DEVELOPMENT OF COMPOSITE GLUED LAMINATED TIMBER

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ABSTRACT

Research into the development of a timber reinforcing system dates back to the late 1800's. While many systems have shown promise from a mechanical property improvement side, economics have limited these studies to research projects and not commercial production. However, with the decrease in availability of prime lumber stocks and the corresponding price increase, interest in reinforcing lumber to make it technically and economically competitive with other construction materials has resurfaced. This study focuses on the fiber reinforcement of glued laminated timber. Extensive work has been done in the area of aramid fiber reinforced plastic (AFRP) glulam timber, however, there are no known studies on the use of carbon fiber reinforced plastic (CFRP) or glass fiber reinforced plastic (GFRP) glulam timber. This study is intended to serve as a preliminary investigation to determine the viability and merits of these two unstudied fibers and their use in different orientations. The report includes a comprehensive literature review on the current state of reinforced timber and the subsequent test program. In the test program, the two different fiber types were tested, each in three different orientations. The results indicated that, in all cases, the application of the fiber reinforcement enhanced the flexural capacity of glulam beams. The maximum enhancement of 53.0% was achieved using CFRP. However, considering project economics, GFRP appeared to be the superior reinforcing material. The stiffness enhancement results were not discernible above the variability of the wood because of the small fiber fraction used.

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1.0 INTRODUCTION

Wood has a wide use in the construction industry, ranging from simple framing in housing projects to its use in the construction of large scale arches in commercial ventures. Because of the wide range of applications of timber and the versatility of wood as a construction material, the demand for wood products is correspondingly high. However, nature is showing that it cannot keep up with the ever broadening demands placed on it. Since prime lumber is becoming increasingly scarce, economics have led to a higher cost for wood products. This increase is making wood less competitive with other construction materials. As a result, to compensate for declining lumber stocks and increasing costs, researchers have turned their attention to the development of engineered wood products.

Two of the main types of engineered wood products include glued laminated wood members and reinforced wood members. Glued laminated timber has been in commercial production for well over 50 years and its design and construction criteria have become standardized (Canadian Wood Council, 1990).

The development of the application of wood reinforcement has been studied by many different research groups, with some projects dating back to the late 1800's. A reinforcing system would result in many possible benefits to a wood section. It may act to improve the mechanical properties of the section, reduce both long- and short-term maintenance, or increase the durability of the section. In addition to this, a reinforcing system may make some wood products more economically competitive with other engineering materials.

The need to investigate performance enhancing systems for wood and wood products is multifaceted. The major concern lies in the perversity of wood as a construction material. Since wood is a naturally occurring substance, there are no control systems on its growth or development. It is characterized by variability not only between species groups, but also within species groups. Much like flaws in a steel section may provide an initiation point for fatigue cracking of the section, knots, splits and cracks often act as an initiation point in the failure of a wood section. Given the randomness of knots, even two pieces of wood from the same tree may behave very differently under loading.

As with any engineering material, efficiency is greatly influenced by the ability of an engineer to design for a material as close to its actual behaviour as possible, while still invoking sufficient safety to prevent unpredicted structural failure. It is therefore important from an engineering perspective to try to reduce section variability, thereby maximizing the efficiency of the member. A method of creating a more predictable and reliable timber section is needed.

The basic concept behind previous reinforcement studies was to enhance the weak properties of wood with another material, similar to the concept of reinforced concrete. In the past, a variety of different wood reinforcing systems have been developed and many different patents awarded. Most of these systems showed that some appreciable performance gain was obtainable. However, few, if any, have proven to be economical enough to reach the production stage. Today, considering environmental and economic limitations, the need for an enhanced wood product has reached the forefront of structural engineering research.

1.1 RESEARCH APPROACH

As previously discussed, the primary motivation behind reinforcing wood comes from the need to produce a product that is more competitive with other engineering materials on both a performance and an economic scale.

In the past, research has focused on the application of the reinforcing systems to traditional lumber products, including sawn timber and glulam. However, in the past 10-15 years, engineered wood products have become more commonplace with products such as waferboard and parallam becoming an integral part of the wood product industry. It is clear that there are many different areas of research that require further investigation. For the purpose of this research, the focus will be on the development and testing of fiber reinforcement as it applies to glulam timbers.

The approach of this research will be to investigate the improvement of the mechanical properties achieved through fiber reinforcement. Stock specimens will be obtained from a local glulam supplier and the fiber reinforcement applied by hand, in accordance with the fiber manufacturer's specifications.

The improvement of mechanical properties will be measured by comparing reinforced properties with unreinforced ones. Specifically, stiffness enhancement will be measured by comparing the reinforced Modulus of Elasticity with that of the specimen prior to reinforcing. Strength enhancement will be measured by comparing the moment capacity of unreinforced specimens at failure with the reinforced specimens capacity at failure.

It is not possible to draw direct comparisons within a single member for the strength enhancement because the test used to determine the ultimate moment capacity is destructive. A nondestructive test procedure may be used to determine Modulus of Elasticity (MOE), therefore an MOE prior to reinforcing may be determined on each individual specimen.

1.2 OBJECTIVES

The purpose of this research was to determine if fiber reinforced glulam technology had potential for further development.

The objectives for this project were as follows:

1. To determine if fiber reinforcing of glulam timber provides flexural capacity enhancement when compared to an unreinforced specimen;
2. To determine if fiber reinforcing of glulam timber provides stiffness enhancement when compared to an unreinforced specimen;
3. To conduct a series of comparative tests to decide which fiber type will provide the best reinforcing system;
4. To conduct a series of comparative tests to decide what fiber fraction and profile provide the greatest enhancement; and,
5. To develop an outline for a future research program in the field of fiber reinforced glulam timber.

It should be noted that since one of the prime functions of this report is to serve as a preliminary series of tests for future work, the number of samples reinforced with each fiber type and orientation was limited to one specimen each. This is partially due to time constraints and partially due to the economics available for this preliminary study. It is recognized that the results obtained may be skewed because of the perversity of one particular specimen, nevertheless, it is felt that the general trends will be sufficiently obvious that future recommendations may be drawn from the broad scale.

1.3 RESEARCH METHODOLOGY

The project had two main phases. In the initial phase, an extensive literature review was conducted, in conjunction with a series of field visits to related manufacturing plants. These visits were designed to provide the researchers with a manufacturing perspective for reference to future application of the technology in industry.

The second phase involved a test program. The program was designed to meet the objectives of the project. Testing was conducted at the I. F. Morrison Structural Engineering Laboratory at the University of Alberta.

1.4 REPORT OUTLINE

An extensive review and evaluation of past research is presented in Chapter 2. Chapter 3 details the experimental program conducted to meet the objectives of the project and Chapter 4 presents the test results obtained from the experimental program. Chapter 5 provides a discussion and analysis of the results, with the summary and subsequent conclusions presented in Chapter 6.

2.0 LITERATURE REVIEW

2.1 METALLIC REINFORCING SYSTEMS

The majority of the early work on wood enhancement techniques focused on the use of metallic reinforcing systems. Reports of steel reinforced timber systems are recorded as far back as the mid-1800's with some still patented from the early 1900's (Bulleit, 1984).

Many different types of metals have been used to try to reinforce timber. Some of the past systems developed include a wood-aluminum system (Mark, 1961) and numerous different steel reinforcing systems. While other materials have also been tested, the most popular metallic systems were steel based. These steel systems include: the use of steel strips, both continuous (Borgin et al., 1968) (Figure 2.1) and intermittent (Coleman and Hurst, 1974), laminated to the exterior of wood beams; the development of beams with internal vertical plates, known as flitch beams (Kumar et al., 1972) (Figure 2.2); the embedding of a steel wire mesh between the lams in a glulam beam (Bulleit et al., 1989); and, the application of various different steel bars, rods and plates. Some of these systems were also designed using prestressed reinforcing materials (Bohannan, 1962 and Peterson, 1965).

Some success has been achieved in material performance with the use of these steel reinforcing systems. The work done by Bulleit et al. (1989) showed that stiffness increases were in the order of 24-32% and moment capacity increases in the order of 30%. These are fairly typical enhancement values when metallic reinforcing systems have been used.

Despite the moderate increase achieved in the engineering properties of the wood, the majority of these researches were not taken beyond the experimental stage. There are a variety of reasons for this. First and foremost has been the economics. Current large scale manufacturing costs of these products have not outweighed the structural advantage achieved. Secondly, the difficulty of developing a successful connection between the different components has also limited commercial production.

For the most part, the majority of the metallic reinforcement systems have continued to show relatively minor enhancement. Nevertheless, recent advancements have been made in the area of metallic reinforcing systems that have shown promise. One of the main causes for poor enhancement with many of the metallic reinforcements has been the difficulty in developing a system to anchor the metallic reinforcement to the timber specimen. However, Gardner (1991) developed a system which located a steel reinforcing bar "inside" of a glulam sample. Two adjacent lams in a glulam specimen were "grooved" to accommodate a reinforcing bar and then the section built-up, using traditional glulam manufacturing techniques (Figure 2.3). The resulting specimen removed the problem of a weak connection in the same manner as reinforcing steel in concrete. Test results of these specimens showed that some of the mechanical properties were enhanced by as much as 280% when compared with unreinforced specimens. This particular system has shown that the mechanical properties of a timber section may be dramatically improved using metallic reinforcement, while remaining economically competitive. Today, this product is in use in many structures in Australia (Gardner, 1991).

Another important advantage of reinforcing timber is its long term performance. Long term creep in timber has been a major concern for a structural member under sustained loading and high humidity conditions. The studies by Gardner (1991) have shown that the steel reinforcing in the tested glulam beam had significantly reduced the creep of the member to an almost negligible level.

While there now appears to be renewed interest in the use of metallic reinforcing systems, it appears that applications may still be limited because of the inability to provide a reliable connection between the two materials, particularly for sawn lumber.

There is ongoing research to develop a system for anchoring reinforcement. One such anchoring system, developed in the former Soviet Union (Turkovsky et al., 1991), involves the use of a bracket structure embedded into the beam to support external reinforcing rods (Figure 2.4). This system has been shown to be sufficiently successful at providing a suitable joint between the timber member and the metallic reinforcement that it is now in use in many structures in the former USSR (Turkovsky et al., 1991). However, once again production costs have limited this system to a restoration capacity as opposed to a “new product” one.

2.2 FIBER REINFORCING SYSTEMS

While studies involving the fiber reinforcement of wood were undertaken concurrently with the work being done involving metallic reinforcements, the focus didn’t turn to the area of fiber research until it was thought that metallic reinforcing systems could only yield a fraction of the improvement achieved through the use of fibrous reinforcement. As a result, over the past 10-15 years the majority of the work has centered around the investigation of fiber reinforced members.

2.2.1 Sawn Timber Specimens

With the possible exception of the work done by Gardner, research in the use of fiber reinforcement has shown more promise than that of the metallic reinforcement,. Studies by Spaun (1981), Rowlands et al. (1986), van de Kuilen (1991) and many others have shown that the use of fiber reinforcing systems can result in substantial additional moment capacity and deflection reductions in the order of 50%.

The relative results are dependent on the type of reinforcing fiber used. To date, research has focused on the use of aramid, carbon and glass fibers. Plevris and Triantafillou (1992) conducted extensive testing on these three types of fiber as a reinforcing system for sawn timber. Specifically, they examined ultimate moment capacity, curvature ductility, rigidity and axial force capacity. They found that for each fiber type, the bending strength of the specimens increased almost linearly with increasing fiber fraction up to a critical value, after which it essentially became constant. The difference in the fibers came in the slope of the different initial linear portions. They found that the carbon fiber reinforcing provided the greatest initial strength and stiffness, followed by aramid fibers and finally glass fibers. This is consistent with the relative strength of the pure fibers. The research also revealed that the relationship between curvature ductility and fiber reinforced plastic (FRP) area fraction is defined by an almost exponentially increasing branch. This suggests that there is a very beneficial effect from the FRP on the ductility of the system. The rigidity of the specimens was also examined. It was found that even a small carbon fiber fraction area (1%) can result in an initial stiffness increase in the order of 60%. They concluded that even a small fiber fraction area can have a dramatic enhancement on some mechanical properties.

These results parallel the results from Rowlands et al. (1986). Their test results showed that, by applying various reinforcing systems to wood structures, tensile strength capacities may be dramatically increased. Specifically, their test program showed that this increase may be as much as 110% with glass reinforcement of solid Douglas-fir specimens versus unreinforced ones.

Rowlands et al. (1986) also concluded that glass fiber was the superior wood reinforcement system, from both a technical standpoint and an economical one. While carbon fiber and aramid fiber do have higher strength than glass fiber, the capacity of the wood limits the load carried by the fiber. Even with a greater volume of glass fiber required, economics dictate that the glass fiber remains more economical than the other fibers. Plevris and Triantafillou (1992) came to a similar conclusion in the comparative tests that they conducted.

Plevris and Triantafillou (1995) also conducted a series of long term creep behaviour tests, discovering a number of differences in the long term behaviour of the different fibers. These tests showed that the creep behaviour of FRP reinforced wood is primarily dominated by the creep of the wood.

This study also showed that, for carbon fiber reinforced plastic (CFRP) and the glass fiber reinforced plastic (GFRP), a greater fiber fraction decreased not only the initial, but also the long-term stresses. However, the individual behavior of the aramid fiber reinforced plastic (AFRP) gave a substantially different result than the CFRP and GFRP.

For both CFRP and GFRP, the fiber stresses, over approximately the first 50 days of loading, increased significantly because of the high rate of creep of the wood. However, after the 50 days, the stress in these two FRP's stabilized as the creep of the wood stabilized under the sustained loading. In the case of the AFRP, the initial stresses decreased slightly in the first few hours or days because the AFRP was found to have a higher initial creep rate than the wood. It was then observed that the stresses in the AFRP increased between the 3rd and 50th days of loading, because the wood creep rate was greater than that of the AFRP. However, in the long term, after the 50 days of loading, the rate of creep of the wood stabilized at a lower rate than that of the AFRP and the stresses in the AFRP began to decline again.

The response of the CFRP and GFRP sections were quite similar, but the use of AFRP resulted in curvatures and stresses that were slightly higher than those of the other composites, except for the long-term stress in the laminate. Therefore, if creep control were essential, either CFRP or GFRP is recommended.

In all, these researches showed the most obvious advantage of a wood reinforcing system is that it increases the mechanical properties of a given specimen. They also give an indication of the promising potential of fiber reinforced timber. Considering the volume of wood structures constructed today coupled with the ever increasing demand for performance from engineered structures, improved or engineered wood and wood products have become a necessity.

As previously mentioned, another concern with wood as a structural material is its variability. Variability of a construction material can often lead to design limits with uneconomical factors of safety. However, the possibility that a member may have inherent flaws dramatically reduces "safe" design values. Most recently, work done by Gardner (1991) and Plevris and Triantafillou (1992) indicates that the addition of reinforcement to timber specimens leads to a smaller variability between tested specimens.

A further benefit of a fiber reinforcing system, particularly an external one, is that it provides enhanced fire and weather protection. Tingley (1994) reported that Kevlar® (aramid fiber) reinforced plastic (KRP) has a very high strength retention value under high temperature and that the composite action of the KRP with the wood performed better than wood alone. A study by Tang and Adams (1973) showed that fiber reinforced transmission poles exhibited a greater resistance to the effects of weathering and other deterioration processes, in addition to an increase in strength and stiffness. Mitzner (1973) conducted a number of tests on the durability and maintenance of plywood overlaid with glass fiber reinforced plastic. Test results showed that the reinforced sheets exhibited greater durability and required less maintenance in addition to increases in strength, stiffness and impact resistance.

Another significant improvement in capacity of timber using a fiber reinforcing system versus timber with no reinforcement has come in the strength of a specimen perpendicular to the grain. The tensile strength perpendicular to the grain often limits the load-carrying capacity of some timber structures, most notably in the capacity of the joints to carry load. Enquist et al. (1991) examined the tensile strength perpendicular to grain enhancement of Swedish whitewood by applying glass fiber reinforcement. Test results indicate that with the use of a glass reinforcement of 450 g/m^2 on each side of the specimen, the load-carrying capacity increased by at least 110%. It was noted that the failure of these specimens was caused by either bending or shear and not by tension perpendicular to the grain.

Further to this, Plevris and Triantafillou (1992), and many others, have suggested that the use of an acceptable reinforcement system will allow for the use of either less material or the use of a poorer quality wood. With the ever increasing awareness of our environment and the steadily dwindling supply of natural resources, the development of a more environmentally conscious and economically viable product is becoming foremost in the minds of construction material researchers.

2.2.2 Glulam Timber Specimens

Glulam members provide many advantages over traditional sawn timber members. One of the most important advantages is that the variability of the section is reduced. In the glulam manufacturing process, joints, knots and other defects are randomly placed through the member, which lessens the impact that a single knot will have on the section's mechanical properties. This creates more uniformity between individual members and higher allowable stresses over sawn timbers of the same wood type.

Another important advantage is in the quality of the wood in the specimen. Because of the procedure used in the manufacturing of a glulam member, different grades of lumber may be used in different regions of the section. A manufacturer may use lower grade lumber in the areas of low stress, thereby saving the higher quality lumber for the regions of high stress. This results in a lower demand on the better grade timbers and a more economical section.

Given the improvement that glulam technology has offered as an engineered wood product and the advancement that has resulted from fiber reinforcement studies, progression in the field of engineered wood products is naturally leading to the combination of the two sciences and the development of fiber reinforced glulam technology.

The concept of reinforced glulam is not new. Extensive research in the field of reinforcing glulam timber, using both metallic and fiber reinforcement, has been ongoing for more than 25 years in North America and Europe (Gardner, 1989). However, until the last 6 years, all of the systems have essentially failed. The reason for this is simple. Economics. Until recently, prime lumber stocks have been relatively abundant, therefore, engineered wood products have been unable to compete economically. However, with the declining stocks, a corresponding price increase has followed, thus opening the door for renewed interest in the investigation and development of reinforced wood products.

While connections have, for the most part, remained an obstacle in the area of metallic reinforcing systems for timber, fiber reinforced timber systems have risen to the forefront of timber engineering. Advancements in the field of fiber technology have been rapid over the past 25 years. This, combined with the economic push, has resulted in the move towards renewed interest in fiber reinforced timber.

While there have been many experimental glue systems that have resulted in wood-glue or fiber-glue bond failure, there have been no known reported failures due to the bond between sawn timber specimens and acknowledged glue systems, nor between fiber reinforcement and acknowledged glue systems. Considering reinforced concrete as a model, these bonding characteristics suggest that the concept of placing the fiber reinforcement between lams may be the most ideal type of construction.

The theory of placing the fiber reinforcement between layers in a glulam member has many benefits. From a structural standpoint, "internal" fiber placement offers protection to the fiber from potential damage. This possible damage may include weathering or that sustained during transportation or placement of a member. Specifically, it would reduce the deteriorating effect of ultraviolet rays on glass fibers or accidental nicks created when members bang against one another during placement. In essence, "internal" fiber placement would offer the same protection to the fiber reinforcement that minimum concrete cover offers to the steel bars in reinforced concrete.

In addition to this important structural advantage, there is an aesthetic advantage. Many architects and owners enjoy the natural presence that wood construction offers, however, with any type of reinforcing system visible, this nature-like effect is lost. With internal reinforcing placement, the natural appeal of wood is maintained, while still offering the structural advantages of the reinforced system.

The three predominant fibers used in reinforced sawn timber research have been glass, aramid and carbon. The majority of research in the past has been done using glass fiber for reasons previously discussed.

Research on different fiber types used for reinforcing glulam timber has been limited. The only significant amount of research has been done on an aramid fiber reinforcing system by Tingley (1990). Tingley has reported that a KRP system used in glulam specimens, known as FiRP panels (Figure 2.5), has resulted in upwards of 115% enhancement of design strength, a deflection reduction in the range of 11-50% (Tingley and Leichti, 1993), and a reduction in the coefficient of variation between reinforced and unreinforced test specimens of 50-75% (Tingley, 1994). These enhancements come at a fiber fraction of 1.2-1.3%.

However, the issue of long term performance is of question in this case. As previously discussed, aramid fiber reinforced timber may develop long term creep problems. Because of this, the majority of research today is focusing on carbon and glass fiber applications.

2.3 FIBER TYPES

When comparing equal quantities of fiber, there are two main factors that affect fiber strength. There is the type of the fiber and the orientation of the fiber as it is applied to the timber.

Much research has been done into the different fiber types. As already mentioned, the three primary types of fiber investigated as a reinforcing material for timber have been glass, carbon and aramid.

One of the most comprehensive studies on different fiber types was undertaken by Rowlands et al. in 1986. In this study, it was concluded that glass is the technically and economically superior material for wood reinforcement. They found that Douglas-fir reinforced with an 18% by volume of glass fiber produced 40% stiffness enhancement and doubled the strength over similar unreinforced wood. They also concluded that graphite reinforcement will further stiffen the specimen, but provided little strength enhancement beyond that of glass. The likely reason for this is that wood compression failure governed the load carrying capacity. Another finding was that the cost, strength and stiffness of the Kevlar® fiber products used in their research was between the values for glass and graphite.

It should be noted that, for any one fiber type, there is a considerable range in the cost, strength and stiffness. These properties are a function of the weight and classification of the specific fiber used. The conclusions of Plevris and Triantafillou are based on the typical properties of the different fiber types and are based on general trends.

Plevris and Triantafillou (1995) conducted a comparative study on the long term creep behaviour using different fiber types. In that, they concluded that the creep response of GFRP was nearly identical to that of CFRP, while AFRP was characterized by higher creep strains which was attributed to the relatively high creep response of aramid fibers, especially during short term loading.

From many studies, these two in particular, it is clear that glass is the preferred fiber type. This is primarily based on the fact that the material does the job at a fraction of the cost of other fiber types.

However, in addition to fiber type, the orientation of the fiber reinforcement is also an important consideration. Fiber mats come in many different orientations, including woven roving, chopped strand mats, cloth mats, including unidirectional and bidirectional tapes, and hybrids (Figure 2.6). In 1965, Thenkston conducted a series of tests on fiberglass reinforced beams that made a comparison between these different orientations. He found that unidirectional nonwoven roving mats were found to be the most suitable fiber orientation for wood reinforcement.

Rowlands et.al.'s (1986) study included a comparison of eleven different fiber types and orientations, including unidirectional glass roving, nonwoven unidirectional glass roving, bi-directionally woven glass roving, auto fiberglass, glass prepreg, unidirectional Kevlar®, cross-woven Kevlar® cloth, heavy cross-woven roving Kevlar®, Kevlar® prepreg, unidirectional graphite, and graphite prepreg. The results also indicated that the unidirectional reinforcements were superior to other types with the exception of the cross-woven prepregs. The cross-woven prepreg performed almost as well after severe weathering as did the unidirectional glass-epoxy reinforcement under normal dry conditions.

On a side note, both research groups noted that it is of the utmost importance that sufficient adhesive must be provided to ensure adequate wetting of fibers, as reduced strength can result from a poor resin bond.

2.4 BONDING ADHESIVES

Despite the number of different adhesives available, most experimental programs to date have used an epoxy resin as the bonding agent. This is in part due to the fact that epoxies are generally regarded as the strongest of all the compatible adhesives available and also because virtually none of the research to date has reached commercial stage and economics have not been considered. In the fiber comparison study that Plevris and Triantafillou (1992) conducted, the bonding agent was an epoxy adhesive resin. In their research there were no reported failures that were a direct cause of the adhesive.

Comparison type studies have been conducted on different bonding adhesives. Thenkston (1965) included a comparison of a water-based adhesive and an epoxy resin in his fiberglass reinforcing study. He found that the epoxy resin performed very well, however the water-based resin was abandoned because it performed poorly.

Spaun (1981) used a phenolic resorcinol formaldehyde adhesive and fiberglass to reinforce finger joints in timber beams. These beams were then tested for increases in bending strength and tension capacity. He found that the glue performed well and the joint capacity increased as much as 40% over unreinforced joints.

Rowlands et al. (1986) have also conducted one of the most comprehensive wood-fiber adhesive studies to date. In their program, they tested a total of ten different adhesives, including three epoxies, two resorcinol formaldehydes, two phenol resorcinol formaldehydes, two isocyanates and a phenol formaldehyde. Test results showed that, under normal conditions, the three epoxies, which included a domestic, a room-setting and a higher temperature adhesive, exhibited superb performance with the three different fiber types tested. The resorcinol formaldehydes and the phenol resorcinol formaldehydes also appeared to be totally adequate under these conditions with glass and graphite reinforcement, however the performance was only rated as marginal when used with the Kevlar® fiber. Neither the isocyanates nor the phenol formaldehyde proved suitable under the test conditions.

As with much of this research, economics again must be taken into consideration. Rowlands et al. (1986) concluded that the relatively inexpensive phenol resorcinol formaldehydes performed essentially as well as the resorcinol formaldehydes. Considering this, and recognizing that epoxies were the most expensive of the three acceptable adhesives, economics dictate that the preferable adhesive for creating a wood bond with either glass or graphite fiber is the phenol resorcinol formaldehyde.

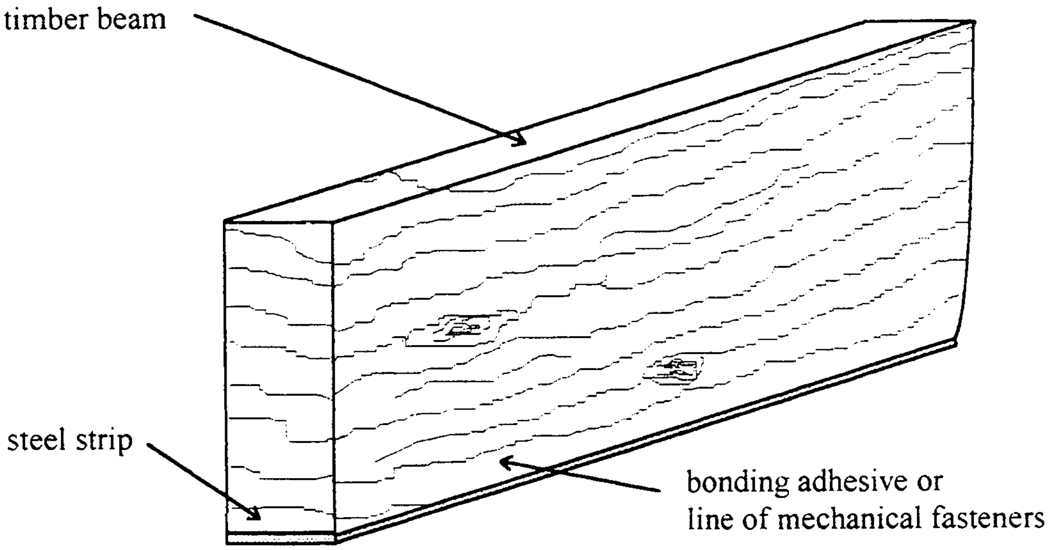


Figure 2.1 Bonded Steel Strip Specimen

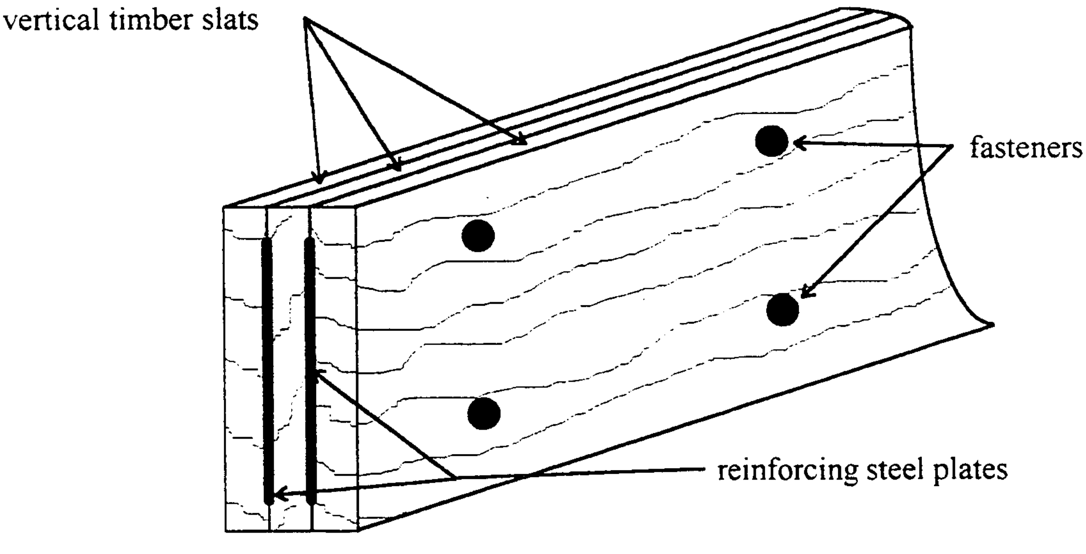


Figure 2.2 Flitch Beam

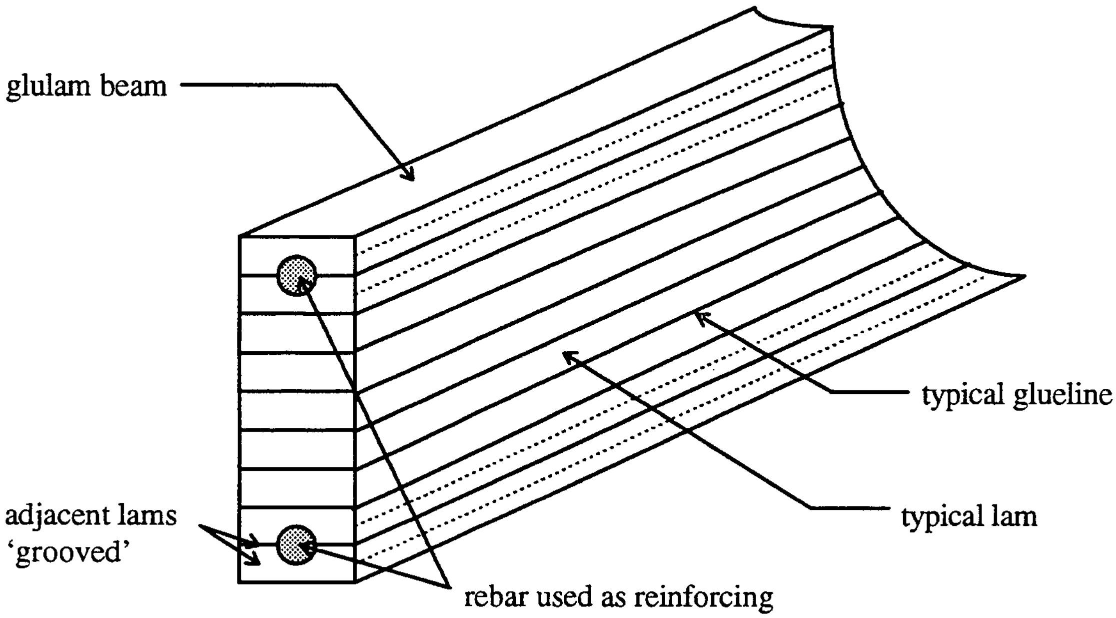


Figure 2.3 Rebar-Glulam Beam

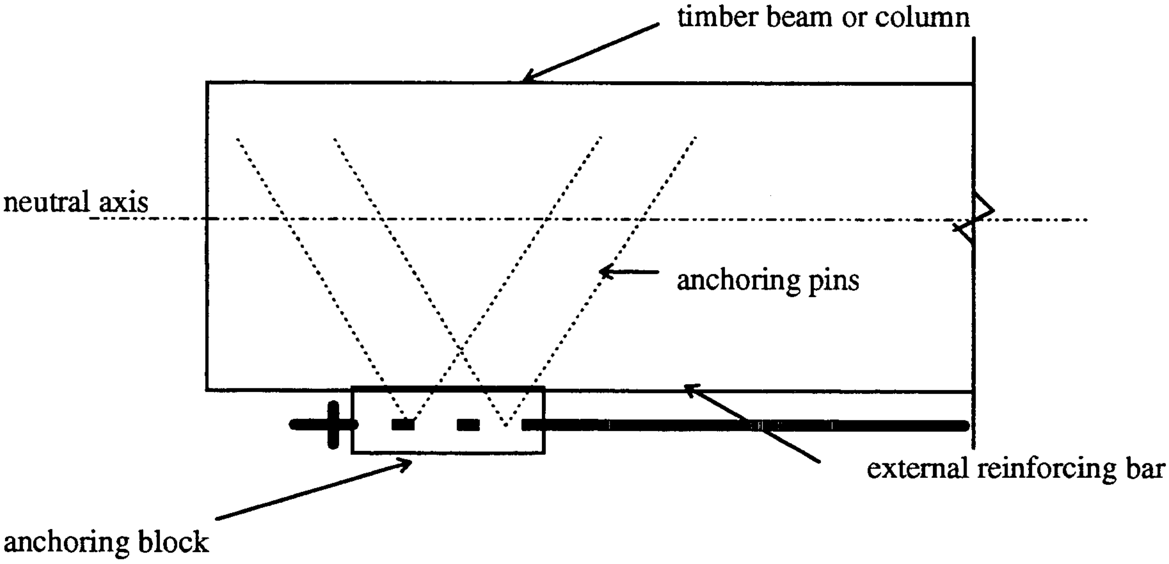


Figure 2.4 Turkovsky Reinforcing Anchor Bracket

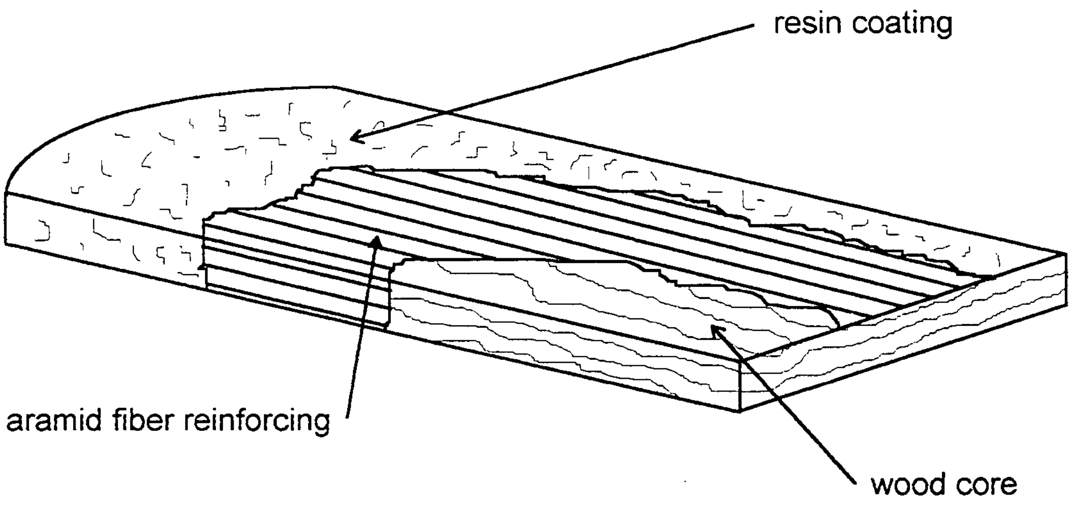
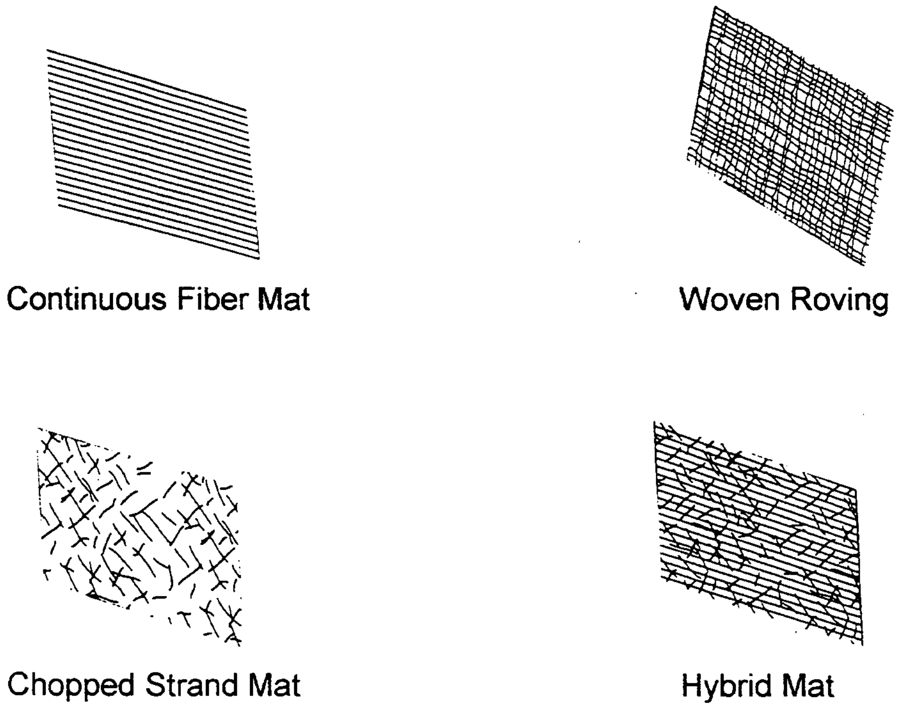


Figure 2.5
Tingley's FiRP Panel


Continuous Fiber Mat

Woven Roving

Chopped Strand Mat

Hybrid Mat

Figure 2.6
Different Fiber Orientations

3.0 EXPERIMENTAL PROGRAM

A test program was designed and conducted. The purpose of this program was to gain an understanding of the behaviour of fiber reinforced glulam timber and to determine a starting point for future research. The program consisted of a series of glulam beams with differing amounts, orientations and types of fiber pasted to the exterior of the specimens. These specimens were then tested to failure and a comparison drawn with unreinforced samples.

3.1 TEST PROGRAM SPECIMENS

A total of eight specimens, two unreinforced and six fiber reinforced, were tested in the experimental program. Test specimens were obtained from standard stocks at Western Archrib of Edmonton. The specimens were made from regular S-P-F stock timber. The bond between the lams was achieved using a phenolic resorcinol formaldehyde adhesive, supplied to Western Archrib by Borden of Canada.

The beams had a nominal cross-sectional area of 40 mm x 240 mm, giving a depth-to-width ratio of approximately 6:1. Specimen clear span length was selected to be 3840 mm which gave a span-to-depth ratio of approximately 16:1, thereby insuring pure bending behaviour. A specimen of 4280 mm total length was selected for two main reasons. It would allow for an approximate overhang of 220 mm in the testing apparatus as required in the ASTM Standard and it is a standard size produced by Western Archrib. A total of 13 lams were in the make up of these beams (Figure 3.1).

As previously discussed, the two parameters used to evaluate the effectiveness of the fiber reinforcing were the ultimate strength enhancement and the stiffness enhancement. Due to the destructive nature of determining an ultimate strength, strength enhancement was determined relative to the two unreinforced specimens tested. However, it was possible to determine an exact stiffness enhancement for each specimen. Each specimen that was to receive any fiber reinforcement was initially preloaded to approximately 50% of the capacity specified in CSA/CAN O86.1-94 (1994). From this data, the initial unreinforced stiffnesses for each individual specimen were determined.

3.2 TEST SET UP AND TESTING APPARATUS

Figure 3.2 shows the test setup used in this program. Two-point loading was selected for the test program because this would allow for a constant moment span region over the middle third of the beam. The test system was designed such that the primary information to be collected during testing was the load applied to the specimen and the resulting deflection. This was achieved by placing a load cell between the jacking system and the specimen to measure the total applied load. A secondary load measuring system was installed by placing load cells at each of the reaction points at the end of the samples.

The deflection of the specimen was measured at the centerline, using a cable transducer. From this centerline cable transducer, the total centerline deflection of the specimen, and therefore the apparent MOE, could be determined. By measuring the deflection at each of the applied point loads, the true MOE of each specimen could also be determined. Since the constant moment span deflection for a beam of this size with two evenly spaced point loads would be quite small, the cable transducer data was checked by placing an LVDT such that it directly measured the deflection in this region.

The specimens were laterally braced to ensure that the results obtained were a function of in-plane behaviour.

3.3 TYPES AND AMOUNTS OF FIBER USED IN TEST PROGRAM

As previously discussed, the primary types of fiber used in past timber reinforcing systems included glass, aramid and carbon. In the case of fiber reinforced glulam, to date extensive studies have been conducted on the use of KRP in FiRP panels (Tingley, 1990; Tingley and Leichti, 1993; Tingley, 1994). However, there have been no studies that have focused solely on the use of either glass or carbon fiber with glued laminated timber beams. Therefore, the test program was laid out to establish whether or not there was any potential for the use of these two fiber types as reinforcing material for glulam specimens.

Table 3.1 provides some of the physical properties of the tow sheets used in the experimental program.

Table 3.1 Properties of the Tow Sheets Used

Physical Property	Carbon Fiber Tow Sheet	Glass Fiber Tow Sheet
Forca Grade	FTS-C1-20	FTS-GE-30
Fiber	High Tensile Carbon	E-glass
Fiber Density (g/cm^3)	1.82	2.55
Tensile Strength (MPa)	3 480	1 520
Tensile Modulus (MPa)	230 540	72 590
Ultimate Elongation (%)	1.5	2.1

Under the test program, three different fiber orientations were examined. The first orientation was a full length 1-ply reinforcement along the bottom of the outer most tension lam. Beams with this reinforcement orientation were labeled with the "-1" suffix. The second orientation was a full length 2-ply reinforcement along the bottom of the outermost tension lam. Beams with this reinforcement orientation were labeled with the "-2" suffix. The third orientation was a full length 1-ply reinforcement along the bottom of the outermost tension lam, but extending up both sides of the beam to an approximate height of 74 mm, thus forming a reinforcement scheme U-shaped in cross-section. Beams with this reinforcement orientation were labeled with the "-3" suffix.

Initially, it was decided that a 40% fiber and 60% resin by weight mixture would be used. However, during the make-up of the specimens, it was found that this ratio provided an insufficient amount of resin to fully saturate the fiber. Previous work by Rowlands et al. (1986) indicated that a fully saturated fiber matte is required in order to develop the full capacity of the bonding system. Based on this premise of thorough saturation, it was found that a fiber to resin ratio of 1:3 for specimens with a single layer of reinforcing and a ratio of 1:2 for specimens with a double layer was required for the resin and fiber types used. Table 3.2 presents the amount of fiber and resin in each of the reinforced specimens.

Table 3.2 Quantities of Fiber and Resin Used

Specimen ID Number	Desired Fiber : Resin Ratio	Mass of Fiber Used (g)	Mass of Resin Required (g)	Mass of Resin Used (g)	Actual Fiber : Resin Ratio
PTG-1	1 : 3	66.9	200.7	212.2	1 : 3.17
PTG-2	1 : 2	134.0	268.0	293.3	1 : 2.19
PTG-3	1 : 3	290.3	870.9	890.3	1 : 3.07
PTC-1	1 : 3	41.5	124.5	135.1	1 : 3.26
PTC-2	1 : 2	82.2	164.4	180.6	1 : 2.20
PTC-3	1 : 3	185.2	611.2	633.4	1 : 3.42

3.4 FIBER FRACTION OF EACH SPECIMEN

The fiber fraction is the cross-sectional area of fiber in the specimen, as a percentage of the sum of the total area of wood and fiber. Obviously, the amount of fiber reinforcing applied to the specimen will affect the amount of enhancement that is achieved in the specimen. Theoretically, this relationship should be linear up to the capacity of the wood in the compression zone of the specimen. After that, any additional increase in fiber fraction should have little or no effect on the enhancement of a given specimen. The start of this "plateauing" of the curve will represent the optimum fiber fraction for further design work. Table 3.3 presents the fiber fraction for each of the reinforced specimens.

Table 3.3 Fiber Fraction of Each Specimen

Sample ID	Fiber Cross-Sectional Area (mm^2)	Total Cross-Sectional Area (mm^2)	Fiber Fraction (%)
PTC-1	4.38	9608	0.046
PTC-2	8.93	9806	0.091
PTC-3	20.6	9600	0.22
PTG-1	4.78	9769	0.049
PTG-2	9.42	9637	0.097
PTG-3	22.3	9759	0.23

3.5 APPLICATION OF FIBER REINFORCEMENT

After having determined the unreinforced MOE for each specimen, the specimens were then reinforced with the above described fiber systems. Fiber reinforcement was applied as outlined in the FORCA TOW SHEET TECHNICAL NOTES (1995) (Appendix A) received with the fiber and bonding epoxy from the supplier, with the following changes or notes:

- Under section 4-5 Adhesion of Tow Sheet, it is recommended that the maximum length of tow sheet used be less than 2 m. According to the supplier, the reason for this is ease of handling. Normally, the tow sheets are applied in widths of 0.5 m-2.0 m and lengths greater than 2.0 m can lead to hardening of the epoxy resin before placement is complete. Since the width of the tow sheet used in this application was approximately 40 mm, it was easy to fully apply the tow sheet within working limits of the epoxy resin. A further benefit of using full length tow sheets was that there were no points of possible discontinuity created in the construction of the fiber reinforcement.
- In accordance with section 4-6 Protection, a curing period of 1 week was used since the average ambient air temperature in the testing area was found to be 21°C (+/- 3°C) for the week following application. Samples were cured for a minimum of 7 days and 15 h before testing. The maximum curing period was 12 days and 18 h before testing.
- Section 4-7 Finish Coat, was omitted in the construction of the specimens. There was no concern of deterioration of the fiber reinforced specimens because they were tested immediately after the curing period and they were not exposed to adverse conditions.

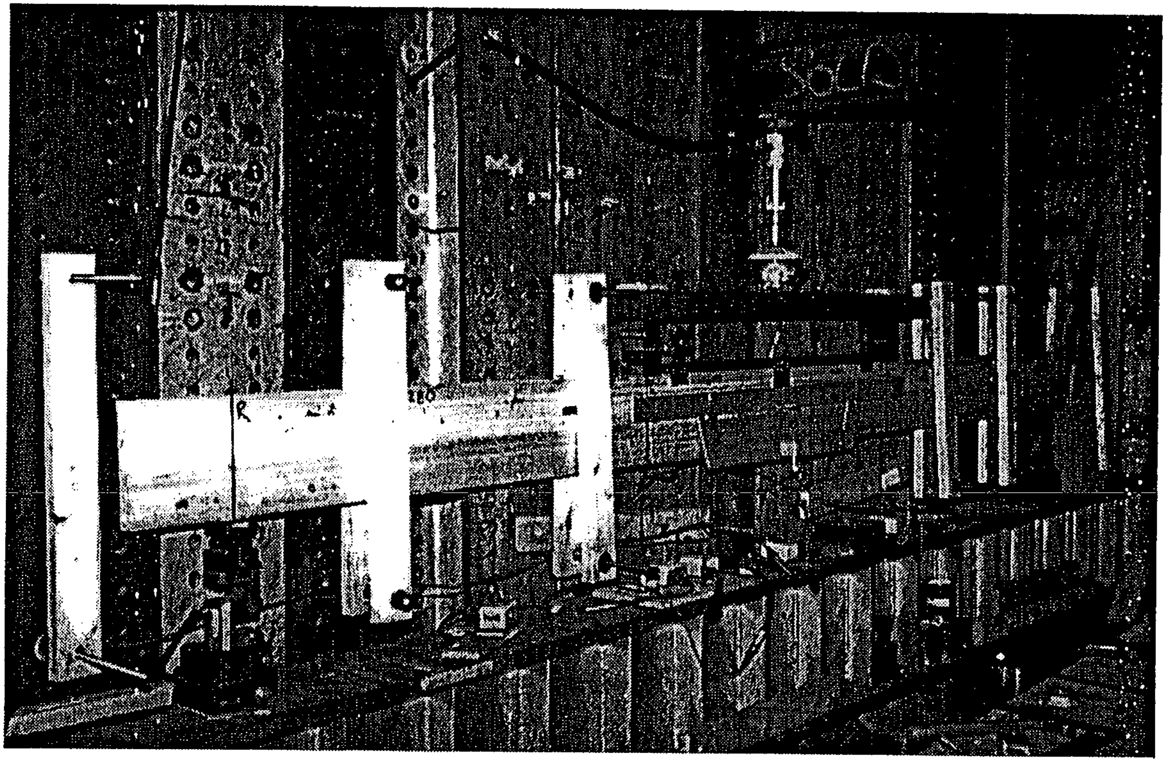


Figure 3.1 Typical Specimen From Supplier Placed in Test Set Up

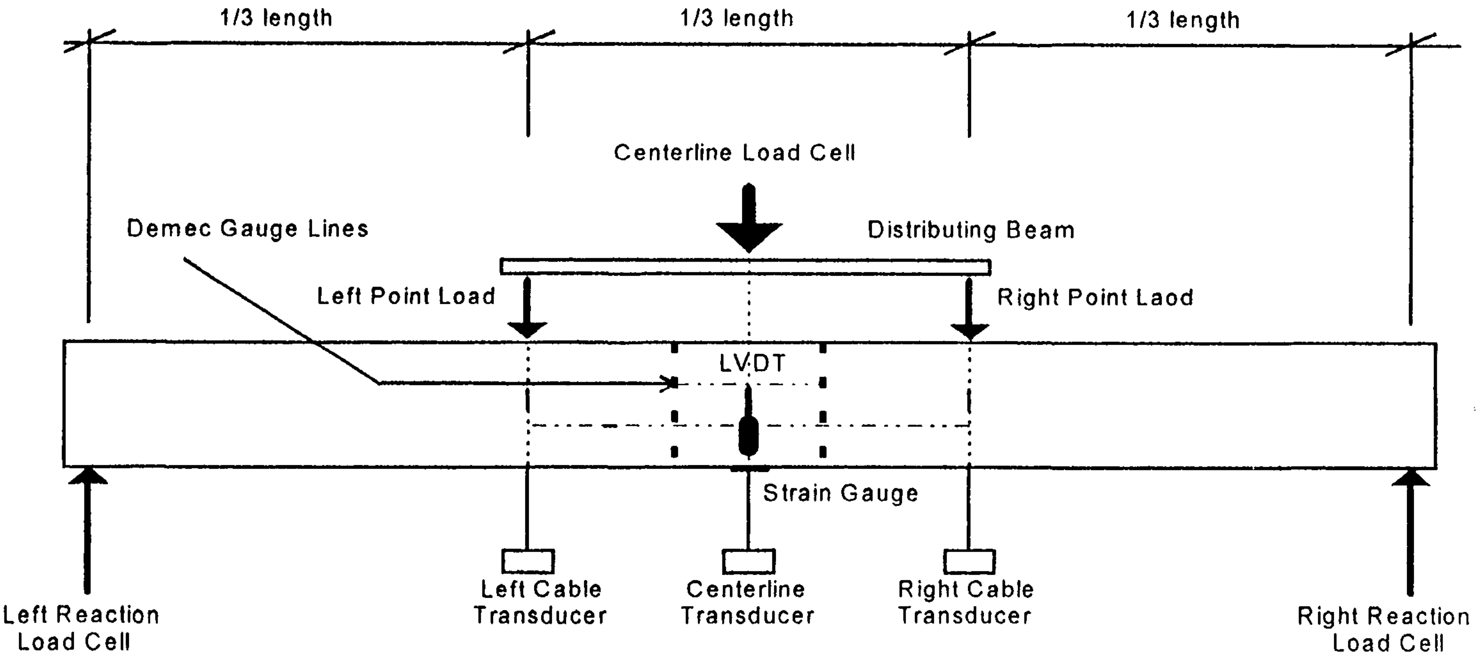


Figure 3.2 Schematic of Test Set-Up

4.0 TEST RESULTS

4.1 UNREINFORCED SAMPLES

4.1.1 Sample PTN-1

The ultimate failure load of PTN-1 was found to be 20.9 kN. The failure of this specimen occurred because of a fracture in the second lam up from the tension face. This fracture initiated at a knot located just outside of the constant moment span. It was observed that the bottom tension lam fractured immediately below this location. The failure of the beam then propagated through a series of knots, as shown in Figure 4.1.

4.1.2 Sample PTN-2

The ultimate failure load of PTN-2 was found to be 22.1 kN. The failure of PTN-2 occurred due to a fracture at a finger joint in the bottom lam. This finger joint was located approximately two-thirds of the way from the centerline to the left load point. It was observed that, after the bottom tension lam fractured, the failure propagated through a series of knots in the next five lams, located approximately at the load point, as shown in Figure 4.2.

4.2 REINFORCED SAMPLES

Samples PTC-1, PTC-2, PTC-3, PTG-1, PTG-2 and PTG-3 were the six samples that received the different types and amounts of fiber reinforcing.

Before each sample was reinforced, it was loaded to approximately 50% of the unreinforced ultimate load, as determined from the supplier's specifications. The data from this initial loading test was used to determine an unreinforced stiffness for each of the individual specimens. This unreinforced stiffness was used to determine the stiffness enhancement of the sample, achieved through the specific fiber reinforcing applied to the individual sample.

Since the determination of the ultimate strength is a destructive test, it was not possible to determine an unreinforced ultimate strength for each of these samples. In order to calculate the amount of enhancement provided by the fiber reinforcing, the ultimate strength of the two unreinforced specimens was used in the subsequent ultimate strength enhancement calculations.

4.2.1 Sample PTC-1

The ultimate load of PTC-1 was found to be 27.2 kN. The failure appeared to occur because of a large knot located 790 mm to the right of the centerline, in the third tension lam from the bottom of the sample. This fracture lead to a shear failure from this location to the right hand end of the specimen. The fracture also propagated further fracture through the region between the centerline and the right hand load point, as shown in Figure 4.3.

Fracture of the bottom tension lam occurred 150 mm to the right of the centerline, which in turn caused a stress concentration in the fiber reinforcing at this point and, ultimately, in the fracturing of the fiber reinforcement.

4.2.2 Sample PTC-2

The failure load of PTC-2 was found to be 32.7 kN. The failure appeared to occur because of a shear failure between the second and third lams from the bottom of the specimen. There was no visible explanation for the failure to occur at this location. The second lam from the bottom also fractured 800 mm to the left of the centerline of the specimen. This fracture propagated further fractures through a series of knots located between 700 mm and 1000 mm to the left of the centerline, as shown in Figure 4.4.

Crushing of the top lam was also observed at a location 7 mm to the right of the centerline. The fiber reinforcing fractured at a location of 1540 mm to the right of the centerline. There was no visible explanation for fracture at this location.

4.2.3 Sample PTC-3

The failure load of PTC-3 was found to be 32.9 kN. The failure appeared to occur because of a combination of a finger joint and a series of knots located 195 mm to the left of the centerline, in the second and third tension lams from the bottom of the sample. The fracture then propagated through a series of knots up to approximately the neutral axis of the sample, as shown in Figure 4.5.

Both the front and back side reinforcing delaminated from the wood at failure. In this delamination, it was observed that it was the wood that sheared, not the bonding adhesive.

4.2.4 Sample PTG-1

The failure load of PTG-1 was found to be 26.3 kN. The failure appeared to occur because of a knot in the extreme tension lam, located 865 mm to the right of the centerline. Because of the fracture in this outer tension lam, a stress concentration occurred in the fiber reinforcing, leading to the fracturing of the reinforcing at this location. The failure pattern then followed a series of knots, primarily located 465 mm to the right of the centerline, as shown in Figure 4.6.

There was evidence of sloped grain failure in the fractured lams.

4.2.5 Sample PTG-2

The failure load of PTG-2 was found to be 28.3 kN. The failure occurred through a series of knots located in the fourth tension lam from the bottom of the specimen, centered approximately 190 mm to the right of the centerline. The failure pattern then appeared to pass through a finger joint located in the second tension lam from the bottom, located 30 mm to the right of the right hand load point, as shown in Figure 4.7.

There was no evidence of crushing in the compression zone and the fiber reinforcing did not fracture during the loading of the specimen.

4.2.6 Sample PTG-3

The failure load of PTG-3 was found to be 32.2 kN. The failure appeared to be directly related to a large, partially rotten knot, located 60 mm to the left of the centerline in the fourth tension lam from the bottom of the specimen. This, coupled with a knot at 75 mm to the left of the centerline in the sixth lam from the bottom and crushing in the top lam, appeared to have lead to the failure of the sample, as shown in Figure 4.8.

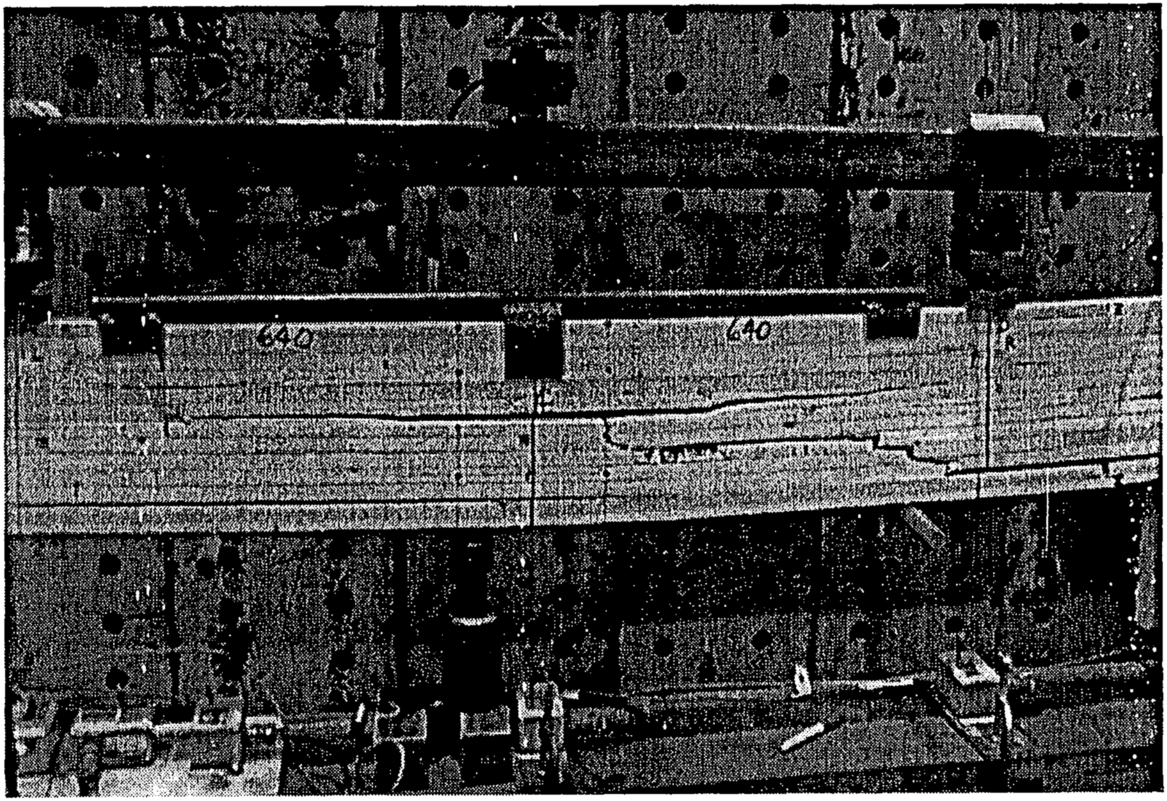


Figure 4.1 Failure of Sample PTN-1

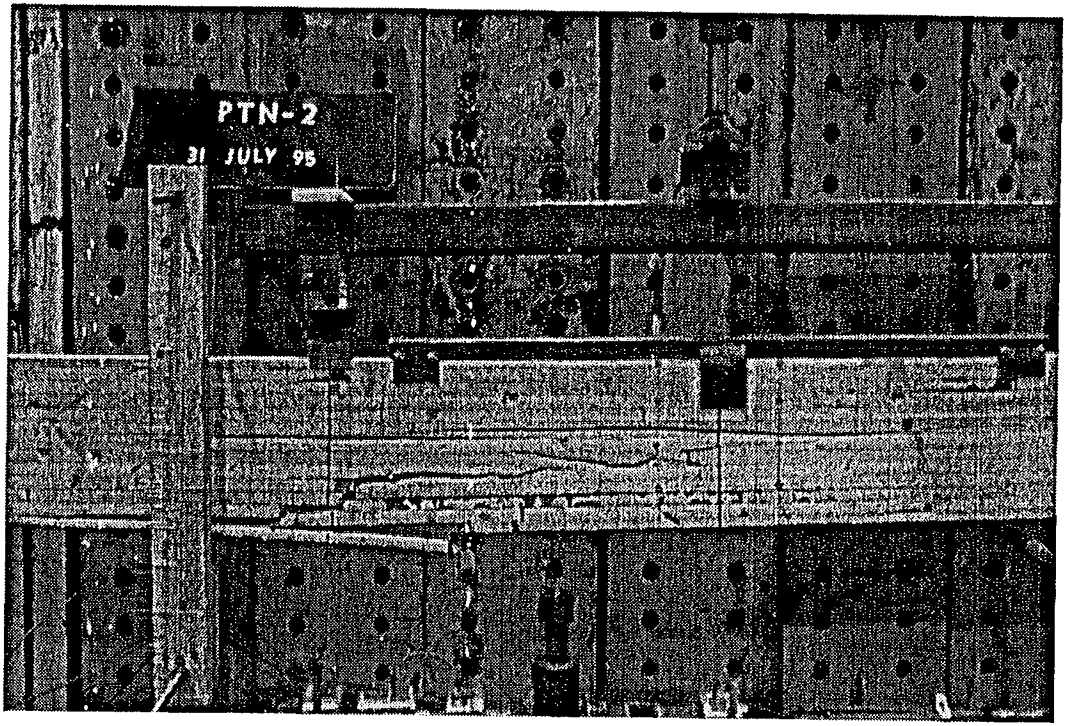


Figure 4.2 Failure of Sample PTN-2

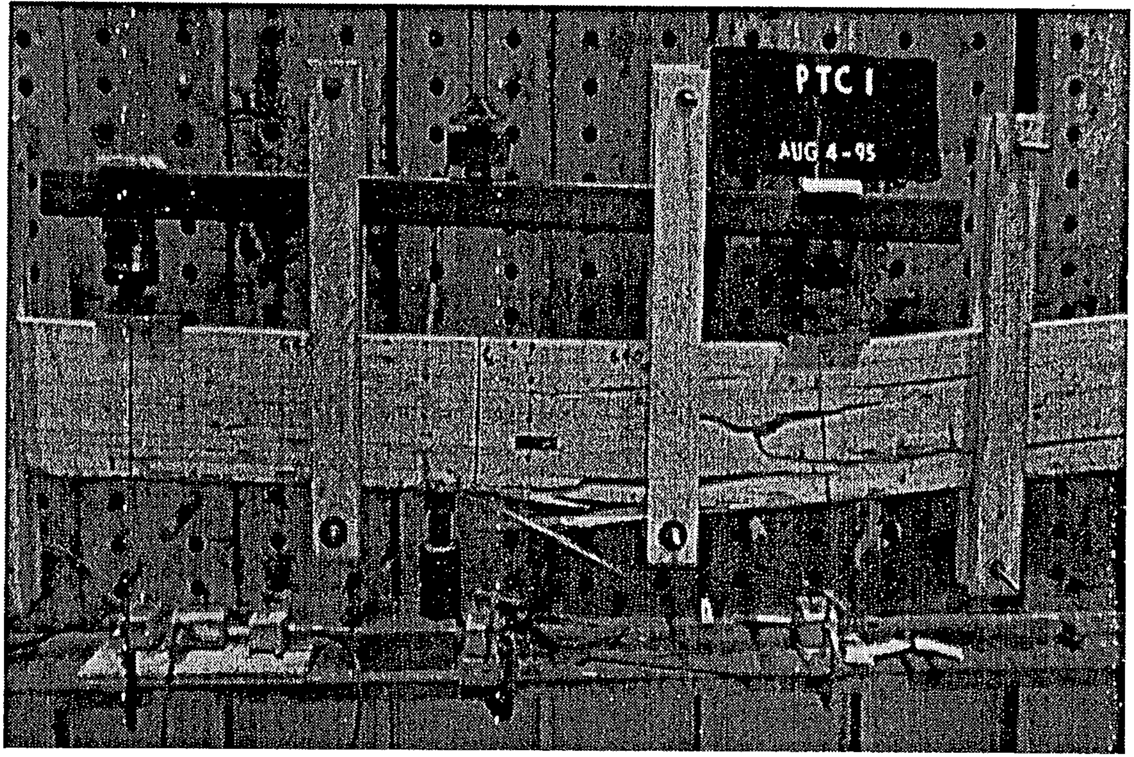


Figure 4.3 Failure of PTC-1

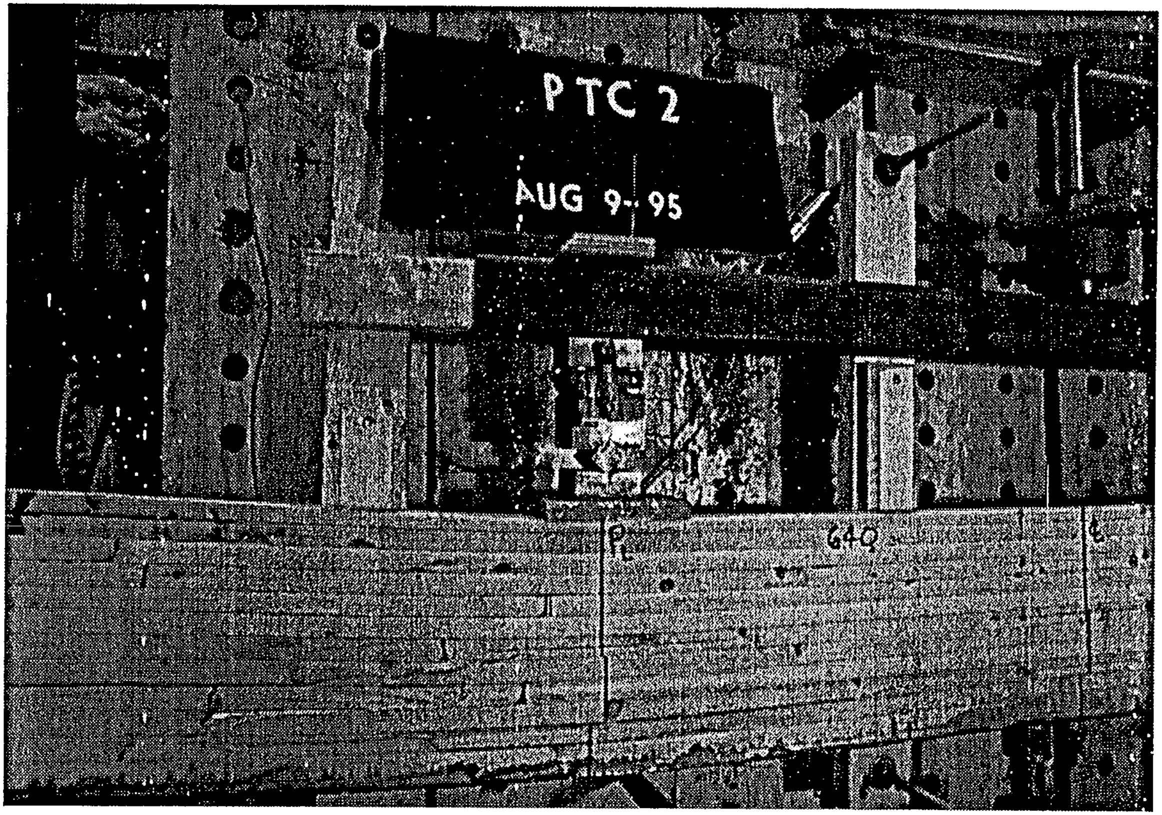


Figure 4.4 Failure of PTC-2

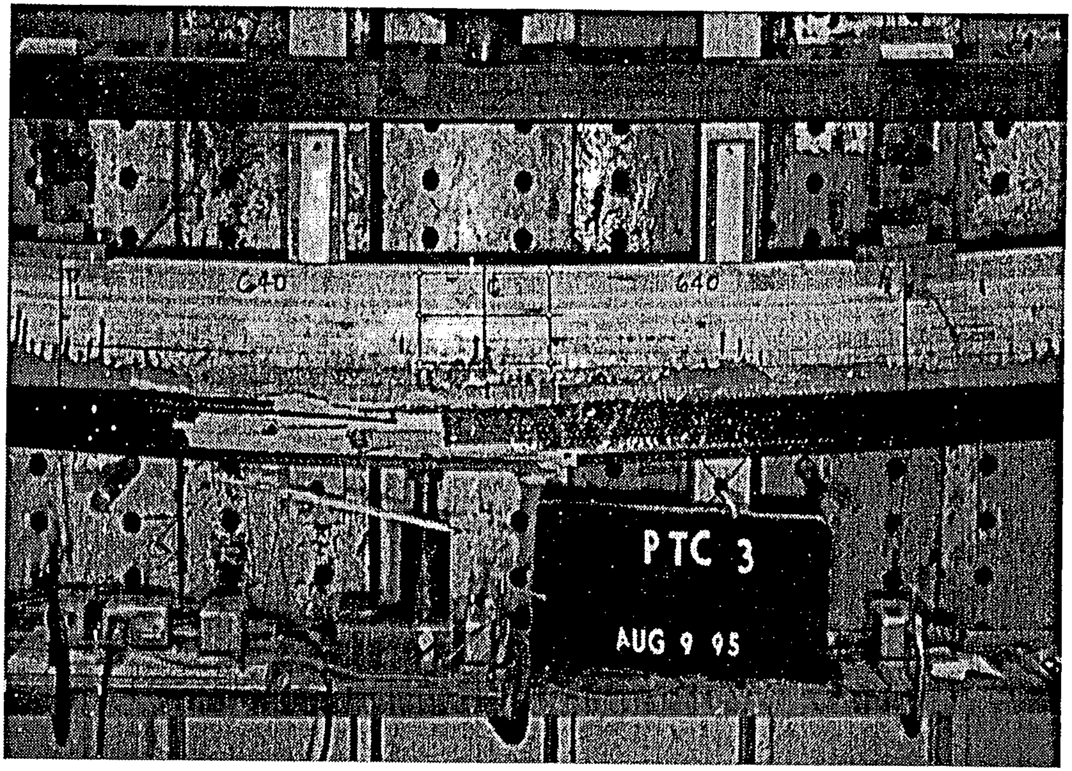


Figure 4.5 Failure of PTC-3

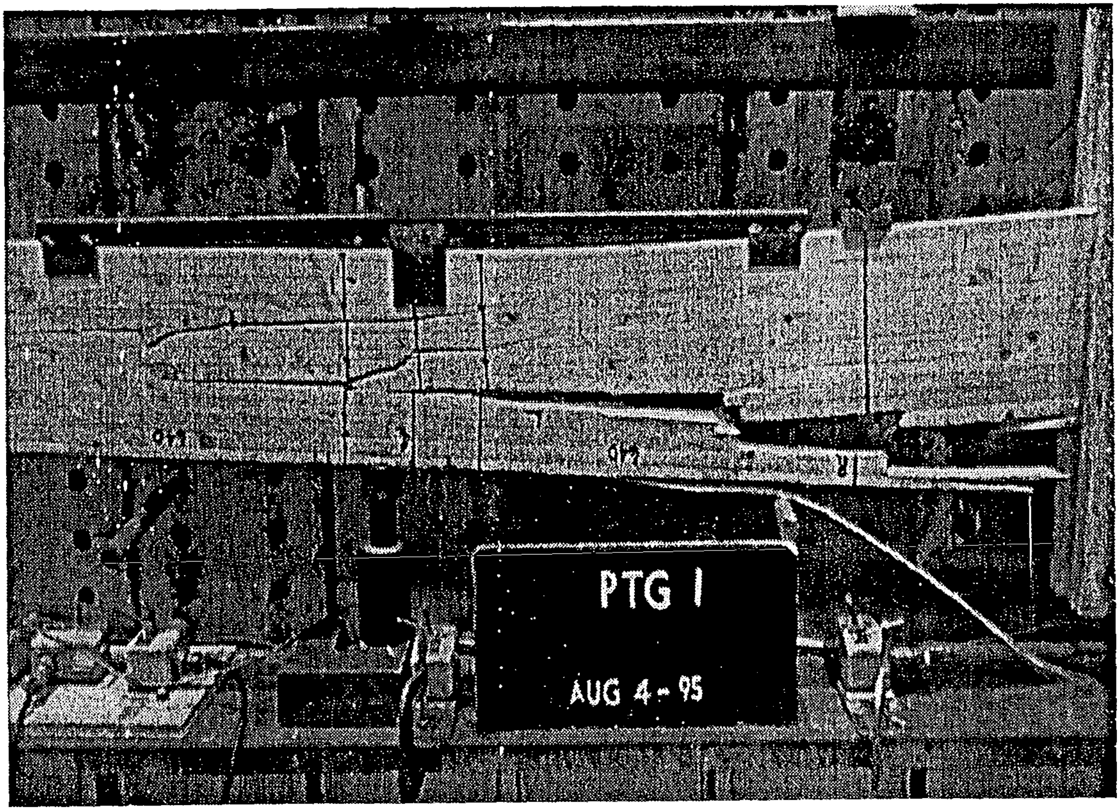


Figure 4.6 Failure of PTG-1

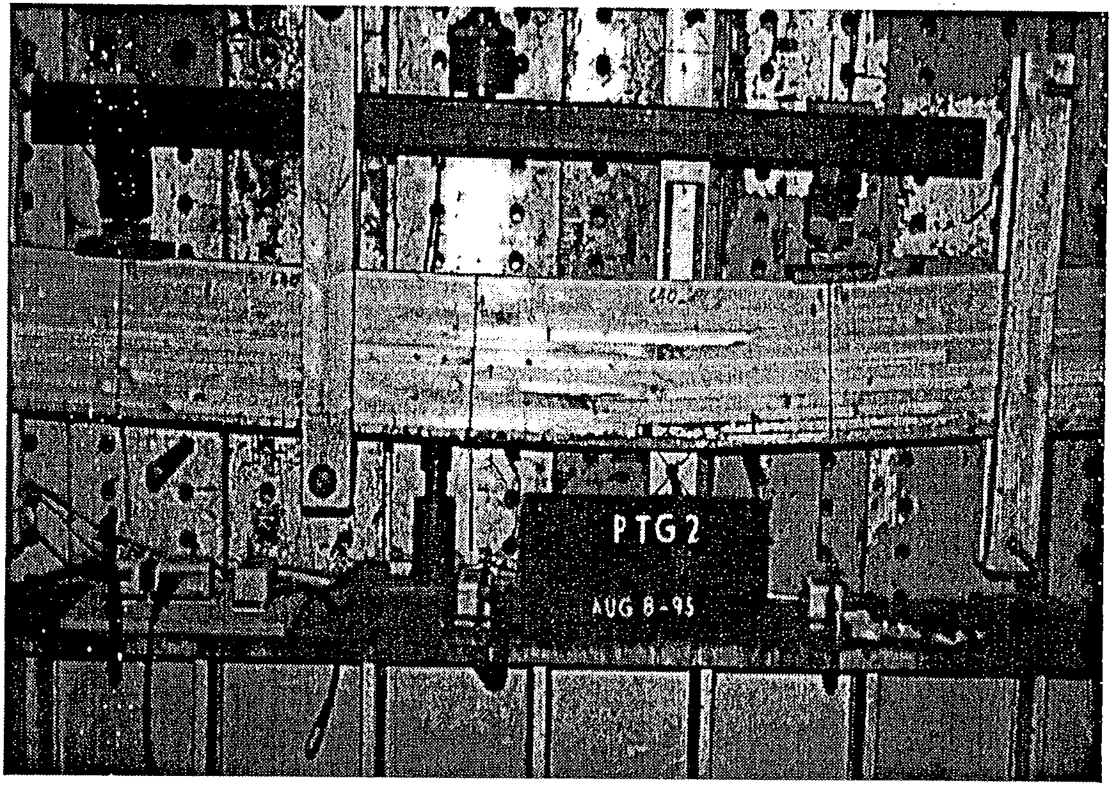


Figure 4.7 Failure of PTG-2

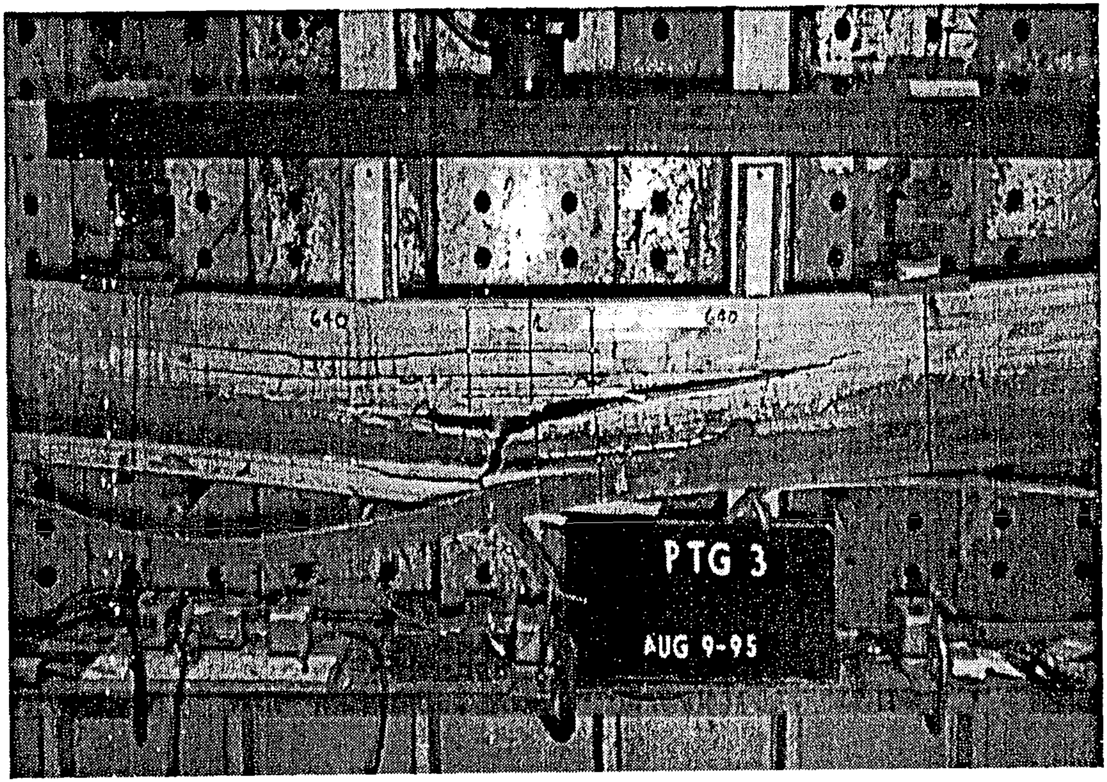


Figure 4.8 Failure of PTG-3

5.0 DISCUSSION OF RESULTS

5.1 ULTIMATE STRENGTH ANALYSIS

The values reported for the experimental failure loads were determined from the peak values recorded during testing of the specimens. The upper bound solution is determined using a fully plastic section, as shown in Figure 5.1.

However, this analysis inherently assumes that the wood has the capacity to undergo plastic deformations. Since wood generally fractures almost immediately after the ultimate strain has been reached, this assumption is not valid unless confinement is provided to the wood section. Therefore, an ultimate strength analysis was done to determine the ultimate strength, assuming linear strain behaviour up to the strength at fracture and strain compatibility between the strain in the fiber reinforcing and the ultimate strain in the wood, that is, $\varepsilon_f = \varepsilon_{uw}$. The ultimate strain in the wood was determined by extrapolating the strain data collected to the failure load, using either the strain gauge data or the demec gauge data as appropriate. It is recognized that this may not represent the exact true behaviour, however it gives the "best estimate" available.

Table 5.1 presents a comparison between the experimental failure load, the upper bound solution from the plastic section analysis, and the ultimate load as determined using the fiber-wood strain compatibility.

Table 5.1 Ultimate Strength of Test Specimens

Specimen ID Number	Experimental Failure Load (kN)	Strain Compatibility Analysis (kN)	Upper Bound Solution (kN)
PTN-1	20.9	n/a	n/a
PTN-1	22.1	n/a	n/a
PTC-1	27.2	22.8	35.8
PTC-2	32.7	27.4	43.8
PTC-3	32.9	30.3	50.1
PTG-1	26.3	24.4	37.5
PTG-2	28.3	24.8	39.0
PTG-3	32.2	28.3	45.3

From these results, it was observed that the actual failure load was less than the upper bound solution, as expected. However, the strain compatibility analysis provided a theoretical result that was significantly less than the actual load. There are a number of reasons for the conservativeness of this result. First is that there is most likely a stress redistribution between the fiber reinforcing and the adjacent tensile wood fibers. Since the fiber is not stressed to its ultimate load, this redistribution could account for the greater actual failure load. Secondly, the extrapolation procedure only provides an estimated strain at failure and this estimate would be conservative in all cases using a linear extrapolation if the behaviour of the specimen became nonlinear as it approached failure. Finally, it is important to remember that there may be significant variations simply due to the perversity of wood as structural material.

5.2 ULTIMATE STRENGTH ENHANCEMENT

In all cases, the fiber reinforced specimens showed an increase in strength over the unreinforced samples. Table 5.2 shows the percent fiber fraction and the amount of ultimate strength enhancement achieved in each of the reinforced test specimens.

Table 5.2 Ultimate Strength Enhancement

Specimen ID	% Fiber Fraction	% Ultimate Strength Enhancement
PTC-1	0.046	26.5
PTC-2	0.091	52.1
PTC-3	0.22	53.0
PTG-1	0.049	22.3
PTG-2	0.097	31.6
PTG-3	0.23	49.8

These results indicate that there is definite potential for the use of fibrous material as a reinforcing system for glulam timber members. With a fiber fraction as small as 0.046% by area, an increase of 26.5% in the strength of the member was achieved in the case of specimen PTC-1.

Of the results obtained, the greatest capacity increase for the respective fiber types was observed in the specimens that had the reinforcing wrapped partially up the sides of the glulam beam. However, it was noted that for the carbon fiber reinforced member PTC-3, a 142% increase in the fiber fraction only resulted in a 1.7% increase in the capacity, when compared to PTC-2. For the glass fiber reinforced member PTG-3, a 137% increase in the fiber fraction resulted in a 58% increase in the capacity, when compared to PTG-2. This suggests that the more efficient section is the one that has the two layers of reinforcing on the exterior face of the bottom lam.

The reasons for this are twofold. First of all, in the case of the specimens with the two layers of reinforcing on the exterior face of the bottom lam, there is a greater amount of reinforcing material further away from the neutral axis. Since the capacity of the section is a function of the depth of the reinforcing, the greater the distance between the centroid of the reinforcing and the neutral axis of the specimen, the greater the contribution of the reinforcement.

Secondly, the double layer of fiber has a greater fracture resistance when a stress concentration is suddenly placed on it. As well, there is a greater amount of epoxy resin, which further enhances this fracture resisting capacity.

There are mixed indicators as to which sample shows the greatest amount of promise for future study. Numerically, specimen PTC-2 seems to have the most significant impact on enhancing the ultimate strength of the unreinforced sample. In this sample, two layers of carbon fiber reinforcing were laminated to the bottom of the extreme tension lam. With a fiber fraction of 0.091% by cross-sectional area, a resulting capacity increase in the order of 52.1% was achieved. However, when economics are considered, specimen PTG-2 shows more economical promise. The carbon fiber used cost 78% more than the glass fiber used, but only provided 65% more strength enhancement. As previously outlined, economics are one of the main driving forces behind this research. Therefore, when economics are considered a factor, the glass fiber appears to be the favored reinforcing material.

These results show significant promise, even more so than the work conducted by Tingley in 1994. Tingley reported that with the use of KRP, moment capacity increases in the order of 115% were achieved. However, his work involved using fiber fractions in the order of 1.2-1.3%. With a fiber fraction of 0.091% for carbon, a capacity increase in the order of 52.1% was achieved. With a fiber fraction of 0.097% for E-glass, a capacity increase in the order of 31.6% was achieved. It should be noted that there are some inherent differences between the application of the fiber done by Tingley and the application done in this project. Tingley's work involved the use of FiRP panels, which introduces two layers of reinforcing in the glulam member, one layer in each of the two gluelines closest to the extreme tension fiber in the member. In this project, all of the reinforcement was bonded directly to the bottom of the member, beyond the extreme wood tension fiber. These contrasts in construction may account for the observed differences in behaviour, however, further testing is required to confirm this.

A graphical comparison of the different fiber fractions was done by plotting the percent ultimate strength enhancement against the percent fiber fraction. Figure 5.2 shows this plot for the carbon fiber reinforced specimens and Figure 5.3 shows the plot for the glass fiber reinforced specimens.

The general trend in each plot shows that as percent fiber fraction increases, the percent increase in capacity relative to the unreinforced member correspondingly increases, until it ultimately reaches some sort of a peak value. This is logical because, initially the percent increase in capacity should increase linearly with fiber fraction. However, the compressive capacity of the specimen will begin to play a role in the allowable capacity increase until, eventually, it governs the capacity of the section entirely. At this point, the wood in the compression zone has reached its full plastic capacity and any additional fiber reinforcing added only serves to lower the stress in the fiber, without having an impact on the compressive capacity, or overall capacity of the wood.

This general trend is seen in both plots, however, neither plot seemed to follow the trend exactly. It is again mentioned that only one specimen of each fiber type and fraction was tested and that, given the perversity of wood as an engineering material, one sample may skew the picture in one direction or another. It is therefore concluded that the exact relationship for each fiber type is inconclusive from the data available, however, the general trend meets the expected behavior, as previously discussed.

5.3 LOAD-DEFLECTION PLOTS

A load - deflection plot was generated for each of the reinforced specimens, as shown in Figures B.1 to B.6 in Appendix B. Each plot shows the theoretical behaviour and limits, beside the experimental behavior observed during testing. The ultimate load limit presented on the graph comes from the solution of the fully plastic section analysis from Figure 5.1 and is included on the plot as an upper bound limit.

The proportional limit for each specimen was determined and plotted on the load-deflection graph. The proportional limit was taken as the point where the extreme compression fiber has reached it's maximum capacity, but before the section starts to exhibit any plastic behaviour or before any stress redistribution starts to take place. Material properties from the two unreinforced specimens and the transformed section properties were used in the analysis.

From these load - deflection plots, it can be seen that the experimental behavior of each specimen agreed very well with the expected behavior. In each case, below the proportional limit, the experimental data coincided exactly with the theoretical data. At the proportional limit, the experimental data began to "curl away" from the linear elastic prediction, as was expected. In each case, the experimental failure load fell between the proportional limit and the upper bound solution for the ultimate failure load. The theoretical behaviour of the section was determined on the basis of the linear elastic behaviour exhibited by wood and the assumption that plane sections remain plane. This assumption was tested using demec gauges. In all cases, the demec plots exhibited the general linear relationships, as shown in Figure 5.4.

There were a few noted variations to the linear behaviour. For specimen PTC-1, it was observed that the data from the demec points located at 60 mm from the top compression fiber were consistently slightly out of agreement with the straight line expectation. This was also the case for all of the readings taken at a depth of 180 mm in PTG-3. Data manipulation indicated that if the position of the 60 mm demec points in PTC-1 were in fact at 67 mm, then a straight line plot would result. Similarly, if the position of the 180 mm demec points in PTG-3 were at 188 mm, it would also have produced straight line data.

It was not possible to confirm if these adjusted values were in fact the exact location of the demec points because the demec points were removed after each test for subsequent specimens. The fact that these "misplacements" were consistent through all the different load readings indicates that the depth measurements taken for these positions were incorrect and that the specimens do in fact behave linearly.

There were two other deviations from the linear behaviour in the demec plots. All of the data collected from the demec points located on the bottom fiber of specimen PTC-2 did not follow the linear relationship for loads greater than 15.9 kN. It was noted that a loud crack was heard at approximately 16.0 kN. One possible explanation for the observed deviation in the behaviour could be that this cracking sound corresponded to a small fracture in the tension zone of the specimen, between a depth of 180 mm and the bottom fiber, between the demec points. This small fracture could have resulted in an additional movement between the two demec points, resulting in the "jump" observed in the demec plots.

The second deviation occurred in specimen PTG-1. The linear strain relationship changed at a load of 24.2 kN for the demec points located 5 mm from the top fiber. At this load, the data showed a sudden increase in compressive strain. It should be noted that crushing of the top lam was first observed at a load of 24.0 kN, which would account for this sudden increase in compressive strain.

During the failure tests done on each specimen, a single strain gauge was mounted on the extreme tension fiber, at the centerline of the sample. The purpose of the strain gauge was to verify the plane strain assumption used in the calculations. From the plot of load versus strain gauge reading, shown in Figure 5.5, it can be seen that the plane strain assumption is valid.

5.4 STIFFNESS ANALYSIS

Each specimen that was to receive reinforcing was loaded to approximately 50% (+/- 10%) of its theoretical ultimate load, prior to applying its fiber reinforcement. Data was collected from these tests in order to determine an initial stiffness for the individual specimens. Figure 5.6 shows the typical relationship between total applied load and the total centerline deflection for an unreinforced specimen.

The apparent Modulus of Elasticity was derived from the slope of these graphs using the relationship in Equation 5-1 and the corresponding unreinforced apparent stiffness for the specimen calculated.

$$\Delta = 23*P*L^3 / (648*E*I) \qquad (5\text{-}1)$$

Constant moment span deflection data was collected using an LVDT. The LVDT was positioned to measure the relative deflection between the load points and the centerline. Figure 5.7 shows a typical plot of centerline load against this constant moment span deflection for the unreinforced specimens.

The true Modulus of Elasticity was derived from the slope of this graph, using the relationship in Equation 5-2, which was derived using the area-moment theorem

$$\Delta = P * L^3 / (16*E*I) \tag{5-2}$$

The corresponding unreinforced true, shear free stiffness for the specimen was then calculated from the derived MOE.

Constant moment span deflection data was also collected using a series of cable transducers. The cable transducers were positioned to measure the deflection at each of the load points and at the centerline. By subtracting the average values of the two point load cable transducers from the centerline one, a second determination of the constant moment span deflection could be made. Figure 5.8 shows a typical plot of centerline load against this constant moment span deflection for an unreinforced specimen.

The true Modulus of Elasticity was also derived form the slope of this graph, using equation 5-2 and the corresponding unreinforced true, shear free stiffness for the specimen was determined for comparison purposes.

After the application of the fiber reinforcing, a similar set of data was collected and the reinforced stiffness determined for each sample. Figure 5.19 shows a typical relationship between total applied load and the total centerline deflection for a reinforced specimen, Figure 5.10 shows a typical plot of centerline load against the constant moment span deflection using the cable transducer data for a reinforced specimen, and Figure 5.11 shows a typical plot of centerline load against the constant moment span deflection using the LVDT data for a reinforced specimen.

Using the relationship shown in the plot in Figure 5.9, the reinforced apparent Modulus of Elasticity was determined and the corresponding reinforced apparent stiffness calculated for each individual specimen.

Using the relationship shown in the plot in Figure 5.10, the reinforced true Modulus of Elasticity, using the cable transducer data, was determined and the corresponding reinforced true stiffness calculated for each individual specimen.

Using the relationship shown in the plot in Figure 5.11, the reinforced true Modulus of Elasticity, using the LVDT data, was determined and the corresponding reinforced true stiffness was again calculated for each individual specimen.

Each of these plots, for both the unreinforced and reinforced specimens, were expected to be linear and in all cases, the correlation of the resulting slopes for the graphs ranged from 0.98855 to 0.99996. Correlations of this magnitude indicate that the linear assumption is valid.

Table 5.3 presents a comparison between the unreinforced apparent stiffness and the reinforced apparent stiffness for the specimens.

Table 5.3 Unreinforced and Reinforced Apparent Stiffness

Specimen ID Number	Unreinforced Apparent Stiffness ($N*mm^2$)	Reinforced Apparent Stiffness ($N*mm^2$)
PTN-1	5.54 E+11	n/a
PTN-2	5.05 E+11	n/a
PTC-1	5.02 E+11	4.97 E+11
PTC-2	5.16 E+11	5.17 E+11
PTC-3	5.51 E+11	5.79 E+11
PTG-1	5.18 E+11	5.12 E+11
PTG-2	5.19 E+11	5.54 E+11
PTG-3	5.05 E+11	5.12 E+11

Table 5.4 presents a comparison between the unreinforced true stiffness and the reinforced true stiffness for the specimens from the cable transducer data.

Table 5.4 Unreinforced and Reinforced True Stiffness From Cable Transducer Data

Specimen ID Number	Unreinforced True Stiffness ($N*mm^2$)	Reinforced True Stiffness ($N*mm^2$)
PTN-1	5.59 E+11	n/a
PTN-2	4.84 E+11	n/a
PTC-1	4.88 E+11	4.47 E+11
PTC-2	5.42 E+11	5.45 E+11
PTC-3	5.84 E+11	5.03 E+11
PTG-1	5.07 E+11	4.96 E+11
PTG-2	5.37 E+11	5.55 E+11
PTG-3	4.80 E+11	4.90 E+11

Table 5.5 presents a comparison between the unreinforced true stiffness and the reinforced true stiffness for the specimens from the cable transducer data.

Table 5.5 Unreinforced and Reinforced True Stiffness From the LVDT Data

Specimen ID Number	Unreinforced True Stiffness ($N*mm^2$)	Reinforced True Stiffness ($N*mm^2$)
PTN-1	n/a	n/a
PTN-2	n/a	n/a
PTC-1	4.01 E+11	5.99 E+11
PTC-2	5.22 E+11	6.10 E+11
PTC-3	5.45 E+11	9.65 E+11
PTG-1	5.47 E+11	6.41 E+11
PTG-2	5.57 E+11	7.10 E+11
PTG-3	5.37 E+11	10.57 E+11

Examination of the data using the LVDT shows a number of different results than that from the cable transducer. First of all, there is no unreinforced true stiffness reported for the two unreinforced specimens. This is because, at the time the two unreinforced specimens were tested to failure, the LVDT had not been correctly connected to the data acquisition system and the data was not properly recorded.

It was also necessary to ignore the data collected using the LVDT for the reinforced samples. While the connection between the LVDT and the fluke data acquisition system was confirmed to be intact, the calibration factor determined for the LVDT used was incorrect. Recalibration of the LVDT after testing showed that the factor applied to the LVDT appeared to be out by 13.4%. The data collected using the LVDT was adjusted using the new calibration factor, however, the data still did not agree with the cable transducer, or expected values. It was therefore decided that the LVDT data would be omitted from the analysis. It should be noted that the failure of most of the specimens was extremely explosive and, given that LVDT's are very sensitive instruments, this explosive failure may have caused damage to the instrument, resulting in the erroneous data it generated.

5.5 STIFFNESS ENHANCEMENT

Both the apparent stiffness enhancement and the true stiffness enhancement were calculated for each of the reinforced specimens. Table 5.6 shows both the percent apparent and true stiffness enhancements.

Table 5.6 Stiffness Enhancement

Specimen ID	% Fiber Fraction	% Apparent Stiffness Enhancement	% True Stiffness Enhancement
PTC-1	0.046	-1.00	-8.40
PTC-2	0.091	0.19	0.55
PTC-3	0.22	5.08	-13.9
PTG-1	0.049	-1.16	-2.17
PTG-2	0.097	6.74	3.35
PTG-3	0.23	1.39	2.08
Average		1.87	-3.08

The results presented in Table 5.6 indicate that the application of the fiber reinforcing provides no obvious stiffness enhancement to the glulam beams. The variations shown in the above table are well within experimental variations for the testing of timber specimens. It is well known that, given the variability of wood, even the same member tested more than once will yield slightly different results on each trial. The average values of 1.87% and -3.08% can be considered well within the variability often experienced in timber specimens, and therefore impossible to positively identify any enhancement that may, in fact, exist.

These results are not unexpected. Given that the cross sectional area of fiber is so small when compared to the total cross sectional area of the sample, the fact that the fiber is so much stiffer than the wood has little effect on the overall stiffness of the reinforced specimen. It would be expected that at greater fiber fractions, the stiffness would significantly increase. Given that the maximum fiber fraction used in this research was 0.23%, the effective increases would be so small that it would not be noticeable, when the variation of timber is taken into account.

Work done by Tingley (1994) found that a fiber fraction of 1.2-1.3% provided an increase in stiffness of approximately 30%. Using a linear relationship for comparative purposes, Tingley's results would indicate that for a fiber fraction of 0.1%, the increase in stiffness would be in the order of 2.5%. As previously mentioned, this small an increase may not be apparent, given wood's fluctuating mechanical properties.

Again, it should be noted that only one specimen of each type was tested and that a concrete formalization of the specimen behaviour cannot sensibly be based on a single sample when dealing with a material as inconsistent as wood. It is, therefore, again determined that the exact relationship for each fiber type is inconclusive from the data available.

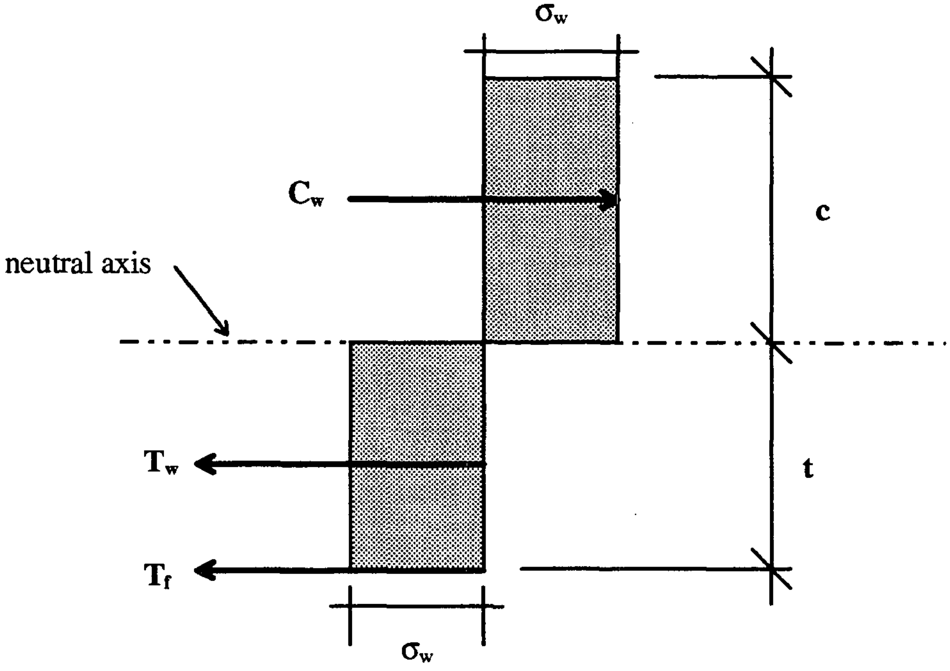


Figure 5.1 Plastic Section Used in the Analysis to Determine P_{ult}

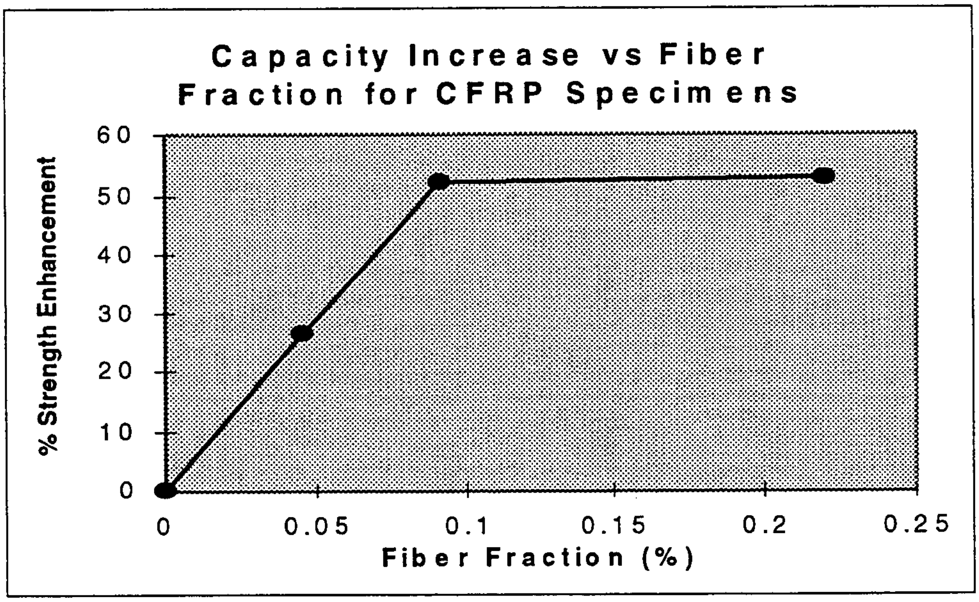


Figure 5.2 Capacity Increase versus Fiber Fraction for CFRP Specimens

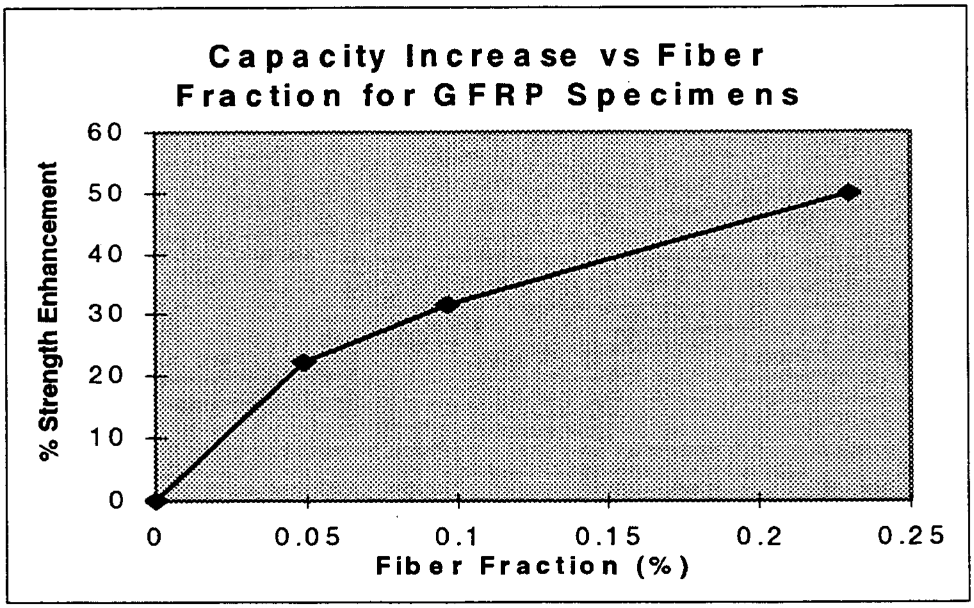


Figure 5.3 Capacity Increase versus Fiber Fraction for GFRP Specimens

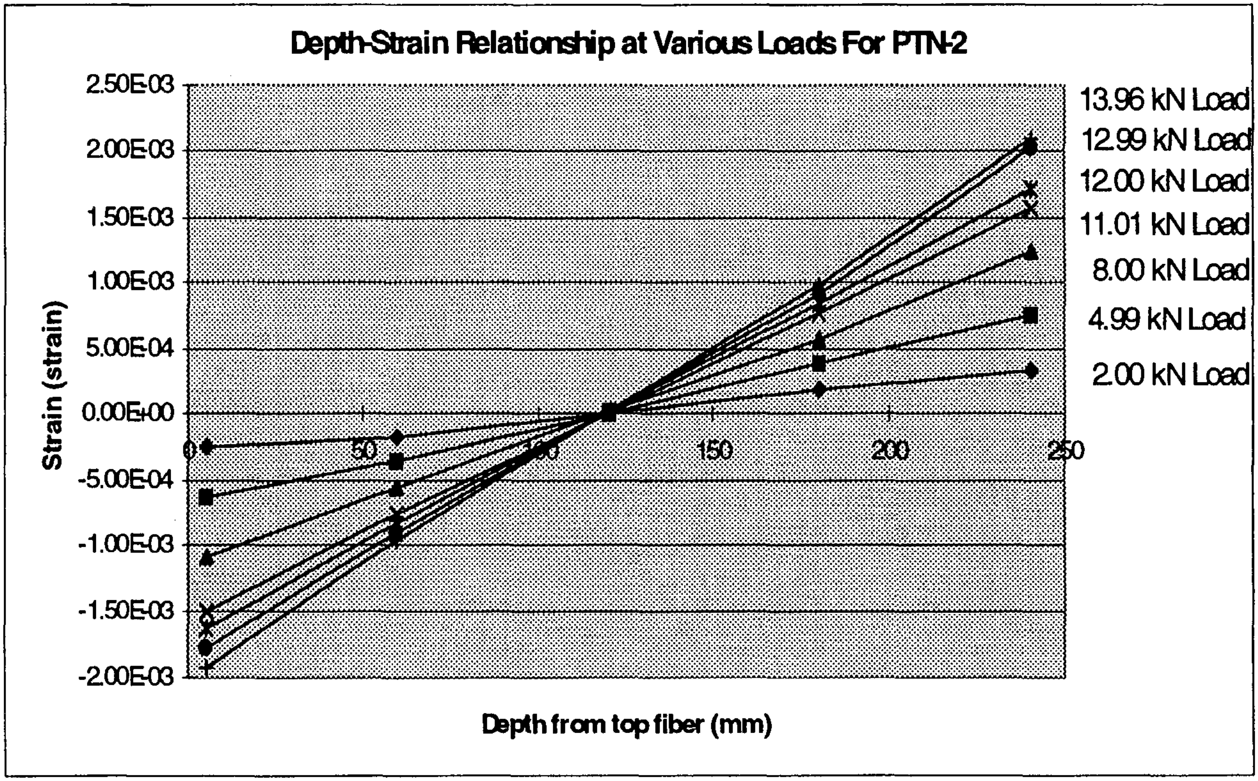


Figure 5.4 Typical Demec Data Plot

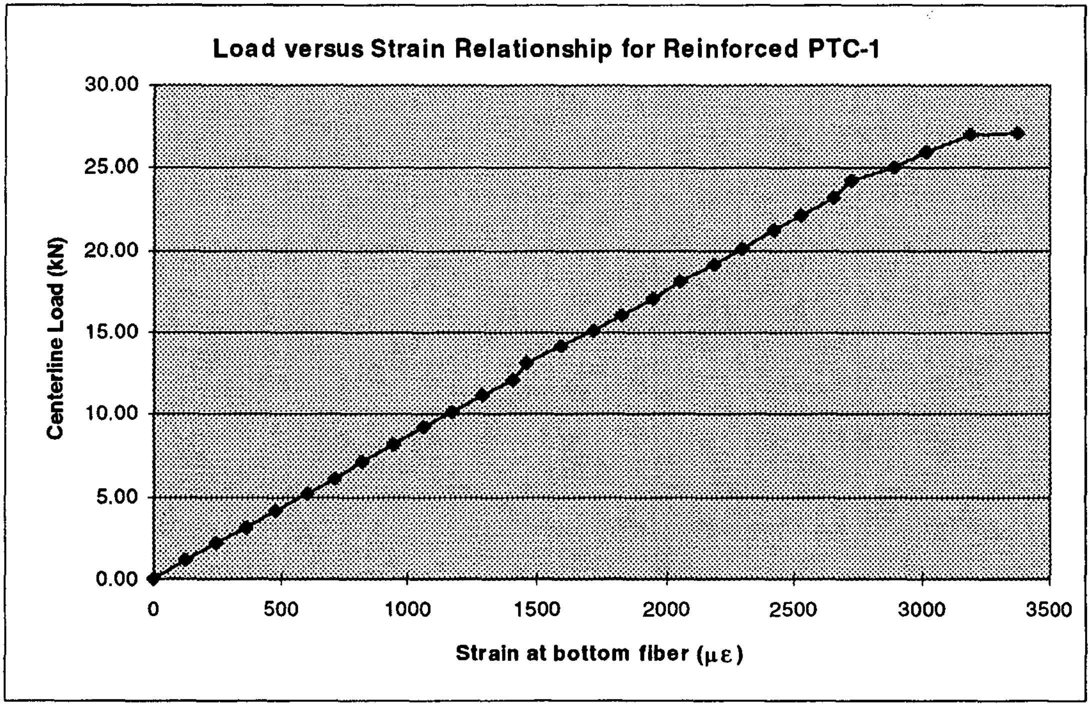


Figure 5.5 Typical Centerline Load versus Centerline Strain

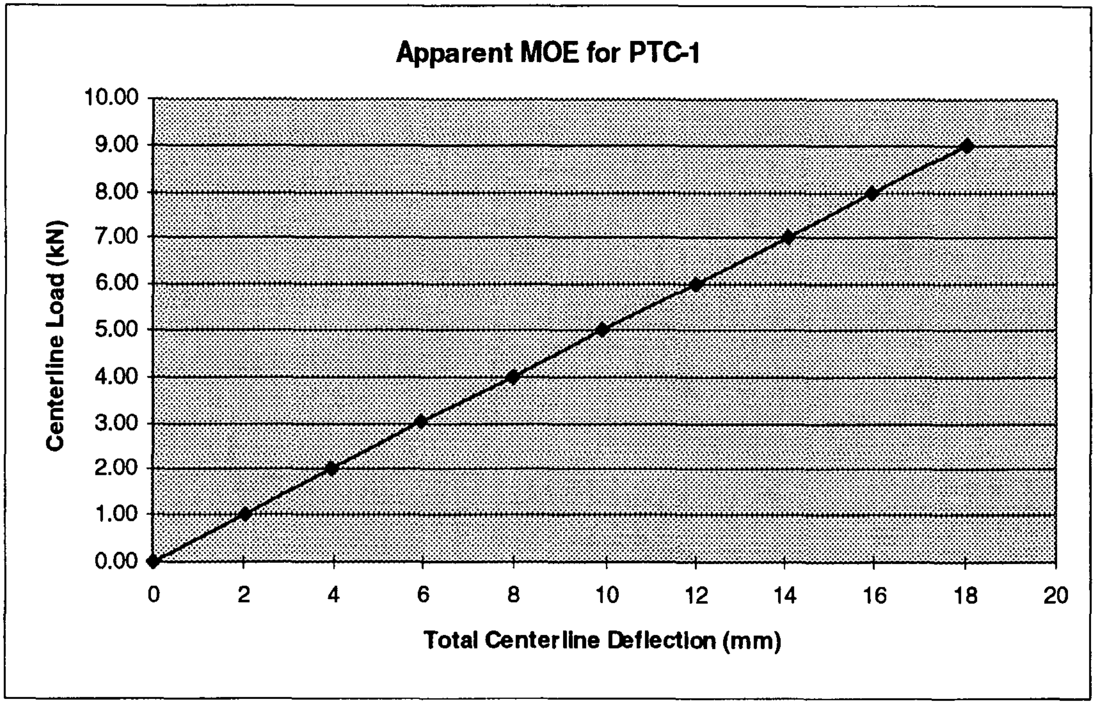


Figure 5.6 Typical Unreinforced Centerline Load versus Centerline Deflection Plot

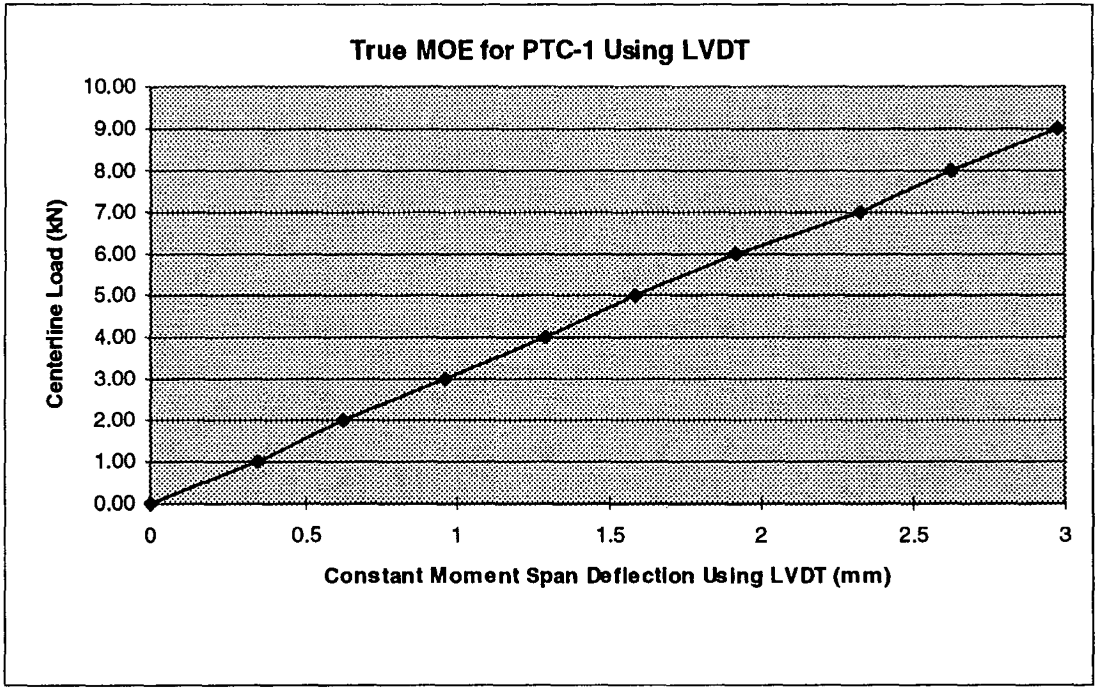


Figure 5.7 Typical Unreinforced Centerline Load versus LVDT Deflection Plot

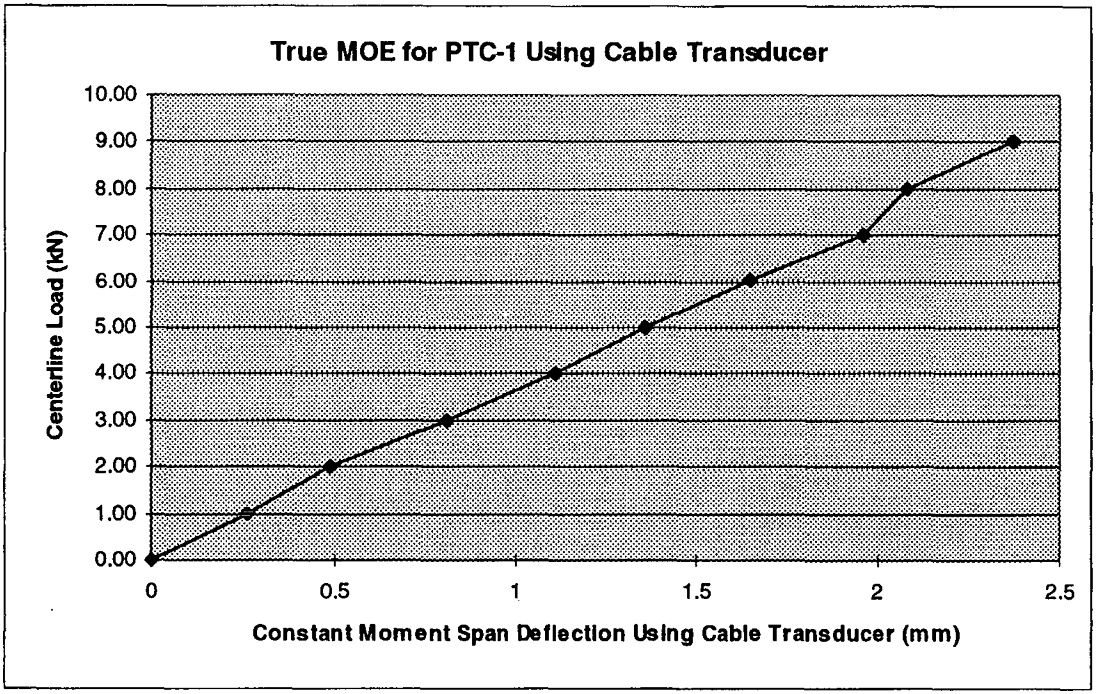


Figure 5.8 Typical Unreinforced Centerline Load versus Cable Transducer Deflection Plot

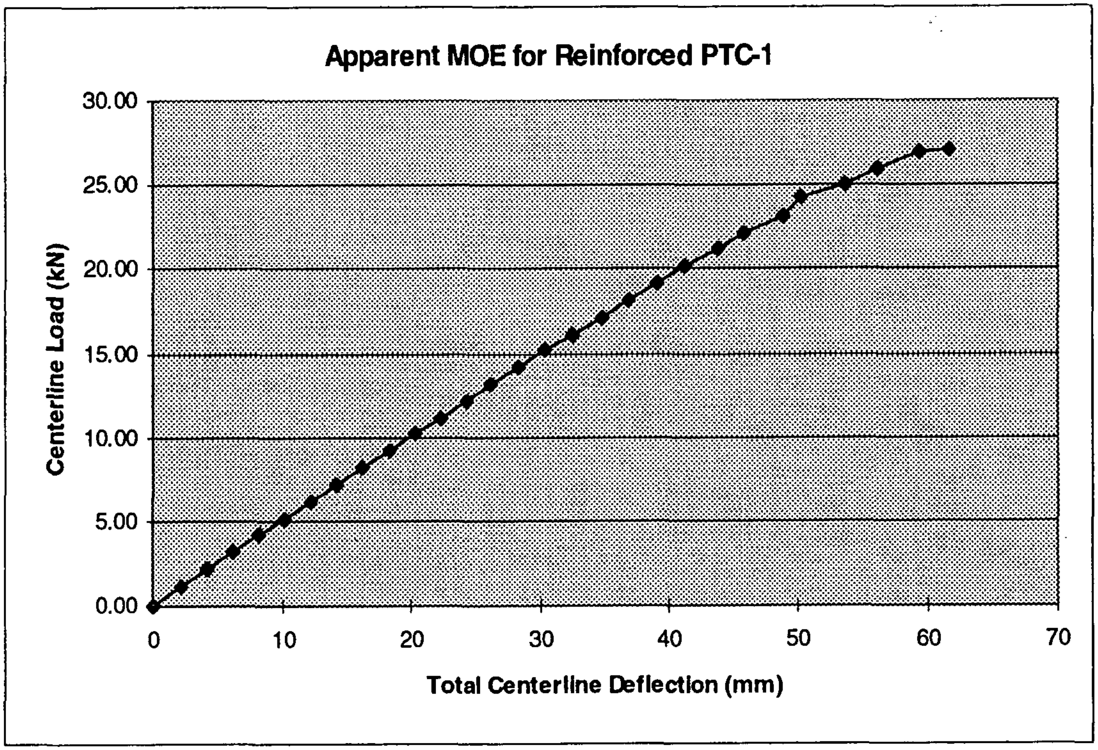


Figure 5.9 Typical Reinforced Centerline Load versus Centerline Deflection Plot

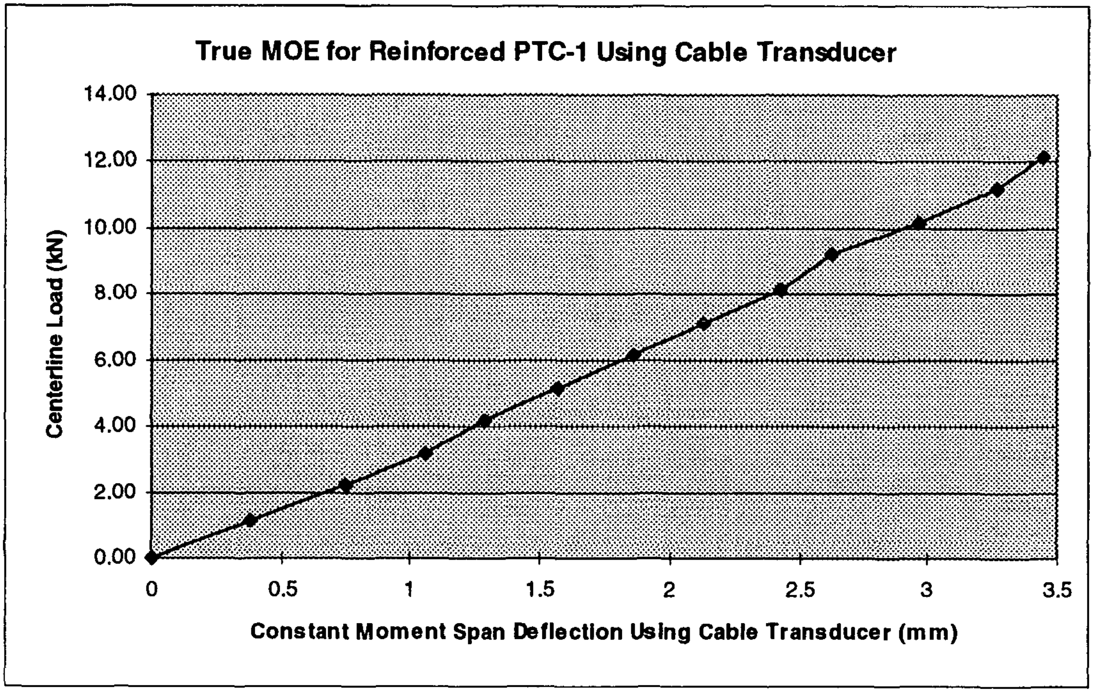


Figure 5.10 Typical Reinforced Centerline Load versus Cable Transducer Deflection Plot

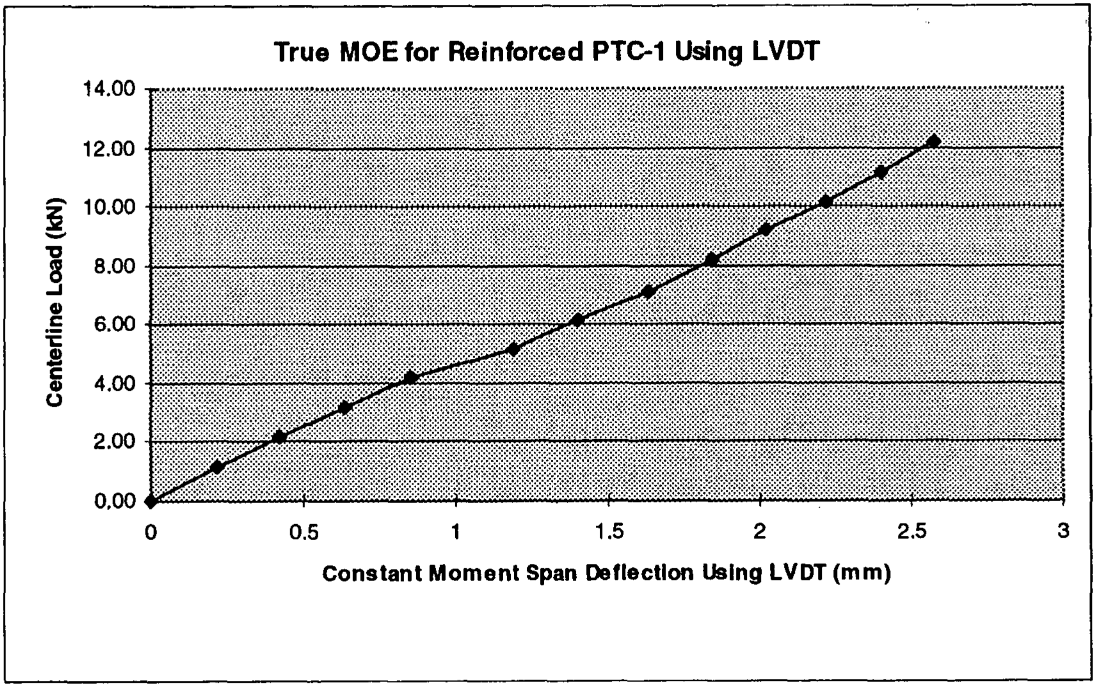


Figure 5.11 Typical Reinforced Centerline Load versus LVDT Deflection Plot

6.0 SUMMARY AND RECOMMENDATIONS

6.1 SUMMARY

The test results clearly indicate that the application of fiber reinforcement to glulam timber provides enhanced flexural capacity. A carbon fiber fraction as small as 0.046% can lead to a 26.5% flexural capacity enhancement. A glass fiber fraction as small as 0.049% can lead to a 22.3% flexural capacity enhancement.

The results also showed that there was little stiffness enhancement of the specimens after they were reinforced, when compared to their unreinforced stiffness. This is most likely due to the small fiber fraction used and the variability of wood. There is most likely a small, yet indiscernible amount of enhancement, but it is masked because of the small fiber fraction. At greater fiber fractions, it is likely that an increase in stiffness will become evident.

In terms of absolute enhancement, the carbon fiber performed better than the glass fiber. This is as expected because of the superior mechanical properties of carbon fiber, when compared to the glass fiber. However, one of the main objectives of this research was to investigate the development of technologically and economically competitive material. Considering this, the glass fiber would appear to be a more superior material to use in the reinforcement of glulam timbers.

From the limited test data, it was not possible to determine the fiber fraction and profile that would provide the greatest enhancement of fiber reinforcing. A more detailed test program would be required in order to determine the optimum fiber fraction. From the data collected, it appears that the greatest enhancement will come from a profile where the reinforcing is placed at a maximum distance from the neutral axis of the specimen.

6.2 RECOMMENDATIONS

One of the purposes of this research was to determine the viability of fiber reinforcing of glued laminated timber as a new construction material. This research has shown that there is definite potential for enhancing the moment capacity of a specimen with fiber reinforcing. From the research, it is unclear whether there is any potential for stiffness enhancement, using fiber reinforcing. This is because of the small fiber fractions used in the project.

The following recommendations are therefore made:

1. Glass fiber should be used in subsequent testing. Although the carbon fiber did provide a technically superior product, when economics are considered, the glass fiber becomes the reinforcement of choice;

2. The application procedure used was determined to be uneconomical and too complicated to be easily implemented in industry. An investigation into other types of application, including bonding agent and procedure used, should be conducted to determine if there is a more efficient and economical method of applying the reinforcing;
3. Specimens with a greater fiber fraction should be investigated to see if there is any significant stiffness enhancement with the fiber reinforcing;
4. Different fiber placements should be investigated. Other researchers have used other types of fiber reinforcing in different locations and reported significant moment capacity and stiffness enhancement. A placement study should be conducted to determine the most efficient location for fiber in the cross section; and,
5. The use of a pretensioned fiber reinforcing system should be investigated. In a non-pretensioned system, the tension lams of the glulam beam may actually fail before the fiber reinforcing comes under load. This would significantly reduce the possible benefits that may be achieved from the fiber reinforcing because the fiber may not be able to withstand the impact load introduced when the lams fracture. A pretensioned system would eliminate such impact loads.

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APPENDIX A

Forca Tow Sheet Application Procedure
(taken from FORCA Tow Sheet Technical Notes (1995))

4-4. Application of primer coat

* No primer coat should be applied if ambient temperature is lower than 5 °C (41 °F), or if rainfall or dew condensation is anticipated. Temperature and degree of dampness of the concrete to be prepared must be confirmed in order to select type of primer which is best suited.

1) FP primer must be thoroughly mixed with hardener at the specified ratio in the mixing pot until it is uniformly mixed (about 2 minutes). Agitation shall be by means of electric hand mixer. Volume of primer to be prepared at one time must be such that it can be applied within its batch life. A mixed primer batch which has exceeded its batch life must not be used. (Life of mixed primer batch is shown in Attach-3. The batch life may vary subject to ambient temperature or volume of the mixed primer batch and care must be taken accordingly.)
2) The mixed primer must be applied using a roller brush. If necessary, a second coat shall be applied after first coat has penetrated into the concrete. Volume of primer to be applied may vary depending on direction or coarseness of concrete surface to be prepared.
3) Applied primer coat must be cured for 3 hours to a half day until tack-free by finger.
4) Surface irregularity caused by primer coating must be ground and removed using disc sander, etc. If any minor protrusions on the concrete surface still remains, such surface defects may be corrected again using epoxy resin putty as needed.

* Work site must be thoroughly ventilated.
Use of fire is strictly prohibited. Because permeable type primer (FP-S) contains organic solvent, care must be taken to prevent inhalation of organic solvent fume. Protective gear such as masks, goggles, rubber gloves, etc. must be used without fail whenever primer is applied.

4-5. Adhesion of Tow Sheet

* No Tow Sheet will not be applied whenever ambient temperature is lower than 5 °C (41 °F), or whenever rainfall or dew condensation is anticipated. Temperature and dampness of the concrete surface to which Tow Sheet is to be adhered must be confirmed in order to select the proper type of resin to be used.

1) Tow Sheet must be cut beforehand into prescribed sizes using scissors and cutter. The size of Tow Sheet to be cut is preferably less than 2m in length. The number of Tow Sheets to be cut shall be limited to the number to be adhered within the day.
2) It must be confirmed that the primer coat applied onto the concrete surface is thoroughly cured. When the primer coat has been left unattended for more than one week after the application, surface of the primer coat must be roughened using sand paper.

3) FR resin must be mixed with hardener at the specified ratio in the mixing pot until uniformly mixed (about two minutes). Agitation is preferably by means of an electric hand mixer. Volume of mixed resin batch must be such that it can be applied within its batch life. A mixed resin batch which has exceeded its batch life must not be used. (Life of a mixed resin batch is shown in Attach-4. The life may vary subject to ambient temperature and volume of mixed resin batch and care must be taken accordingly.)

5) The mixed resin batch must be uniformly applied to the concrete surface using a roller brush (Primary coat). Volume to be applied may vary depending on direction and roughness of the concrete surface. More resin mix must be applied into internal angles than for flat concrete surfaces.

6) Tow Sheet is placed fiber side down onto concrete surface on which resin mix coat has been applied and surface paper is peeled away. Surface of adhered Tow Sheet must be squeezed rather strongly two to three times in fiber longitudinal direction using defoaming roller and rubber spatula in order to impregnate resin into Tow Sheet and to defoam the resin coat. For joining strips of Tow Sheet, a 10 cm overlapping must be maintained in fiber longitudinal direction. No lapping is required in the fiber lateral direction.

7) Tow Sheet so adhered must be left alone for at least 30 minutes. Any lifting or dislocation which may occur during this period must be corrected by pressing down Tow Sheet using a roller or spatula.

8) Mixed resin must then be applied onto the surface of the Tow Sheet (secondary coat). The surface onto which resin has been applied must be squeezed rather strongly two to three times in fiber longitudinal direction, in order to impregnate and replenish resin into the Tow Sheet, using defoaming roller and spatula in the same manner as detailed in item 6) above.

9) In case more than two layers of Tow Sheet must be laminated, the processes as detailed in items 5) through 8) must be repeated.

* Work site must be thoroughly ventilated. Use of fire is strictly prohibited.
Care must be taken to prevent inhalation of resin fumes.
Protective gear such as masks, goggles and rubber gloves must be used without fail during adhesion of Tow Sheet.

4-6. Protection

* In the case of outdoor application, the work must be protected from rain, sand, dust, etc. by using protective sheeting or other barriers.

1) After completion of Tow Sheet adhesion step, the work must be protected against rainfall using

4-4. Application of primer coat

* No primer coat should be applied if ambient temperature is lower than 5 °C (41 °F), or if rainfall or dew condensation is anticipated. Temperature and degree of dampness of the concrete to be prepared must be confirmed in order to select type of primer which is best suited.

1) FP primer must be thoroughly mixed with hardener at the specified ratio in the mixing pot until it is uniformly mixed (about 2 minutes). Agitation shall be by means of electric hand mixer. Volume of primer to be prepared at one time must be such that it can be applied within its batch life. A mixed primer batch which has exceeded its batch life must not be used. (Life of mixed primer batch is shown in Attach-3. The batch life may vary subject to ambient temperature or volume of the mixed primer batch and care must be taken accordingly.)
2) The mixed primer must be applied using a roller brush. If necessary, a second coat shall be applied after first coat has penetrated into the concrete. Volume of primer to be applied may vary depending on direction or coarseness of concrete surface to be prepared.
3) Applied primer coat must be cured for 3 hours to a half day until tack-free by finger.
4) Surface irregularity caused by primer coating must be ground and removed using disc sander, etc. If any minor protrusions on the concrete surface still remains, such surface defects may be corrected again using epoxy resin putty as needed.

* Work site must be thoroughly ventilated.
Use of fire is strictly prohibited. Because permeable type primer (FP-S) contains organic solvent, care must be taken to prevent inhalation of organic solvent fume. Protective gear such as masks, goggles, rubber gloves, etc. must be used without fail whenever primer is applied.

4-5. Adhesion of Tow Sheet

* No Tow Sheet will not be applied whenever ambient temperature is lower than 5 °C (41 °F), or whenever rainfall or dew condensation is anticipated. Temperature and dampness of the concrete surface to which Tow Sheet is to be adhered must be confirmed in order to select the proper type of resin to be used.

1) Tow Sheet must be cut beforehand into prescribed sizes using scissors and cutter. The size of Tow Sheet to be cut is preferably less than 2m in length. The number of Tow Sheets to be cut shall be limited to the number to be adhered within the day.
2) It must be confirmed that the primer coat applied onto the concrete surface is thoroughly cured. When the primer coat has been left unattended for more than one week after the application, surface of the primer coat must be roughened using sand paper.

3) FR resin must be mixed with hardener at the specified ratio in the mixing pot until uniformly mixed (about two minutes). Agitation is preferably by means of an electric hand mixer. Volume of mixed resin batch must be such that it can be applied within its batch life. A mixed resin batch which has exceeded its batch life must not be used. (Life of a mixed resin batch is shown in Attach-4. The life may vary subject to ambient temperature and volume of mixed resin batch and care must be taken accordingly.)

5) The mixed resin batch must be uniformly applied to the concrete surface using a roller brush (Primary coat). Volume to be applied may vary depending on direction and roughness of the concrete surface. More resin mix must be applied into internal angles than for flat concrete surfaces.

6) Tow Sheet is placed fiber side down onto concrete surface on which resin mix coat has been applied and surface paper is peeled away. Surface of adhered Tow Sheet must be squeezed rather strongly two to three times <u>in fiber longitudinal direction</u> using defoaming roller and rubber spatula in order to impregnate resin into Tow Sheet and to defoam the resin coat. For joining strips of Tow Sheet, a <u>10 cm overlapping</u> must be maintained in fiber longitudinal direction. No lapping is required in the fiber lateral direction.

7) Tow Sheet so adhered must be left alone for at least 30 minutes. Any lifting or dislocation which may occur during this period must be corrected by pressing down Tow Sheet using a roller or spatula.

8) Mixed resin must then be applied onto the surface of the Tow Sheet (secondary coat). The surface onto which resin has been applied must be squeezed rather strongly two to three times in fiber longitudinal direction, in order to impregnate and replenish resin into the Tow Sheet, using defoaming roller and spatula in the same manner as detailed in item 6) above.

9) In case more than two layers of Tow Sheet must be laminated, the processes as detailed in items 5) through 8) must be repeated.

* Work site must be thoroughly ventilated. Use of fire is strictly prohibited.
Care must be taken to prevent inhalation of resin fumes.
Protective gear such as masks, goggles and rubber gloves must be used without fail during adhesion of Tow Sheet.

4-6. Protection

* In the case of outdoor application, the work must be protected from rain, sand, dust, etc. by using protective sheeting or other barriers.

1) After completion of Tow Sheet adhesion step, the work must be protected against rainfall using

PVC sheets in order to autocatalitically cure the adhered Tow Sheet. Care must be taken so that the protective sheets do not come into contact with the surface of the adhered Tow Sheet.

2) Curing of adhered Tow Sheet must be for no less than 24 hours.
3) The following curing time is required in order to achieve full design strength.
   Two weeks curing time @ Average ambient temperature of 10 °C (50 °F)
   One week curing time @ Average ambient temperature of 20 °C (68 °F)

4.7. Finish coat

* Finish coat shall be applied to the surface of adhered Tow Sheet as necessary.

1) Carbon fiber (CF) Tow Sheet, by virtue of the carbon fiber itself, is capable of preventing deterioration of resin by interrupting the ultraviolet rays. However, it is preferable to apply a weather resistant paint coat (urethane system paint, fluorine system paint, etc.) in cases where the concrete surface onto which Tow Sheet has been adhered will be exposed to direct sun light.
2) Application of the paint coat must be carried out after completion of the initial resin curing step, as determined when a nail mark can no longer be left on the surface.
3) Application of finish coat shall be in compliance with the standard application process specific to each type of paint.

APPENDIX B

Specimen Load-Deflection Plots

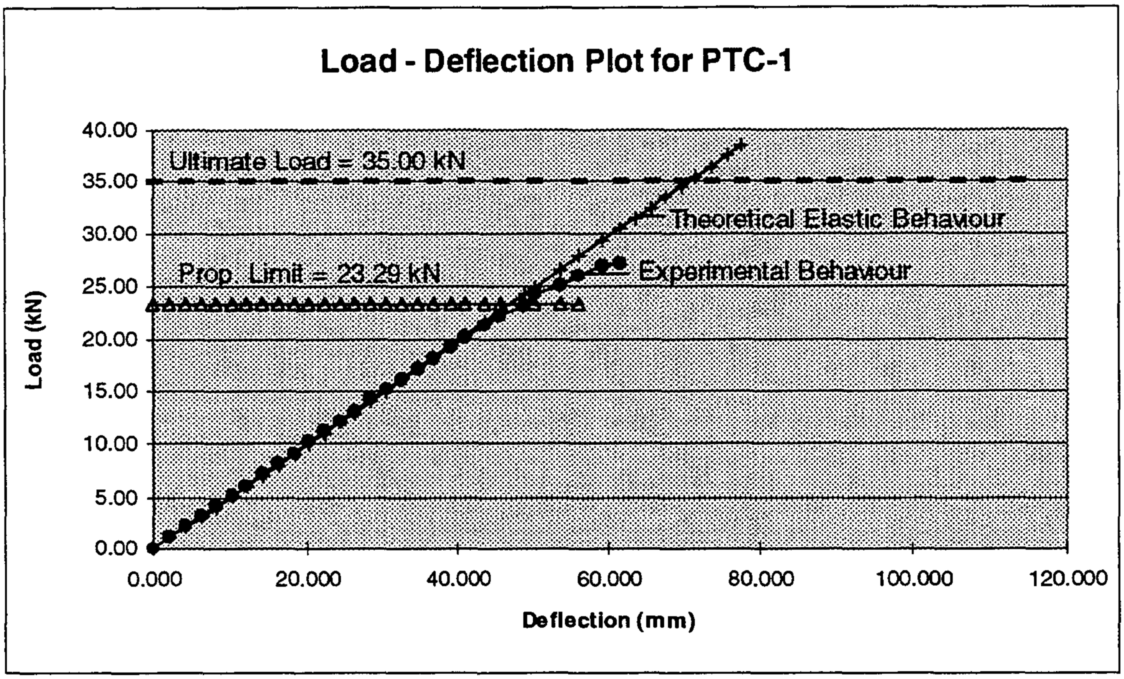

Figure B.1 Load - Deflection Plot for PTC-1

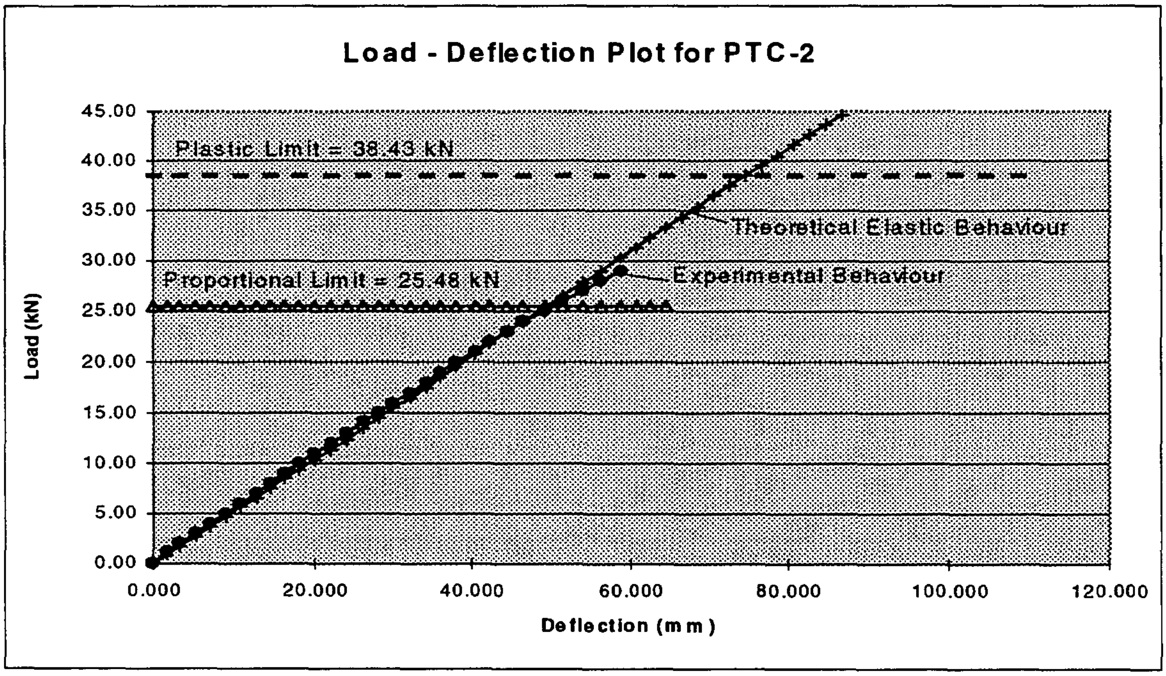

Figure B.2 Load - Deflection Plot for PTC-2

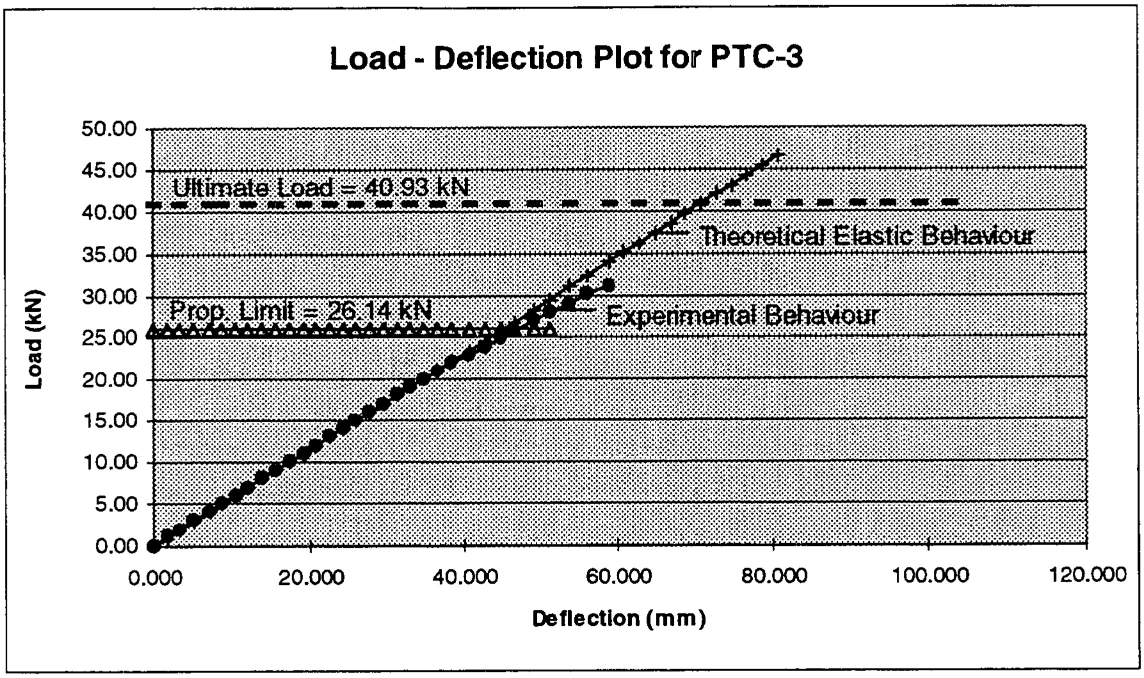

Figure B.3 Load - Deflection Plot for PTC-3

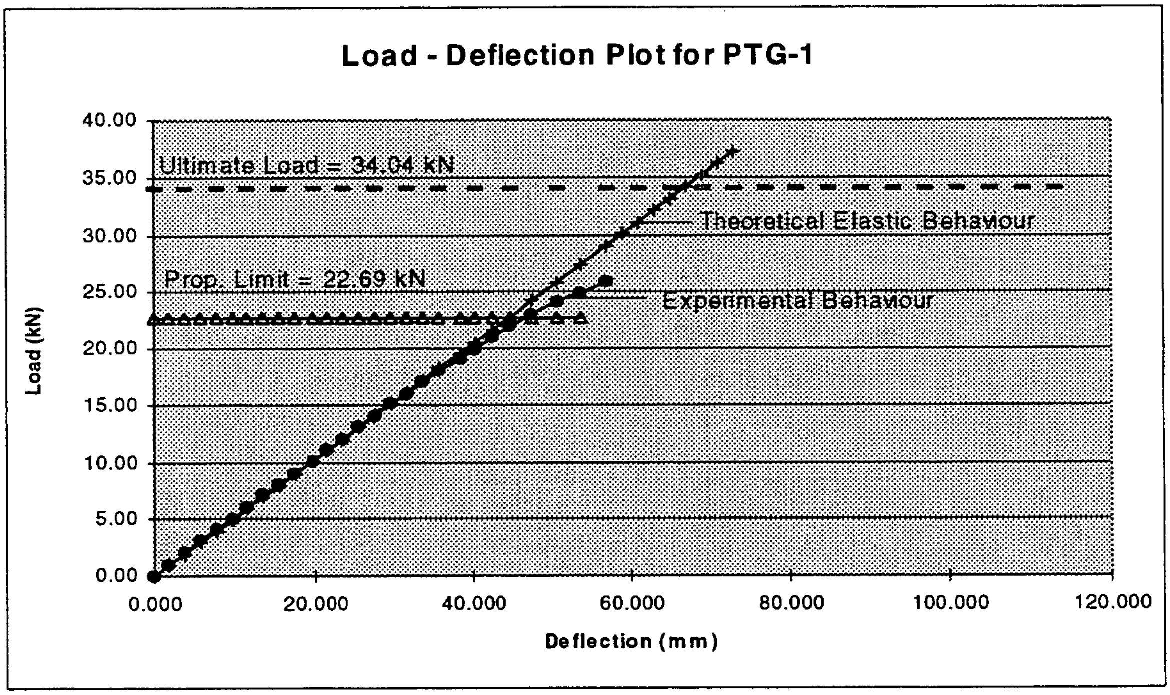

Figure B.4 Load - Deflection Plot for PTG-1

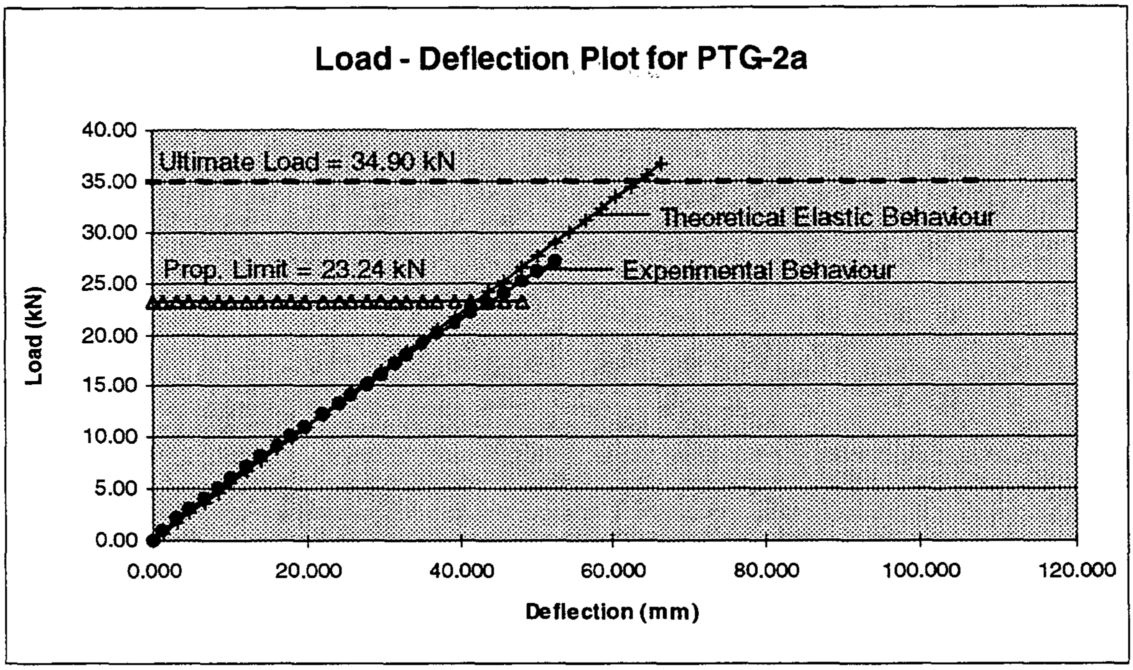

Figure B.5 Load - Deflection Plot for PTG-2

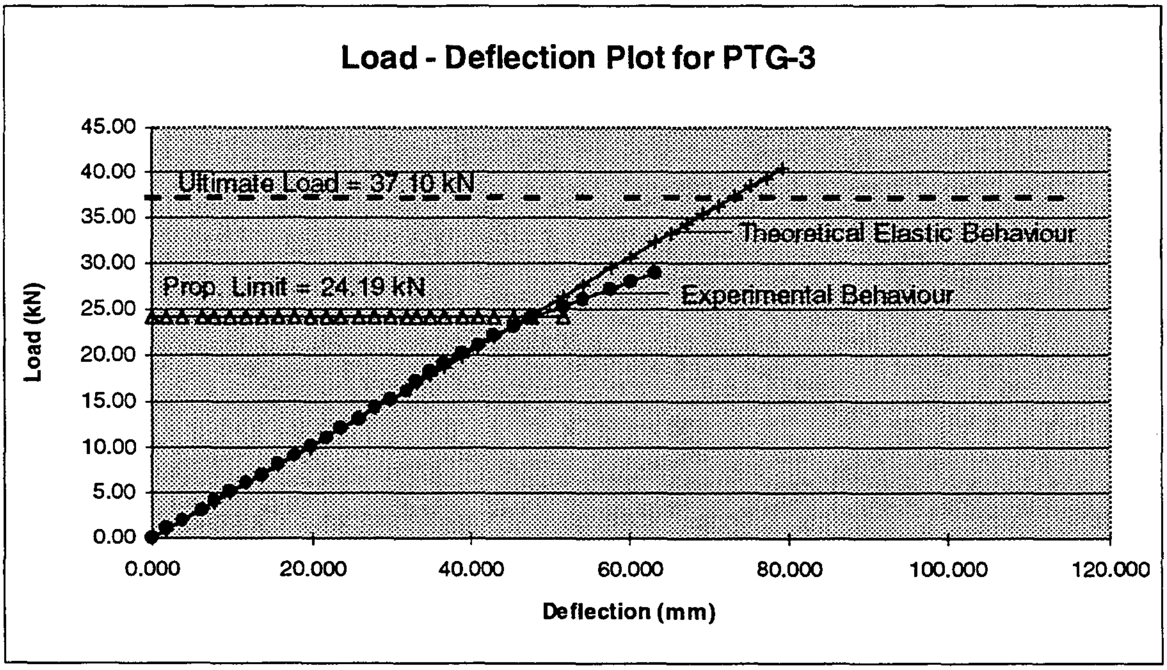

Figure B.6 Load - Deflection Plot for PTG-3