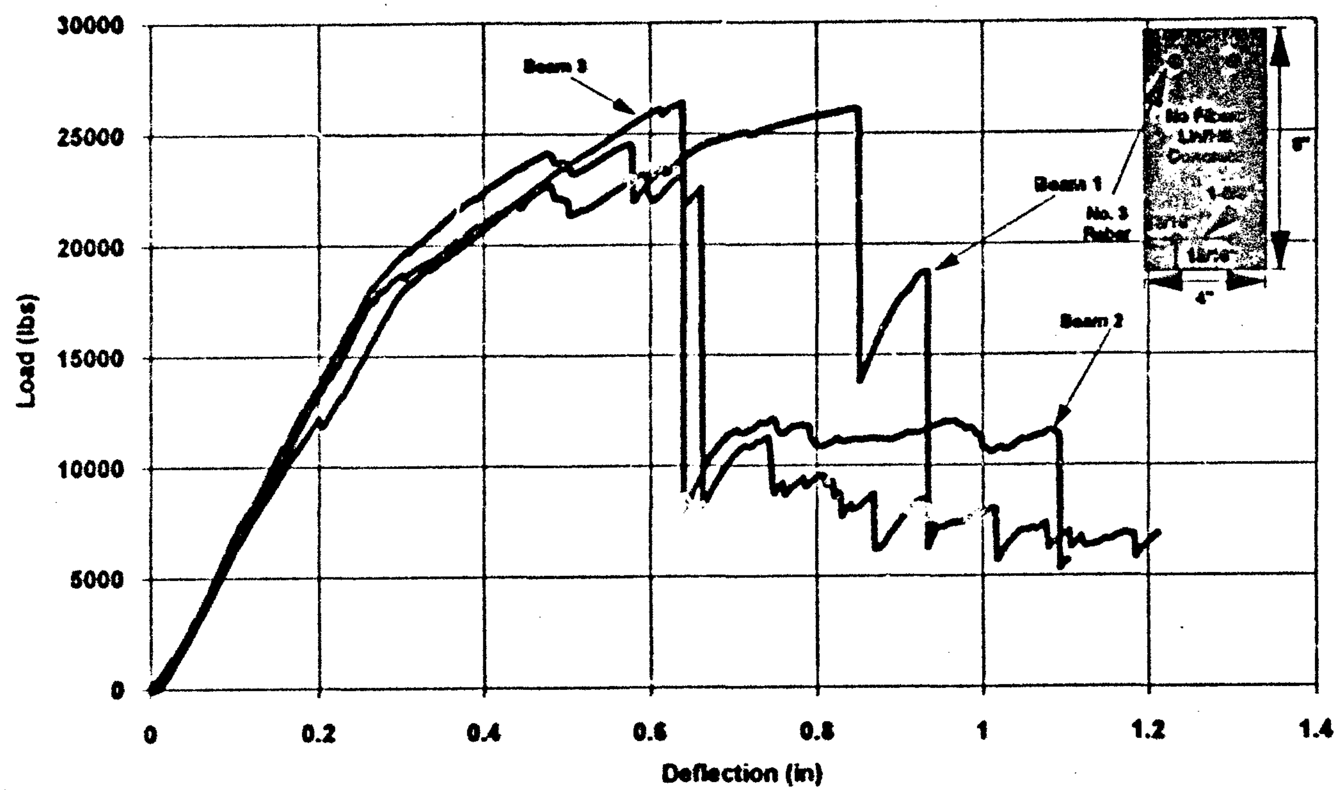

Figure C-3. Load-Deflection Curves For Beam Type SR1.

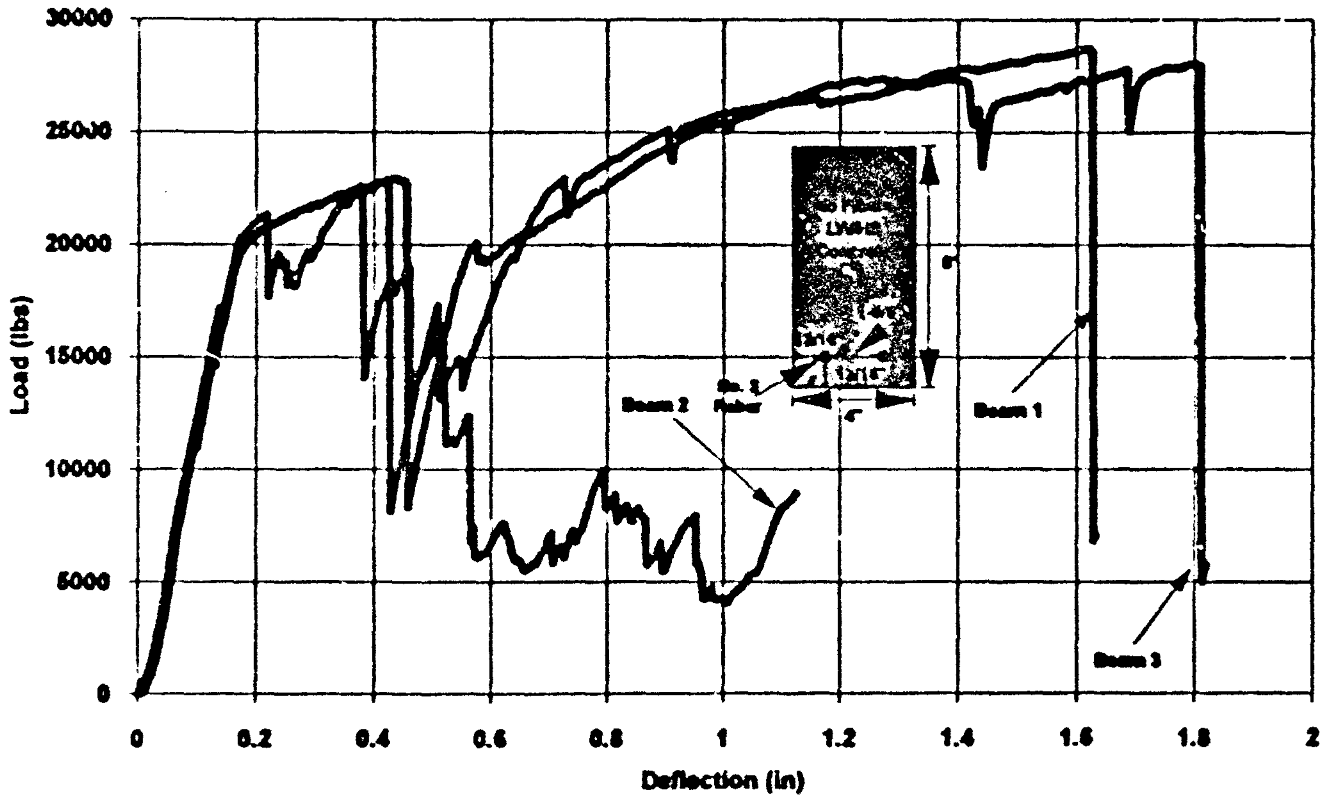

Figure C-4. Load-Deflection Curves For Beam Type SR2.

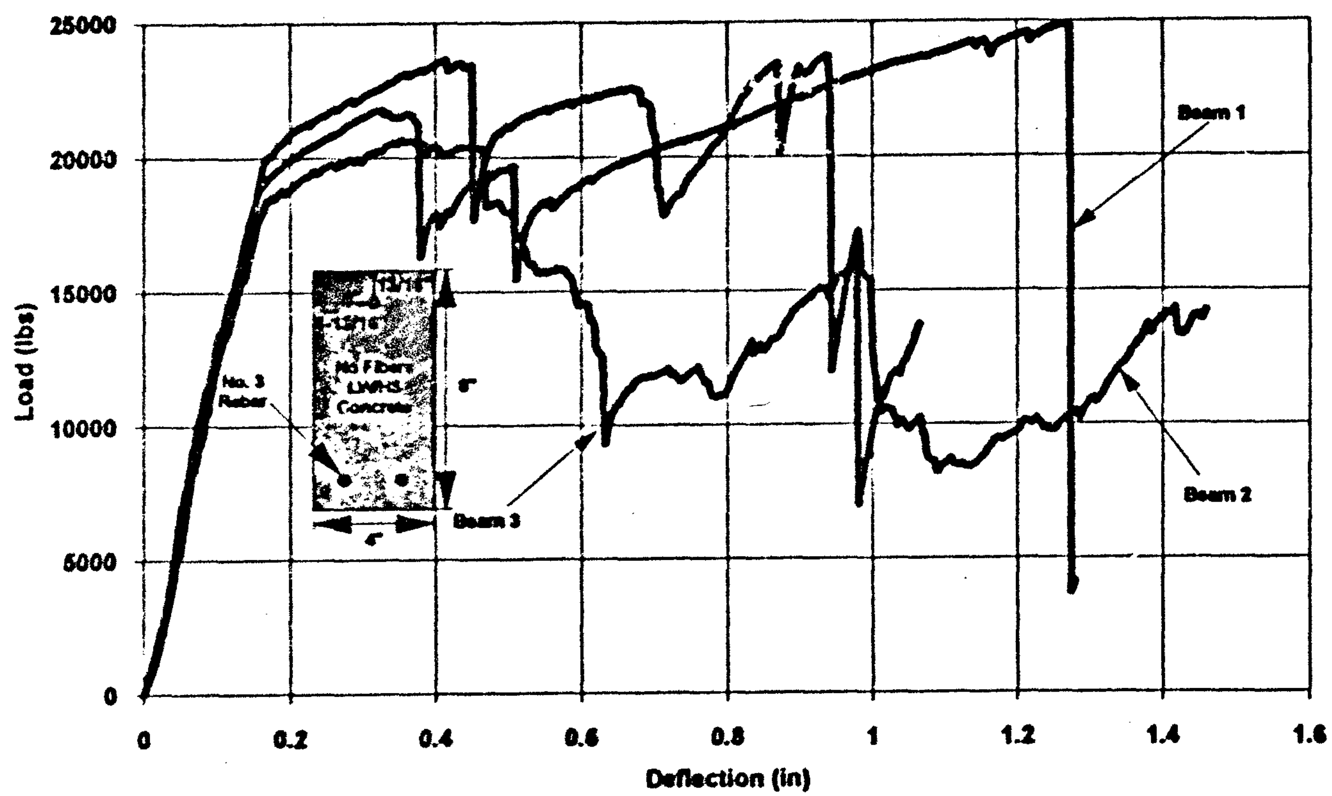

Figure C-5. Load-Deflection Curves For Beam Type SR3.

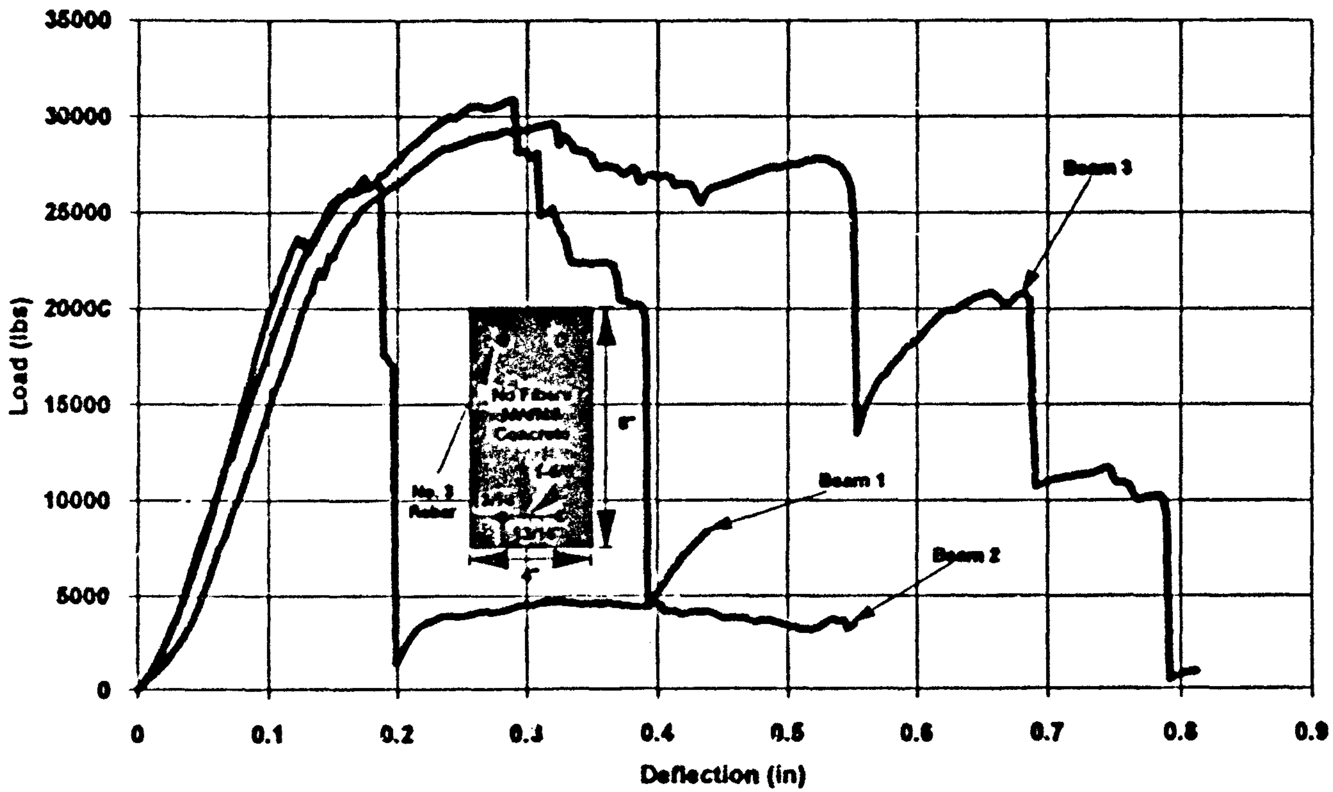

Figure C-6. Load-Deflection Curves For Beam Type SR4.

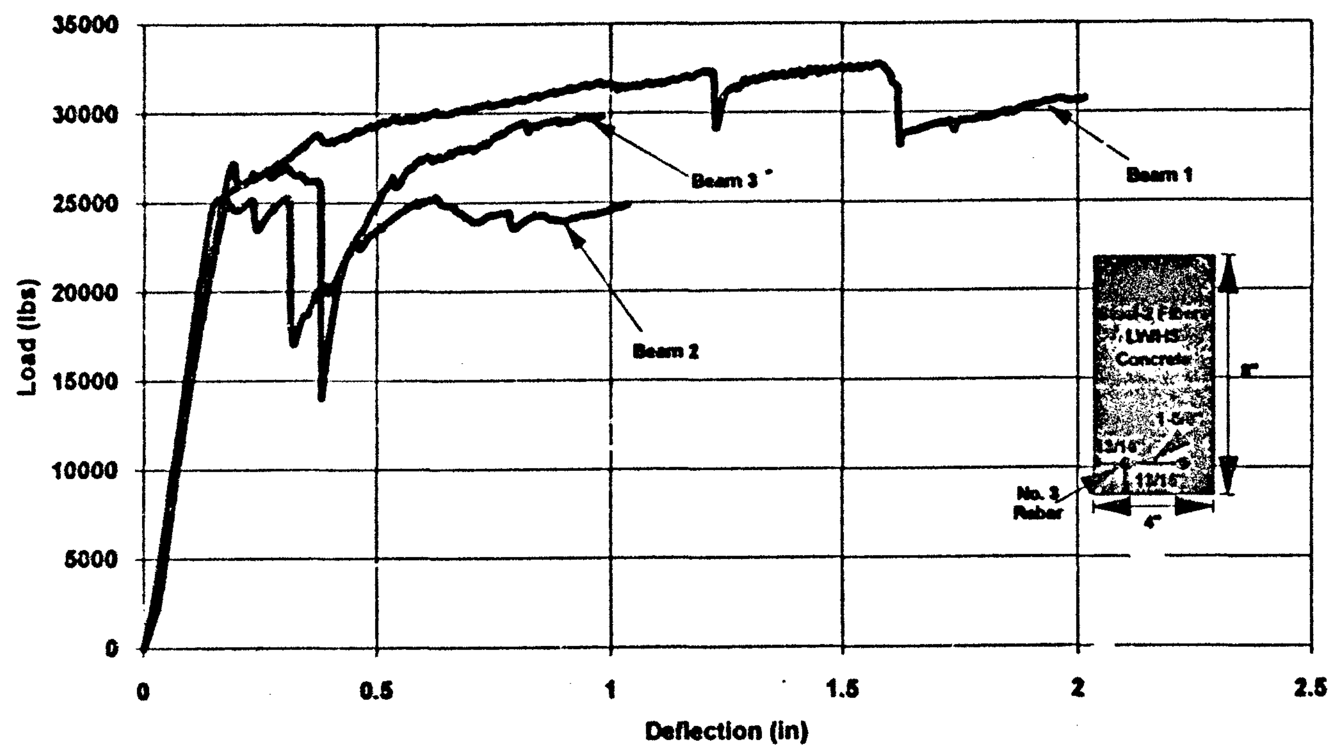

Figure C-7. Load-Deflection Curves For Beam Type SR5.

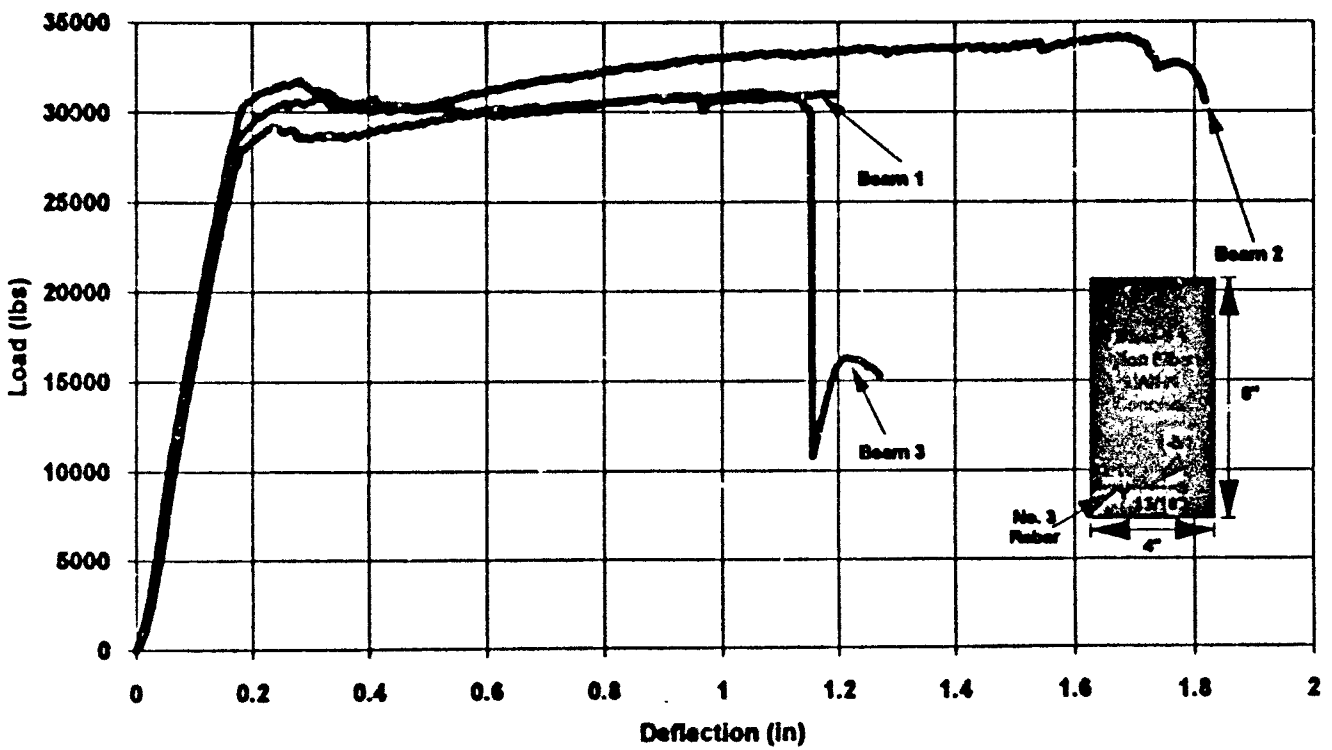

Figure C-8. Load-Deflection Curves For Beam Type SR6.

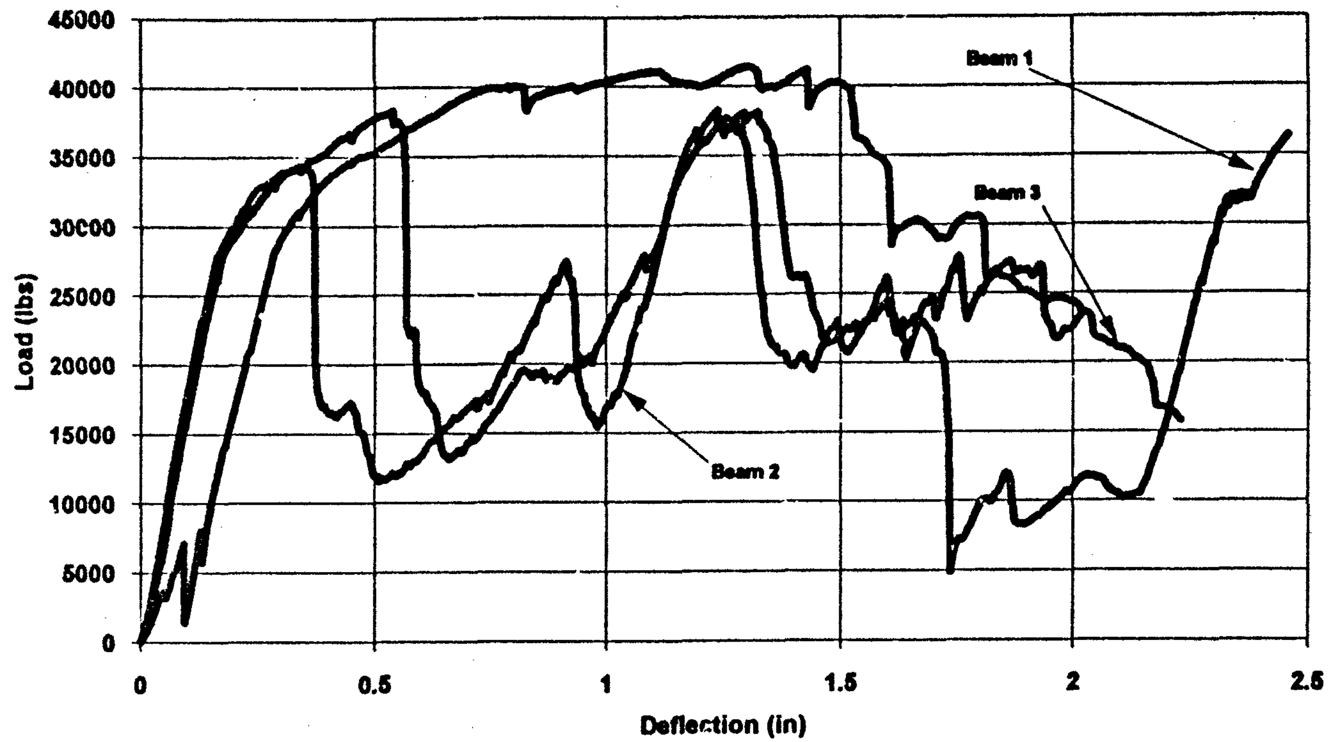

Figure C-9. Load-Deflection Curves For Beam Type SR7.

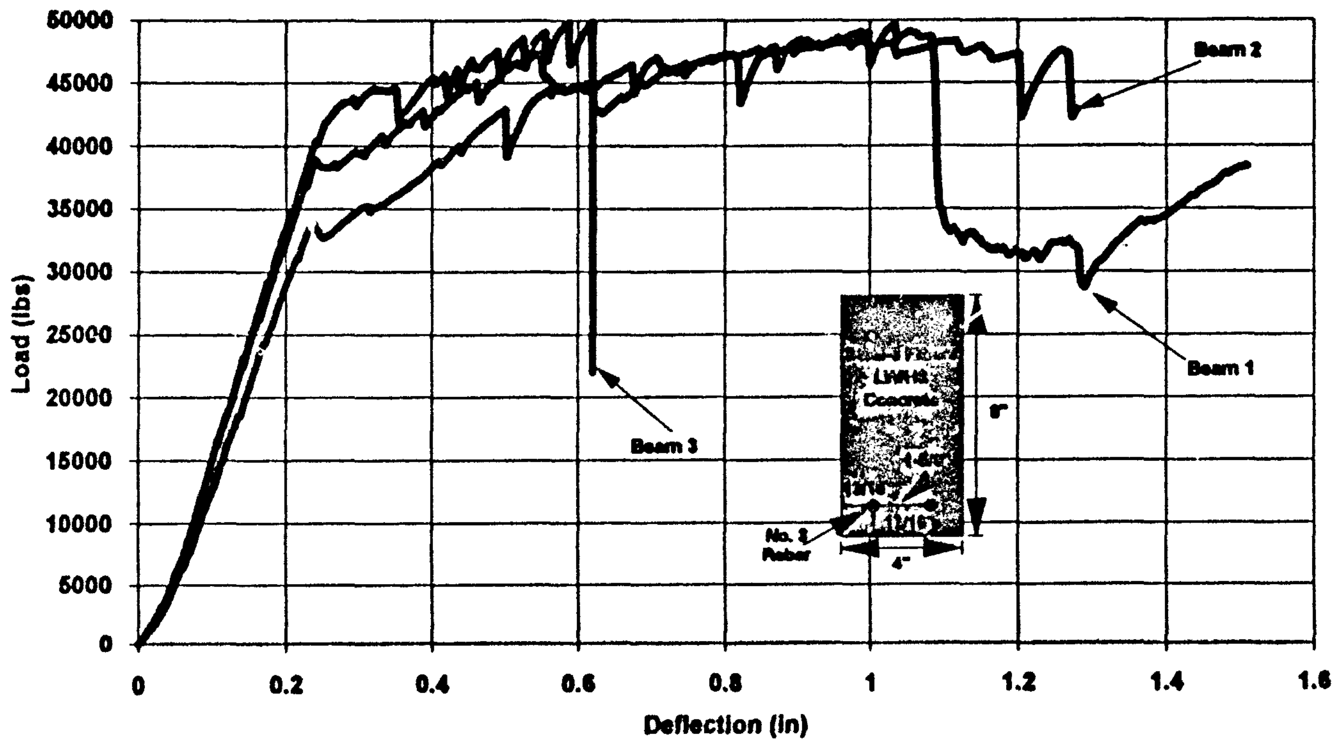

Figure C-10. Load-Deflection Curves For Beam Type SR8.

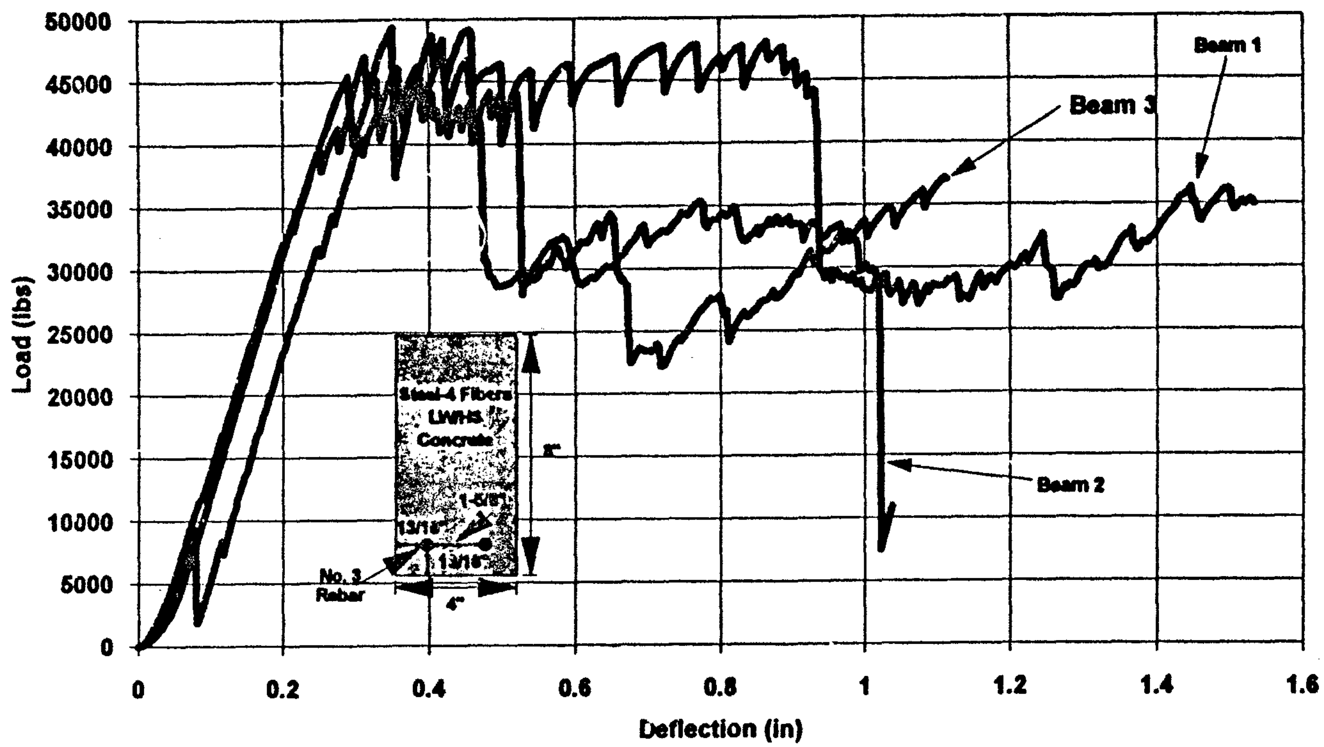

Figure C-11. Load-Deflection Curves For Beam Type SR9.

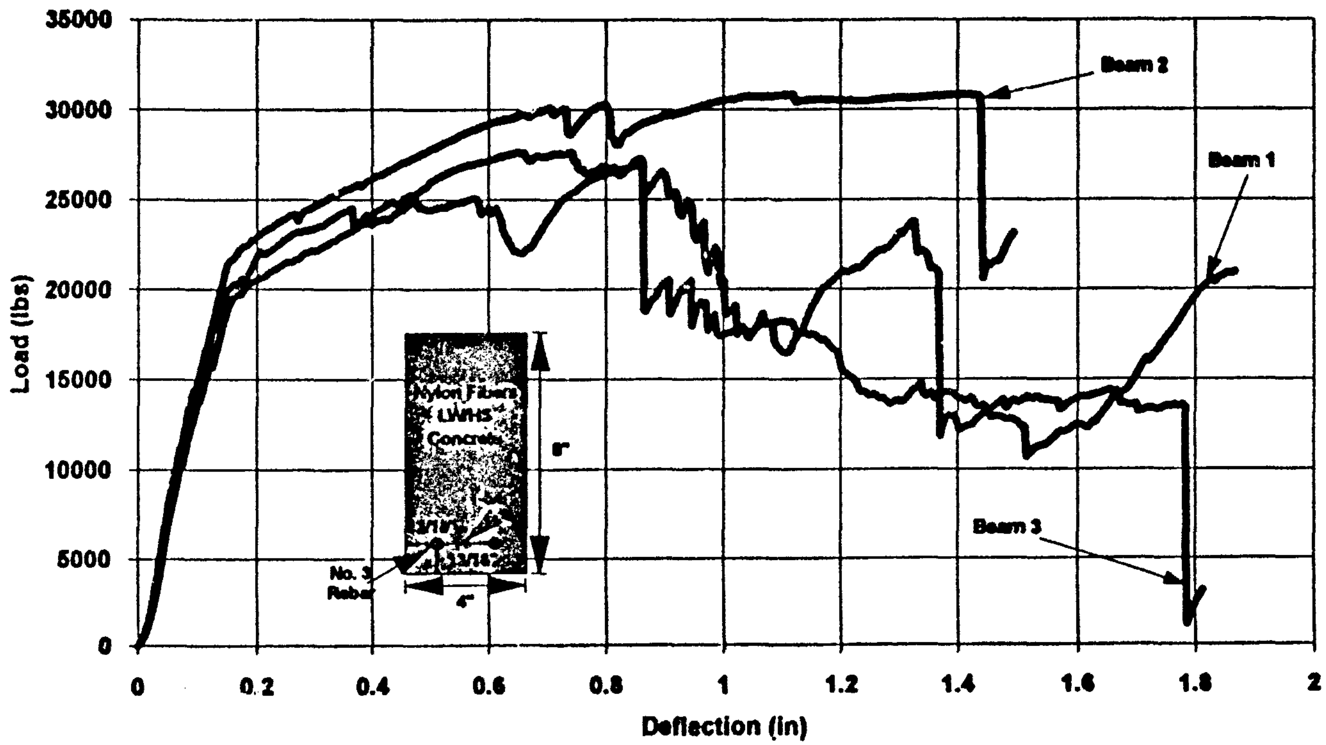

Figure C-12. Load-Deflection Curves For Beam Type SR10.

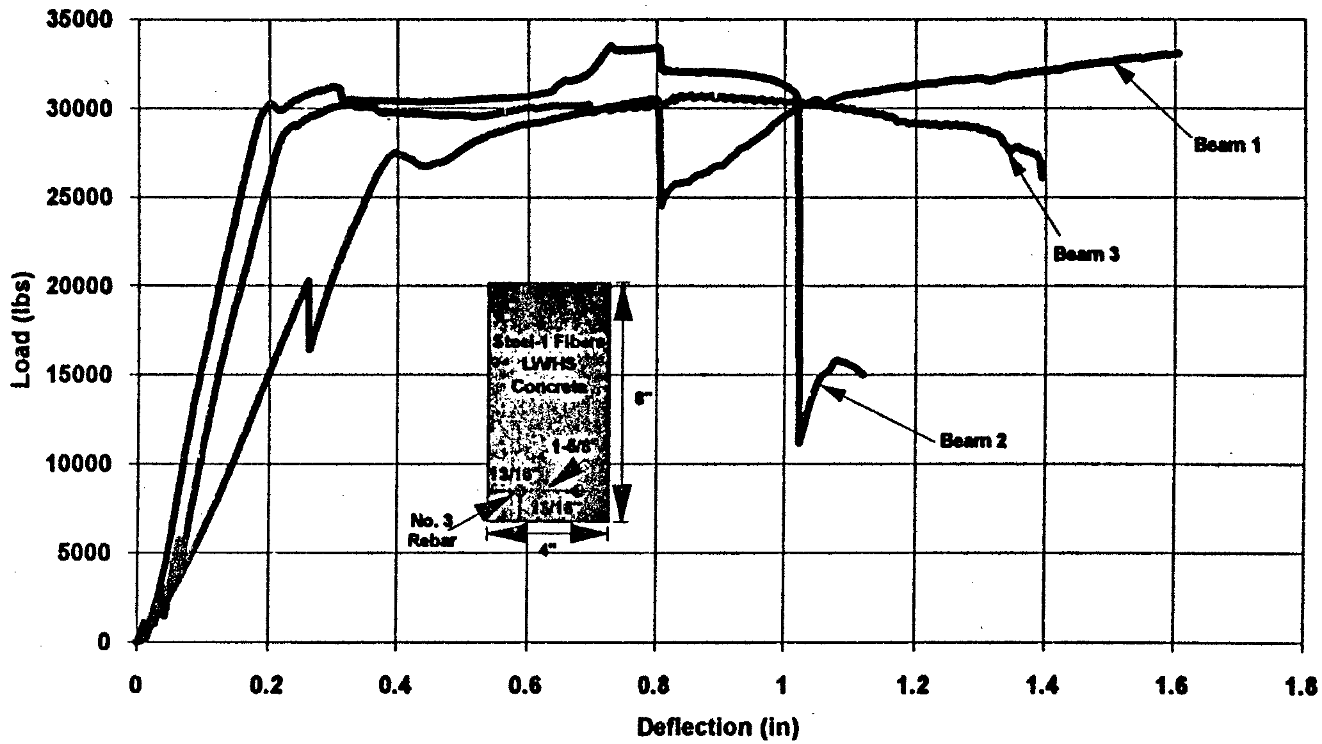

Figure C-13. Load-Deflection Curves For Beam Type SR11.

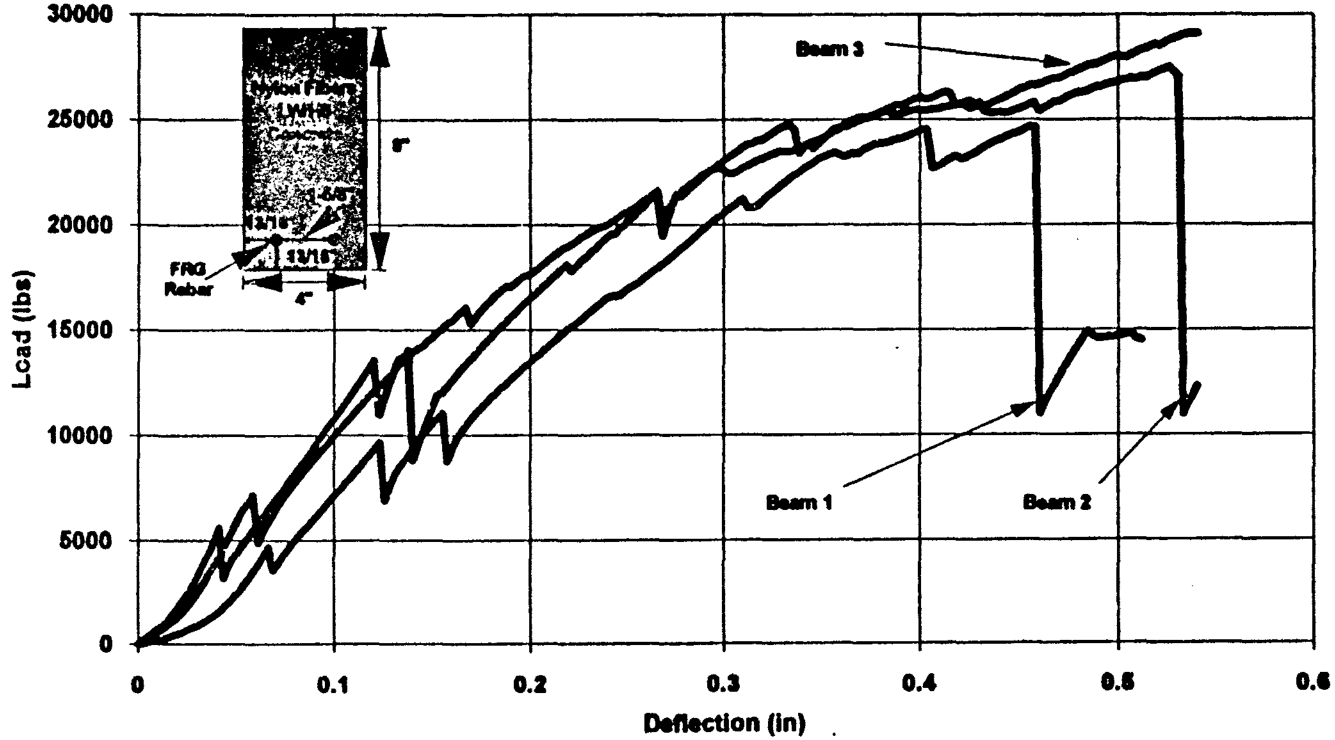

Figure C-14. Load-Deflection Curves For Beam Type FR1.

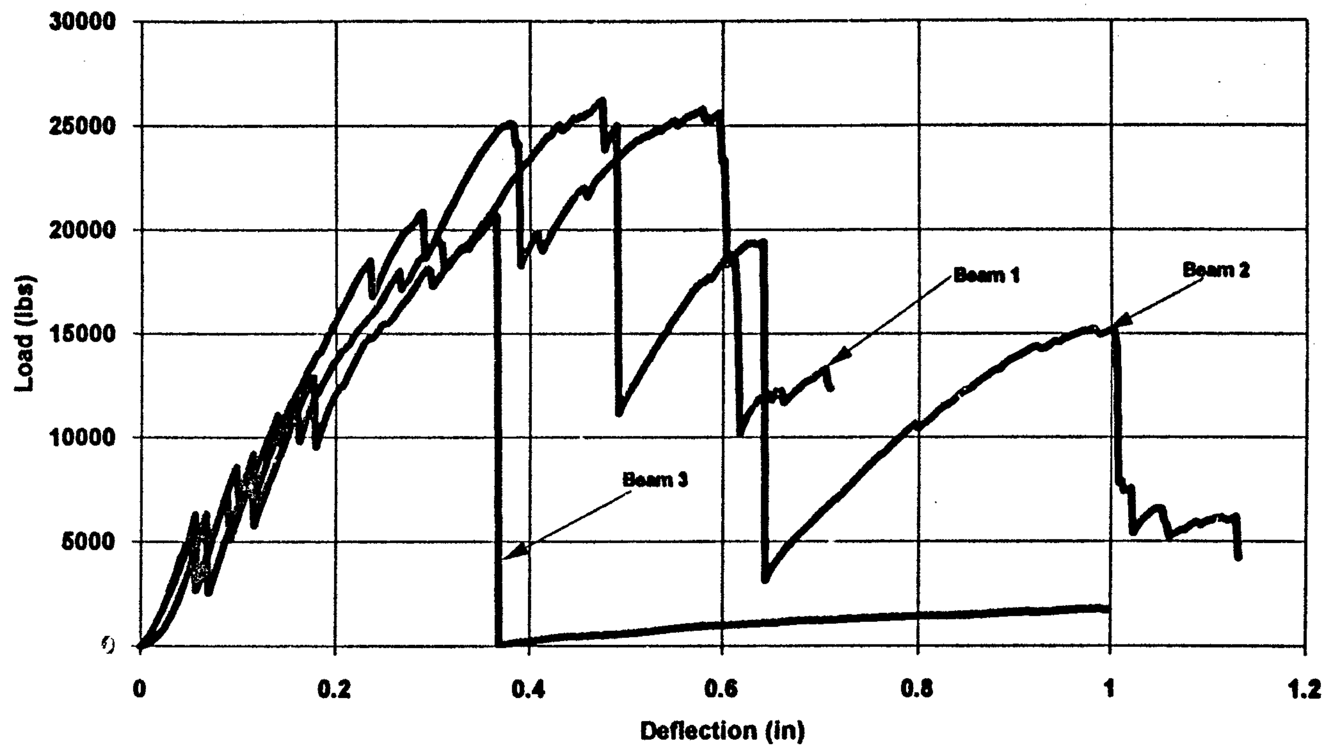

Figure C-15. Load-Deflection Curves For Beam Type FR2.

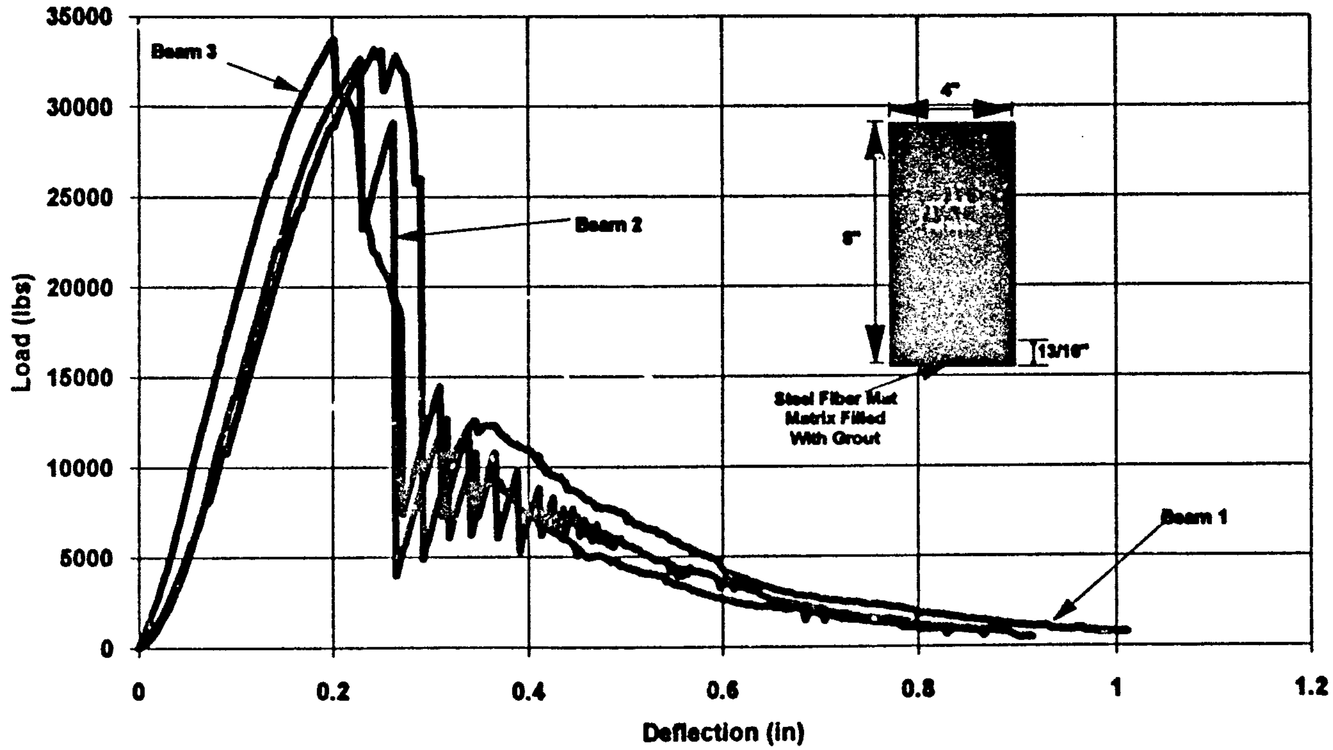

Figure C-16. Load-Deflection Curves For Beam Type M1.

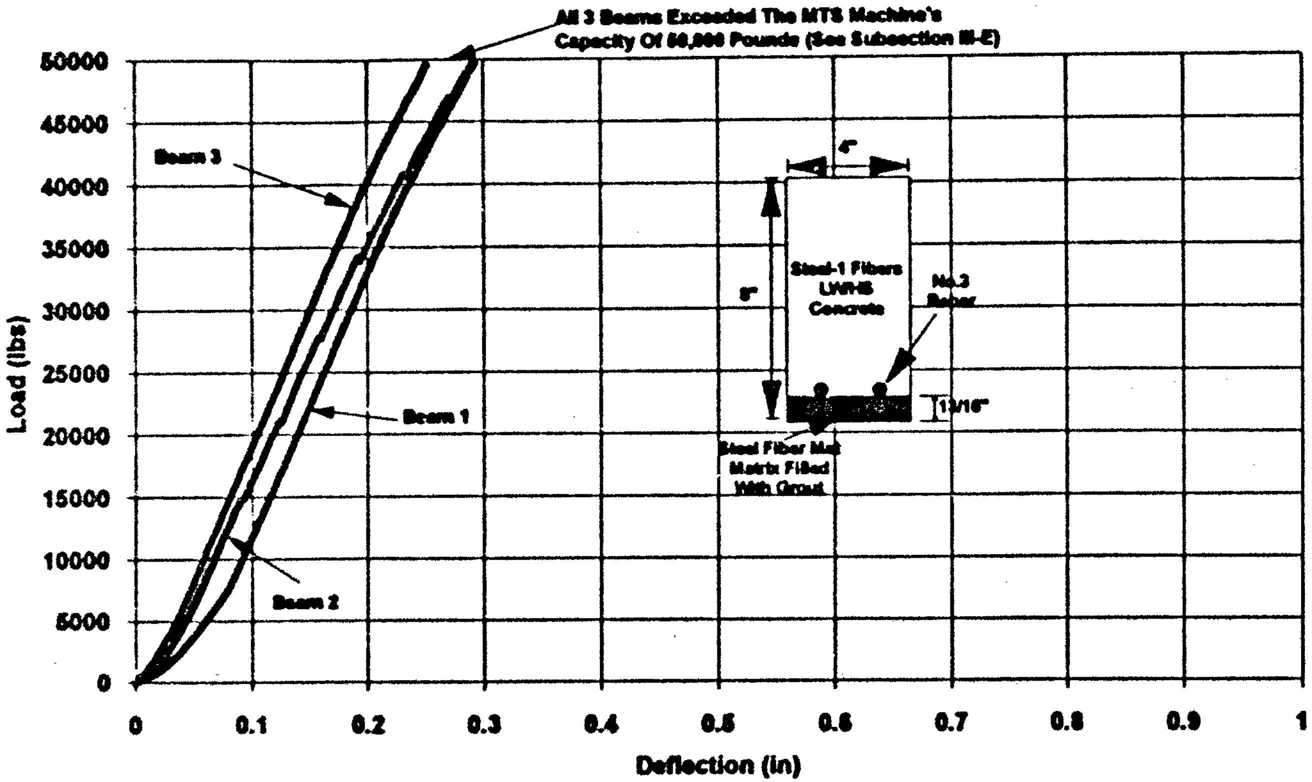

Figure C-17. Load-Deflection Curves For Beam Type M2.