THE UNIVERSITY OF CALGARY

BONDING OF NEW CONCRETE TO OLD CONCRETE

by

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Abstract

The topic of the thesis is the bond of new to old concrete, a topic of fundamental importance for effective concrete repairs. The need to repair concrete is increasing, especially in structures such as bridge decks and parking garages.

Several bonding procedures and tests which evaluate bond have been recommended. However, there is considerable controversy over the best bonding system and the best method of evaluating the bond strength. The first objective of the research was to select the most appropriate bond test method. In order to select this test method, four tests considered to have the best potential to evaluate bonds were assessed experimentally. The tests were:

1. a slant shear test;
2. a flexure test with bond line 45^o to horizontal;
3. a flexure test with bond line 60^o to horizontal;
4. an indirect tensile prism test.

The slant shear test was selected as the most appropriate test and used to determine the effect of various parameters on bond. These parameters included the effects of:

1. thickness of the portland cement mortar layer;

2. local areas of weakness in the bond;
3. different bond material moduli of elasticity;
4. the water cement ratio of the portland cement mortar;
5. substrate moisture condition when a portland cement mortar is used;
6. copolymer PVA based bonding mortars under different curing conditions;
7. a delay between the application of a copolymer PVA bonding agent, and the fresh overlay concrete.

The effects of the above factors were determined using two methods: the theoretical finite element analysis, and the experimental program.

The results of both methods indicated a thick bond layer will cause greater stresses in adjacent concrete, compared to a thin bond layer. The finite element analysis also indicated that local weakness in the bond line can cause very high stresses in and adjacent to the bond. The bond material modulus of elasticity was found to affect stresses at and adjacent to the bond line. Water cement ratios within the range tested were found experimentally to have a minor influence on bond strength. Similarly, the experimental results indicate a moist substrate will provide a small improvement in bond when portland cement bonding mortar is used. The practice of using copolymer PVA as a bonding agent adversely affected bond. A delay between the application of copolymer PVA bonding agent and fresh overlay concrete was not found to have a significant effect on bond strength.

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LIST OF SYMBOLS

A	area of the cross-section of the composite prism
E	concrete modulus of elasticity
E_b	modulus of elasticity of bond material
E_h	hypothetical modulus of elasticity
F_u	composite prism ultimate strength
F_y	gross compressive load on composite prism
S_1	sample standard deviation for the first set of results
S_2	sample standard deviation for the second set of results
S_p	pooled sample standard deviation
T	value of the t statistic
$\overline{X}_1$	experimentally measured mean of the first set of results
$\overline{X}_2$	experimentally measured mean of the second set of results
b	width of composite prism
d	shortest dimension at bond line
f_c	concrete compressive strength
f_r	modulus of rupture
f_t	indirect tensile strength
h	bond thickness
n_1	number of results in the first set of data

n_2	number of results in the second set of data
s	horizontal joint thickness
β_{WM}	mortar strength
β_{WB}	concrete strength
α	degree of statistical significance
σ_y'	stress normal to bond plane
$\tau_{x'y'}$	shear parallel to bond plane
μ_1	actual mean of the first set of results
μ_2	actual mean of the second set of results
ν	number of degrees of freedom

CHAPTER 1

INTRODUCTION

1.1. Introduction

Many situations exist where new concrete must be bonded to old concrete. For example, the practise of bonding concrete overlay pavement onto bridge decks as either a preventative maintenance or a rehabilitation procedure has become common. Repair concrete is frequently bonded to parking structures which have suffered deterioration. Both parking structures and bridge decks deteriorate due to the penetration of road salt, oxygen and water which rust the reinforcement. The steel corrosion occurs due to the reaction with oxygen and water. The reaction can not occur without the presence of an electrolyte. Salt provides the electrolyte as it penetrates the concrete. As a result, rapid corrosion of reinforcement occurs. In forming rust, the reinforcement expands and destroys the overlying concrete. Excellent bond between overlay and original concrete in this type of structure is essential since permeability must be kept low in order to block oxygen, water and salt from the reinforcement.

Many other repairs to concrete structures require the bonding of fresh concrete to hardened concrete. In addition, fresh concrete must be bonded to hardened concrete at construction sites where large pours of concrete cannot be completed at one time or where construction errors are rectified. Typical construction errors which require attention include the misalignment of column base plates, and incorrect levels of floors.

Several problems have been experienced with the bond of fresh concrete to hardened concrete. Bond failure has been caused by several factors, including excessive stresses, improper application of bonding agents, and improper surface preparation. Incorrect application of the bonding agent causes the most bond failures. Poor bond always results when the bonding agent is allowed to harden/cure before application of the overlay. Some bonds have failed because the bonding agent was vulnerable to prolonged exposure to moisture. The performance of concrete bonds has been highly variable, indicating that the parameters that control bond performance are not completely understood.

Before the effect of various parameters on bond can be studied, a reliable bond test must be selected. Several different bond tests exist. There are different opinions on which test is superior, therefore, the first objective of the thesis was to select or design the most appropriate test. This was done by choosing four tests judged to be suitable and testing their sensitivity to a strong and weak bonding agent.

Another objective of the research was to test experimentally the effect of several parameters on bond strength. The water cement ratio, bond thickness and the substrate moisture level of portland cement mortar bonding agents were varied. Polyvinyl acetate (PVA) based bonding agents were exposed to various curing conditions and application procedures.

An additional objective of the thesis was to model the bond test selected as most reliable, with finite elements. The finite element analysis was used to approximate the stresses present in a bond for different bond layer material stiffnesses and geometries.

1.2. Scope of Work

Unfortunately, the topic of bond between fresh and hardened concrete cannot be studied completely in one thesis. As a result, work was limited to static tests and a simple finite element analysis based on linear stress/strain assumption. No microstructural studies were done on the bond between various bonding agents and different concrete surfaces although this could yield useful results. A more accurate stress/strain model in the finite element analysis coupled with a finite element mesh capable of modelling extremely small bond surface features might also provide useful information.

In order to collect existing knowledge about bonding techniques, tests and associated difficulties, a literature survey was completed and is presented in Chapter 2. An important priority was to select a reliable test of bond. As a result, the criteria for choosing the most appropriate tests for further evaluation were determined, and are presented in Chapter 3. The choice of the appropriate strategy used to select the best test was the next required step and is also contained in Chapter 3. The experimental procedure for each test and bonding agent was determined and is detailed in Chapter 4. Then, in Chapter 5, the experimental results are presented and used to select the most suitable test, which was the slant shear test. The stress distributions in the slant shear test were analysed using finite element analysis and are described in Chapter 6. Experimental results found using the slant shear test are discussed in Chapter 7. Conclusions are stated in Chapter 8.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction

In order that bond tests can be evaluated and selected logically, information on stress states in bonds and likely cause of failure is of critical importance. As a result the stress state in bonds and causes of bond failures are detailed in the literature survey. A description of many bond tests used by transportation departments, university researchers and construction product manufacturers is also presented. This is followed by a description of most major bonding agents, related substrate surface preparation and the performance record of the more common ones. Finally, information on other factors that influence bond are reviewed.

2.2. Stress States

There is a wide variety of stress states possible in a bond, depending on the kind of structure in which the bond is located. There is an equally diverse number of opinions about the most desirable and realistic state of stress at the bond in a bond test. Tabor (1979) claims shear stress is most likely to govern the bond strength between repairs and original concrete. According to Pfeifer (1981), differences between thermal, shrinkage and mechanical properties of epoxy mortar patches or overlays (a typical repair material) and the substrate concrete can cause bond failure if the repair is poorly designed. Bond failure, resulting from different thermal, shrinkage or mechanical properties of the overlay and substrate, is caused by shear and tensile stress. Muller (1975) states that the bonds in the first segmental bridges were required to transfer moment and shear as high as 4.14 MPa (600 psi) but that newer segmental joints have shear keys that relieve the bonding agent from any structural role. Muller's statement is contradicted by Schutz (1976) who claims that for precast segmental bridge joints, tensile strength of the bond is more important than shear strength.

One function of the bond layer between segmental bridge components is to prevent penetration of water and salt. Another function is to transfer the compression force due to post-tensioning while avoiding stress concentrations. Where shear keys are provided, the shear strength of the bond material is not important.

The minimum shear strength required for the bond between a concrete overlay and the main course of a bridge deck or an existing concrete pavement has not been fully agreed upon. Manning and Ryell (1975) quoted a direct shear bond strength between 0.28 MPa (Higgins and Peters (1968)) and 0.44 MPa (Furr and Ingram (1970)) as being required for bridge decks. Bergren (1981) of the Iowa Department of Transportation (IDOT) suggests a bond strength of 1.38 MPa (200 psi) is needed between bridge deck and concrete pavement overlays.

2.3. Effect of Bond Layer Thickness on Strength

In addition to the gross stress state on the bond, the performance of bonds between fresh and hardened concrete is affected by the thickness of the bond line.

The inverse relation between bond thickness and bond strength has been noted often in such areas as masonry (Sise (1984)). Grasser and Daschner (1972) studied the effect of horizontal joint thickness of cement mortar in a concrete prism (see Fig. 2.1) and also found prism strength decreased with increasing bond size.

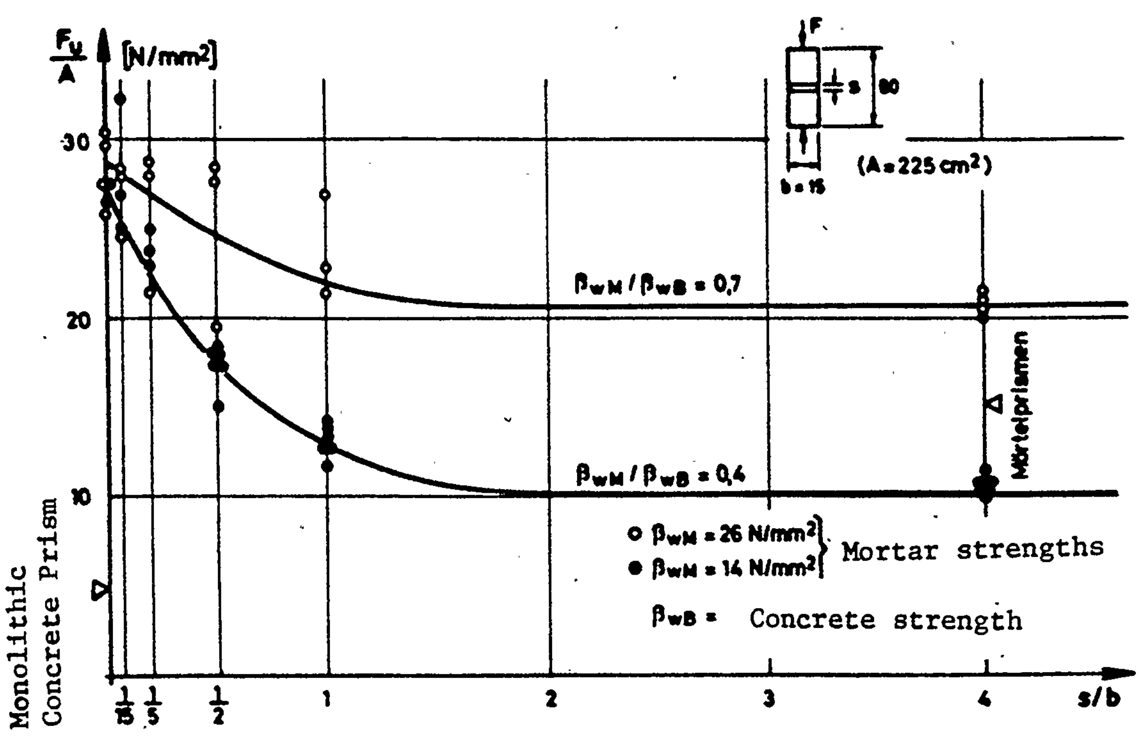


Figure 2.1 Effect of mortar joint thickness on composite prism strength, taken from Grasser and Daschner (1972).

Schutz (1976) claims "creep"* in epoxy glue lines between segmental bridge components is negligible partly because of the small thickness (in some cases less than 1.6 mm (1/16")) of the joint. Although Schutz does not discuss whether this "creep" is beneficial or detrimental with respect to bond strength he presents a formula from Topaloff (1964),

$$E_b = E_h/3(d/h)$$

where

E_h = hypothetical modulus of elasticity

E_b = modulus of elasticity of bond material

d = shortest dimension at bond line

h = bond thickness

which supports his argument about "creep" being small. The "creep" and initial deflection decrease with hypothetical Young's modulus which in turn decreases with bond thickness.

Most transportation departments, including Alberta Transportation (1985), IDOT (1974) and New York State Department of Transportation (NYSDOT) (1985) specify a maximum thickness of 3.17mm (1/8") for bonding mortar for bridge decks, apparently to avoid the weaker bonds associated with thicker bond lines. The maximum portland cement mortar bonding layer thickness is suggested

* Schutz does not define "creep" as strain or displacement

at 2-3 mm (1/16" to 1/8") by the Portland Cement Association (PCA) (1981).

2.4. Test Types

There are numerous bond tests utilizing widely varying stress states. A number of these tests are described in the following sections. The tests can be categorized according to the main type of gross stress state imposed across the bond. Therefore, tests have been labelled as shear, flexure, tension or compression tests. Within some of the main test categories, tests can be further classified according to subdivisions. For example, shear tests can be subdivided into slant shear tests, direct shear tests and other test types. Similarly, tension tests can be divided into two types, direct tension and indirect tension. Tests in the main categories and associated subdivisions are discussed in the following sections.

2.4.1. Slant Shear Bond Test

The slant shear test has been widely used by researchers to determine bond performance. Tabor (1979) claims it is more sensitive to weak bonds than flexural and direct tension tests. Schutz (1968) claims the test is "likely" more representative of field conditions than other tests. The test involves applying a compression load to a composite prism or cylinder which contains a bond plane intersecting the center at an angle, usually 60^o, to the horizontal. The specimen height to width ratio is normally 2. "Slant shear bond strength" is defined as the compressive strength of the composite specimen. The gross stress state at the bond face is a combination of compression and shear.

Several versions of the tests exist. The "Arizona Test" as described by Kreigh (1976) utilizing 152 mm × 305 mm (6'' × 12'') cylinders and concrete base and overlay has been used frequently. The American Society for Testing and Materials (ASTM) C-882 test is similar except 76 mm × 152 mm (3'' × 6'') cylinders are used and mortar is used in the base and overlay components. A 100 mm × 100 mm × 300 mm prism version of the test is contained in the Laboratoire Central des Ponts et Chaussees (LCPC) Recommendations (Sasse and Fiebrich (1983)). Perkins (1984) and Dixon and Sunley (1983) present results obtained using British Standard slant shear bond test, BS6319, with a 55 mm × 55 mm × 150 mm prism. Ciba - Geigy Ltd., an adhesives manufacturer, and FIP (Federation Internationale de la Precontrainte) have also produced test guidelines according to Tabor (1979). As well, Tabor designed a test where 150 mm × 150 mm × 55 mm concrete prisms are cast, and then cracked at 60^o to horizontal using a steel and rubber mechanism. (See Fig. 2.2). The bonding agent and fresh concrete are applied to each half of the original prism which is then cured and cut into 55 mm × 55 mm × 150 mm prisms. This method eliminates the need to cast concrete into molds with 30^o corners and also provides a "naturally" cracked bond surface thus simulating a concrete surface in need of repair.

The effect of varying the bond plane angle was studied by Savage (1967) using 75 mm × 75 mm × 250 mm prisms. With the bond plane at a 50^o angle to the horizontal, prisms containing an epoxy bonding agent failed in the concrete, but 1 of 2 prisms with a 60^o bond angle failed partially at the bond. Both prisms with

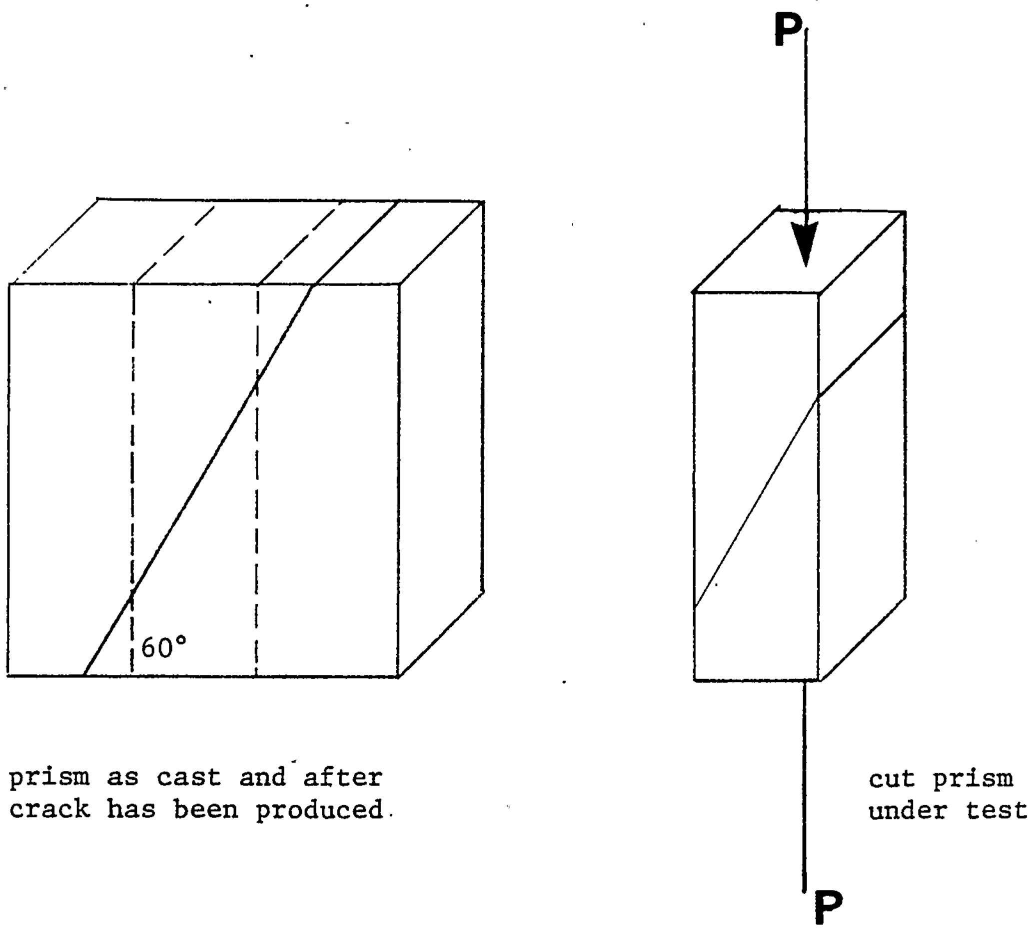


Figure 2.2 Tabor Slant Shear Test

a 70^o bond plane angle experienced partial bond failure. These results indicate that within a certain range of bond plane angles, the resultant bond shear stress component is increased and the bond may become more likely to fail. Rehm and Franke (1982) used a theoretical manipulation of Coulomb's Criterion and the Mohr's Circle and predicted theoretically that the weakest bond plane angle is approximately 65^o.

2.4.2. Direct Shear Test

The most common type of direct shear test uses a shear jig (see Fig. 2.3) to test a cored cylinder taken from a field site such as a bridge deck. In a typical shear jig test, the base portion of the core is held firmly by steel clamps, collars or glue with the longitudinal axis of the core orientated horizontally. A ram pushes (or pulls) another steel collar which is attached to the overlay component of the core. The gross stress state at the bond is a combination of shear and flexure. This type of test has been used by several transportation departments, often with minor modifications. The Iowa Department of Transportation uses a 2 part steel collar with 1 part used to hold the base portion of a 102 mm (4'') core placed

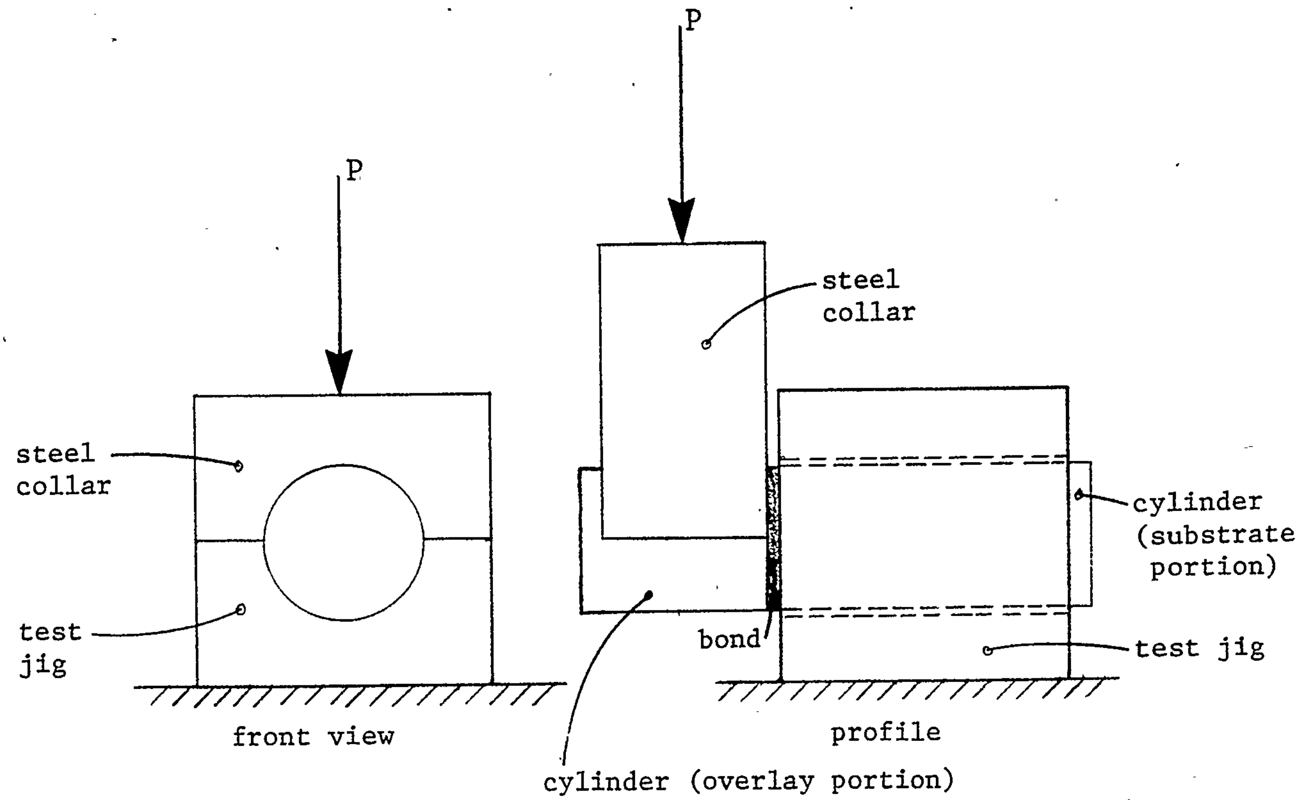


Figure 2.3 Shear jig for direct shear cylinder test

horizontally and the other part used to pull the overlay downward (Bergren (1981)). Gillette (1965) used a device similar to the one shown in Fig. 2.3 to test 76 mm (3'') cores. Sulphur was poured in the small gap between the jig and the core to ensure the core was held firmly.

Several researchers have also utilized direct shear prism tests, where the prisms were either cast for testing or cut from a field site (Fig. 2.4). A direct shear prism test also has been used by Gillette (1965), Felt (1960), Smith, Chojnacki and Langhammer (1967), Dhir (1984) and Furr and Ingram (1970).

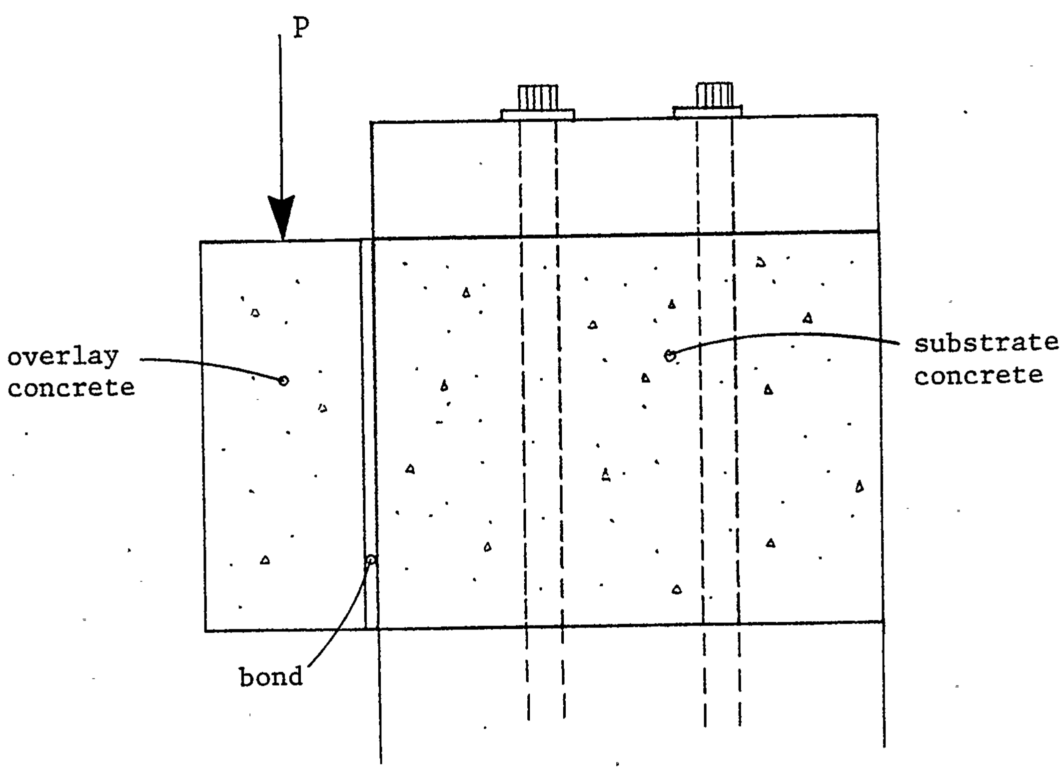


Figure 2.4 Direct shear prism test

2.4.3: Other Shear Tests

Many different forms of shear test have been used or recommended. In order to test the adherence of a particular bonding agent to a hardened mortar, a test is sometimes used involving 3 mortar plates bonded together with the bonding agent under investigation (Fig. 2.5). The middle plate is offset from the other plates, which causes shear and a small amount of flexure at the bonds when the plates are aligned vertically and a compressive load applied. This type of test has been used by Tsuruta (1967) to test epoxy resin and by Perenyi (1968) to investigate polymer mortars.

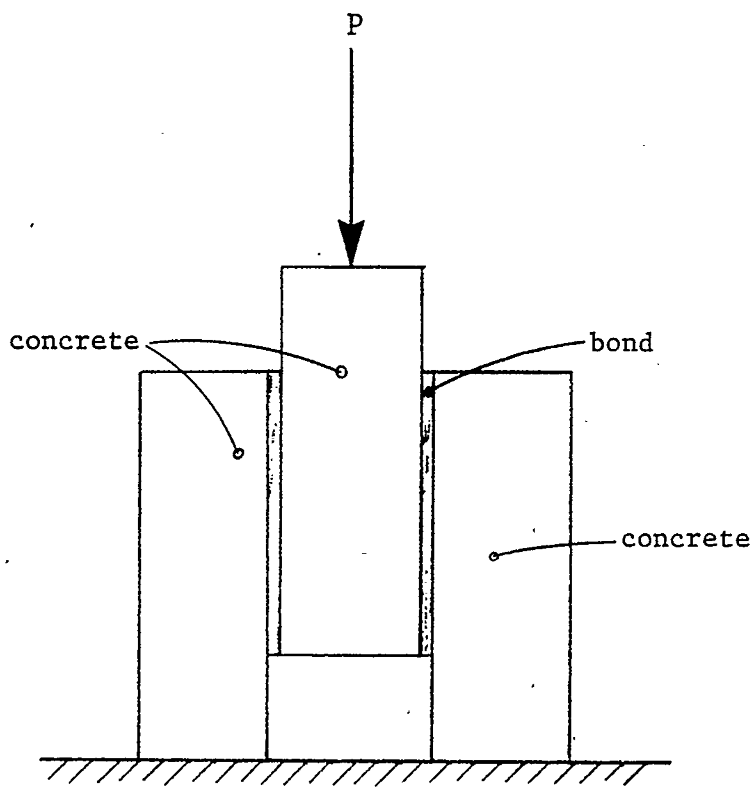


Figure 2.5 Three plate shear test

Several researchers such as Hallquist (1967) used a test with 3 cubes bonded in a row with the middle cube raised above the other two. The 3 cube assembly is loaded in compression. Schutz (1968) described a version of the test used by the U.S. Army where the cubes are 51 mm (2")in size and are laterally restrained by placing the test assembly on a 152 mm (6") wide channel shaped frame. The end plates of the frame are capable of being adjusted to account for slight variations in cube size. The end plates are only slightly more than half the height of the cubes, therefore, the lateral restraint will vary with height. Abdul Rahman and Abdul Karim (1975) used 100 mm cubes which were laterally restrained by 4 horizontal rods attached to vertical metal end plates. As a result the lateral restraint should not vary with height. The stress distribution in Abdul Rahman and Abdul Karim's test is nevertheless very complex.

Base (1963) described a beam with joints at the third points loaded such that the joints were exposed to shear but no moment. Tabor (1978) claimed the complicated loading arrangement required for this test limited its practical value.

Johnston (1963) used lap splice tests to subject bonds to shear, but he admitted the stress state was complex and possibly undesirable. Saemann and Washa (1964) poured reinforced concrete topping on prestressed concrete girders, which subsequently were subjected to loads near the center point, in order to study the effect of girder surface roughness on bond strength.

2.4.4. Flexure

Several types of flexure tests have been used to analyse bonds. Often 2 rectangular prisms are glued together to give a vertical joint at the center line with loads applied at the third points of the composite beam. Similar tests have been used or discussed by Okada and Nishibayashi (1967), Base (1963), Schutz (1968), Dutron and Collet (1967) and Abdul Rahman and Abdul Karim (1975). The stress state at the bond should be one of simple flexural tension and compression.

Tsuruta (1967) used a 100 mm × 100 mm × 400 mm beam, bonded at the vertical center line, in order to test the ability of an epoxy resin to bond fresh concrete to hardened concrete. The beam was loaded by a single point load at the center line. The stresses at the bond line in this test are a combination of shear and flexural compression and flexural tension.

A 76 mm × 76 mm × 305 mm beam with a bond plane orientated at a 30^o angle to horizontal and with a span of 239 mm was loaded at the third points by Moss and Batchelar (1975) to test the bond between new and old concrete. The stress state at the bond is one of shear and tension.

Halmagiu, Vasilescu and Haliska (1967) tested several combinations of bonding agents, fresh concretes, and repair mortars by bonding them to portions of beams that were previously failed and then reloading them. The stress state at the bond in this test would be very difficult to estimate.

A reinforced beam designed to fail in shear when subjected to a center load, was used by Warris (1967) to test the bond between mortar topping and concrete. Prior to testing the beam was inverted so the mortar would be in tension.

Several tests exist for determining the flexural bond strength of mortar joints in masonry. Many of these tests involve multiple brick (and joint) test prisms and therefore, cannot be adapted easily for testing the bond between new concrete and old concrete. A few masonry bond tests such as the Baker test (Baker (1979)), are capable of testing a single joint between two masonry units. The Baker test, when used to test two bricks bonded together, involves clamping one of the bricks to a fixed frame and the other brick to a rotating frame in order to apply a moment (Sise (1984)). The Baker test could be adapted to a composite prism containing base and overlay concrete but more effort would be required compared to a third point bond test. Tests described by Huizer and Ward (1978) and Hughes (1978) are appropriate for testing a small number of joints but like the Baker test are inefficient for testing the bond between fresh and hardened concrete.

2.4.5. Direct Tension

One common type of direct tension test uses cores taken from a field site. This method has been used by Wilk (1977) and Bryant and Clear (1977) in determining the degree of bond between overlays and bridge decks. A test where fresh concrete is cast on the top half of a 160 mm × 320 mm cylinder which is subjected to axial tension is included in an LCPC recommendation (Sasse and Fiebrich

(1983)).

"Pull-off" tests have been used frequently to test the condition of the bonding surface of a substrate concrete and to determine the ability of bonding agents to adhere to existing concrete. In this test, an object which is easily gripped by a pulling device is glued to the bond face of the concrete with a bonding agent. The force required to remove the attached object is recorded as the "pull-off" strength. Warris (1967) notes the "pull-off" strength recorded is often affected by eccentricity in the applied tensile load. In addition the effect of fresh concrete on the bond cannot be determined using this method. A common version of this test is described by American Concrete Institute (ACI) Committee 503 (1973).

Pearson (1943) developed a direct tensile test for masonry in which two bricks were bonded at right angles to each other and pulled apart. This assembly would be difficult to achieve if the bond between new concrete and old concrete was tested. The tensile strength of masonry joints was also tested by Sinha (1983) who bonded two bricks together. Rods were inserted into both bricks with the rods in the upper brick attached to a support and the lower rods attached to a frame. The frame supported a bucket of sand which was filled until the bond failed. The use of a bucket to load the prism would cause some error due to eccentricity.

2.4.6. Indirect Tension

Very few indirect tension tests have been used to study bonds. A test has been used by Tsuruta (1967) where a cylinder, which was split in two longitudinally and rebonded with epoxy, was loaded on its side like the Brazilian test but only over one quarter of its total length.

2.4.7. Compression

A wide variation of compression tests has been used. Abdul Rahman and Abdul Karim (1975) tested 150 mm cubes with a horizontal bond. Taller specimens with dimensions of 150 mm × 150 mm × 600 mm containing horizontal bonds of varying thicknesses were used by Grasser and Daschner (1972). Ohama (1967) tested prisms with a height to thickness ratio of 4 and a vertical bond line. Tsuruta (1967) rebonded beams, which had broken at the vertical center line, with epoxy and loaded the central region in compression.

2.5. Types of Bonding Agent

Bonding agents are used with the intention of insuring a strong bond between old concrete and new overlay concrete. Without a bonding agent, a bond will be weak unless a perfect surface condition exists (Tabor (1979)). Perfect surface conditions are unlikely to exist at construction sites. The most common bonding agents contain portland cement, polyvinyl acetate or epoxy resin as their active ingredient. These bonding agents and a few other less common bonding agents are discussed in the following sections.

2.5.1. Portland Cement Paste and Mortar

There are two types of bonding agents which contain portland cement. Portland cement mortar is the most common type, however, portland cement paste without modification is sometimes used as a bond agent.

2.5.1.1. Effect of Mix Design and Application Methods on Bond Strength

The most common bonding mortar mix contains equal amounts of type 10 cement and sand by weight and enough water to form a "stiff slurry", and is used by several transportation departments including Iowa, Alberta and Winnipeg (Alberta Transportation (1984), IDOT (1974) and Winnipeg Roads and Streets Department (1985)). NYSDOT (1985) uses the same mix except that equal proportions of cement and sand measured by volume are used. Sinno and Furr (1970), however, using a sandblasted surface, have found that a mortar cement/sand ratio of 1:0.75 (by weight) yielded a direct shear test bond strength of 3.69 MPa (535 psi) (average of 2 tests) versus a strength of 2.95 MPa (428 psi) for a 1:1 ratio. A 1:1 ratio of cement and sand by volume is equivalent to about a 1:0.85 ratio by weight assuming specific gravities of 2.65 and 3.15 for the sand and cement respectively. Thus, the results of Sinno and Furr indicate that the 1:1 cement:sand volume ratio mortar used by New York State may be stronger than the 1:1 weight ratio mortar.

Very little has been reported on the influence of the water cement ratio of the mortar on bond strength. Most research reports and transportation department specifications for bonding mortar only contain a sentence that states the mortar shall contain enough water to have a "thick creamy paintlike consistency" (Portland Cement Association (1981)). Similarly the Iowa Department of Transportation (1974) states the mortar must contain enough water to form a "stiff slurry" but not enough water to "run or form puddles in low spots" of the substrate. The Canadian Standard Association (CSA) in Standard CAN A23.1 M77 specifies that the maximum water cement ratio be 0.40 for mortar used to bond floor toppings to substrate.

Portland cement paste is also occasionally used to join fresh concrete to hard concrete. The British Columbia Ministry of Transportation and Highways has used cement paste to bond the top course to the bottom course of many new 2-course bridge decks (Manning and Ryell (1975)). Sinno and Furr (1970) found the direct shear strength of composite prisms where portland cement paste was used as bonding agent was lower by 10% to 30% than the values for portland cement mortar bonded composite specimens, when the bond surface of the substrate was sandblasted. Portland cement paste and portland cement mortar bonds were compared by Felt (1960), for a wide range of surface preparations, using direct shear tests of cores. He concluded that there was no large difference between the mortar and the paste bonds. Dixon and Sunley (1983) used portland cement paste to bond fresh concrete to hard concrete as a control in a series of slant shear tests. They found that failure occurred in the portland cement paste bond but at strengths ranging between 30 and 40 MPa.

Another less common type of bond containing portland cement is constructed by spreading dry cement on a wet substrate surface. According to Felt (1960) this bond yields shear strength similar to previously described bonding methods.

2.5.1.2. Surface Preparation

The surface preparation of the substrate concrete, when portland cement based bonding agents are used, is as important as the mix design and application of the bonding agent.

The surface of the existing concrete, where it will bond to the fresh concrete, must not be smooth, contain laitance, or be unsound, and it must not be contaminated with oil (National Co-Operative Highway Research Program (NCHRP) Synthesis 57 (1979)). There are several test results where bond surfaces contaminated with oil failed at low stresses such as in Warris (1967) and Sinno and Furr (1970).

The most common process for removing contaminants, laitance and a smooth surface from the bond face is to use sandblasting. Compared with other surface preparations which will be discussed later, sandblasted surfaces have permitted high bond strengths according to several researchers including Bergren (1981), Sinno and Furr (1970). Several transportation departments specify that surfaces to be bonded with new concrete must be sandblasted, including Alberta Transportation (1985), IDOT (1974) and NYSDOT (1985).

Several other mechanical processes exist for treatment of bonding surfaces including the use of electric (or conventional) chip hammers, wire brushes, scarification machines, water blasting, vacuum blasting (sandblasting with a vacuum to remove the dust) and surface burning. Sinno and Furr (1970) found the use of a wire brush to remove oil from a substrate bond face ineffective, but also found the use of a chip hammer to be effective. Bergren (1981) preferred sand-blasting or shotblasting over water blasting since water blasting could not remove highway lane markings and tire skid marks. Surface burning should be avoided if possible according to Sasse and Fiebrich (1983) as it causes damage to the bond surface.

Acid etching with hydrochloric acid was a very common method of bond surface treatment, i.e. Westall (1958), but is less used now. In Portland Cement Association (1981), acid etching is described as being an acceptable surface preparation but inferior to mechanical surface treatments. Acid etching was found effective only if the acid residue and weakened concrete surface layer is completely removed (Felt (1960)).

It has long been observed that a bond surface produced by any preparation method that is too rough, is undesirable. Hughes (1951) noted the exposure of a large amount of coarse aggregate near the surface of the base component of part of a 2 layer slab, and found that bond, measured by shearing cores, was much lower than in other parts of the slab. Felt (1960) also noted that a surface which is excessively rough is undesirable. However, a bond surface which is too smooth is not desirable either. In the Canadian Standards Association Code CAN3-A23.3-M83 clause 17.5.3.4 a minimum surface roughness of 5 mm (maximum amplitude between protrusions and depressions on the surface) is specified for precast concrete joint surfaces.

The correct moisture condition of the substrate concrete is a subject of debate, although much research suggests the concrete should be damp, but no free water should exist on the surface according to Portland Cement Association (1976). Both Felt (1960) and Sinno and Furr (1970) found that a dry substrate produces a slightly better bond, as measured using direct shear tests, than a wet substrate. In addition, Warris (1967) found that a dry surface produced a strong bond as measured by a pull-off type test. Alberta Transportation (1985), IDOT (1974) and NYSDOT (1985) all specify that bonding grout must be applied to a dry surface. However, the Kansas Department of Transportation recommends prewetting the substrate concrete and has supporting empirical data (Portland Cement Association (1980)). Tyson (1977) reported surfaces being wetted for bridges in Virginia.

2.5.2. Polyvinyl Acetate

2.5.2.1. General Information

Polyvinyl acetate (PVA) and PVA modified cement has been widely used as an inexpensive general purpose bonding aid. Polyvinyl acetate is usually used in locations that are not exposed to humid, damp conditions for long periods of time (Building Research Establishment Digest (1982) and Shaw (1983)). Older homopolymer PVA has been superseded by copolymer latex PVA which is suggested by Shaw (1983) to have potentially a greater resistance to moisture.

Extensive research has been done on the basic mechanical properties of homopolymer PVA. Researchers, including Geist, Amagna and Mellor (1953) and Perenyi (1968) found that the tensile strength and modulus of rupture of PVA modified mortar cured in a non-humid environment are much higher than the tensile and flexural strength of standard portland cement mortar. They also found the optimum polymer/portland cement ratio for strength was about 0.2. The compressive strength of PVA modified mortar cured in a dry area was also observed by Geist et al (1953) and Perenyi (1968) to be much lower than a similar conventional portland cement mortar cured at 100% relative humidity.

The strength of PVA improves with time far beyond "standard 28 day strength" and at a greater rate than ordinary portland cement mortar according to Perenyi (1968) and Cherkinski (1967) but some other researchers disagree such as Satalkin, Solntesev and Popov (1967).

The deleterious effect of slightly alkaline moisture on PVA by saponification has been noted by many scientists. Decay occurs as the PVA reacts with any calcium hydroxide that is present in moisture to form both polyvinyl alcohol, which is soluble in water, and calcium acetate (Frondistou-Yannas and Shah (1972) and Mattiotti (1969)). Frondistou-Yannas and Shah also note that polyvinyl alcohol when dry is stronger than PVA, therefore, PVA exposed to moisture followed by a dry environment, may recover its strength.

The ability of PVA to bond itself or fresh concrete to hard concrete has been described in several published works. Several cases have been observed where

PVA modified mortar, cured mostly in low relative humidities, produced stronger bonds to concrete than that obtained using portland cement cured at 100% relative humidity, for example Ghosh and Pant (1967), Mattiotti (1969) and Cirrode (1960). The Building Research Establishment Digest (1982) claims PVA modified mortars subjected to suitable moisture conditions have a superior bond to hard concrete when compared to standard portland cement mortar. A few researchers, however, including Ohama (1967), Warris (1967) and Smith, Chojnacki and Langhammer (1967) have tested the ability of both PVA modified mortar and portland cement mortar to bond fresh concrete to hard concrete in dry curing conditions, and found the PVA was inferior. After exposure to high humidities PVA bond to concrete is weakened by moisture according to Warris (1967), Shaw (1983) and the Building Research Establishment Digest (1982). Copolymer PVA was developed to overcome vulnerability to alkaline water according to Shaw (1983) but Frondistou-Yannas and Shah (1972) noted that a copolymer PVA latex film reacted significantly when immersed in an alkaline solution.

The application of PVA in "paint" form, without mortar, is sometimes practised but Warris (1967), after comparing PVA paint and PVA mortar bonds to concrete, found the paint gave a weaker bond. The consequence of applying a second layer of PVA paint if the first coat has dried, apparently has not been researched although Dixon and Sunley (1983) performed a similar study with another type of polymer bonding agent, SBR latex. They found the SBR latex to be adversely affected by a 2 layer application.

2.5.2.2. Surface Preparation

The preparation of the substrate surface to be bonded is important when a PVA based bonding agent is used. Recommendations for surfaces that are to be bonded with PVA mortar or paint are similar to the recommendations for portland cement based bonding agents. The authors of NCHRP synthesis #57 (1979) suggest the substrate surface should be wetted before the bonding agent is applied, in order to aid PVA penetration of the old material.

2.5.3. Epoxy Resins

The most expensive bonding agents commonly used are epoxy resins which are widely used as bonding agents for connecting precast concrete members. The most common type of epoxy resin is a polysulfide polymer. Epoxy resins are used in both glue form (without filler aggregate) and mortar form. Mechanical properties of epoxy resins vary widely since there are 63 chemical types of epoxy according to Schutz (1982) and the amount and gradation of the aggregate can also drastically affect performance (Johnston (1970)). High strengths of epoxy glue and epoxy mortar bonds between hard concrete and either hard concrete or fresh concrete have been noted by many researchers including Johnston (1970), Warris (1967), Smith, Chojnacki and Langhammer (1967), Moss and Batchelar (1975) and Joshi, Singh and Singh (1982). Creep in epoxy bonded joints should not be a serious problem provided the correct combination of epoxy, hardener and filler is chosen (Johnston (1970) and Schutz (1976)). Mix proportions of epoxy and hardener components must be kept exact and application of epoxy should not be undertaken at too low or high a temperature (Shaw (1983)). Epoxy is the most expensive commonly used bonding agent. Surface preparation is similar to that required when portland cement based bonding agents are used except that the surface must be kept dry according to NCHRP synthesis #57 (1979).

2.5.4. Other Bonding Agents

Numerous other bonding agents have been used with varying frequency and success. In the United Kingdom styrene butadiene (SBR) applied alone or as an addition to portland cement paste or mortar is used frequently (Higgins (1982)). However, the use of SBR in North America as a bonding agent is less well known, although it is widely used in bridge deck concrete according to NCHRP synthesis #57 (1979).

Polyester resin, acrylic latex modified cement mortar, and polyvinylidene dichloride have also been used as bonding agents (Shaw (1983), NCHRP synthesis #57 (1979)).

Several tests have been performed on bonds between new and old concrete where no bonding agent has been used. Felt (1960) found the direct shear bond strength of composite prisms that did not contain a bonding agent were sometimes of a reasonable strength but usually lower than prisms where portland cement bonding agent had been used. Tabor (1979) notes that under laboratory conditions, which are superior to those in the field, high bond strength can be obtained without using a bonding agent.

2.6. Summary and Conclusions

The survey reveals that many tests exist and that careful decisions are required to select a few tests for further study (see section 3.1). Portland cement based bonding agents are widely used and appear to be effective, however, certain parameters such as the best water/cement ratio and the effect of bond thickness on strength have not been documented well, and should be investigated further. The optimum moisture condition of the substrate when a portland cement mortar bonding agent is used has been determined previously. However, the optimum moisture level is not completely agreed upon, thus, it will be studied briefly. Polyvinyl acetate (PVA) has been studied previously but many conflicting results exist. Copolymer PVA has been studied to a limited degree. Few published studies have been done on the ability of copolymer PVA to bond new concrete to old concrete in different curing conditions - this will be studied further in both mortar and paint form. However, the appropriate test method must first be selected.

CHAPTER 3

SELECTION OF TESTS AND DESCRIPTION OF TESTING PROGRAM STRATEGY

3.1. Introduction

Several steps must be taken before the most appropriate bond test can be determined. In order to determine which tests should be assessed in detail, criteria for the selection of tests were chosen. Tests were then selected using these criteria. Finally, the experimental program used to select the single most appropriate test was determined.

3.2. Criteria for Selection of Tests

The literature survey uncovered many different bond tests. In order to decide which tests were worthy of further evaluation the following factors were considered:

1. amount of use and recognition in industry and among researchers;
2. type of stress state induced at the bond interface;
3. ability to test both mortar and thin paint or grout as bonding agents.

3.2.1. Effect of Stress States on the Bond

3.2.1.1. Realistic Stress States

The first useful attribute for the stress state at the bond in an acceptable bond test is that the stress state reflect conditions that are likely to occur in a practical bonding application. There are, however, a variety of stress conditions that can occur. In a bridge deck overlay the bond will be subjected to compressive stresses due to wheel loads as well as shear caused by tire traction (especially braking action). Also, shear will be caused by the force transfer due to composite bending of the overlay and base bridge deck. If the bridge deck below the overlay has been contaminated with salt and experienced the resultant reinforcement rusting and concrete spalling, then the bond will eventually be subjected to large tensile stresses. Tensile stress may occur adjacent to, but not directly underneath, wheel loads since the stress distribution beneath a wheel load is approximately the same as that below a concentrated load. Tensile stress from the wheel loads is reduced if there is an asphalt topping over the bridge deck. However, many bridge decks do not have asphalt topping.

Bonding agents are also used to attach repair material (such as concrete or mortar) to assorted holes and pits in various structures. If the repairs were necessitated by concrete spalling then large tensile stresses may occur in the bond for the same reasons as with bridge decks. The repair material often contracts due to drying shrinkage, which can cause tensile stress on the bond as well. Other bond stresses can be extremely diverse since they are dependent on the stresses that exist in the particular structure containing the bond.

Also, cold joints in construction projects are sometimes "strengthened" with a bonding agent. The stresses on the bondline are dependent to a large extent on the stresses experienced by the entire structure or component; hence, the stresses at the bond cannot be typified.

3.2.1.2. Stress State Most Probable to Cause Bond Failure

A second useful characteristic of the stress state in a bond test is that it should be the stress state most likely to cause failure. It is inappropriate to design a test which exposes a bond to a stress combination unlikely to cause failure. An exception to this statement could be made if it is known with certainty that the stress combination achieved by the test is *identical* to the stress state experienced by bonds in most practical applications. This situation, however, is very unlikely since it has been shown above that bond stresses vary too widely to be matched exactly by the single stress state induced by any test.

It is reasonable to state that a bond is most likely to fail from tensile stress. A bond will never fail in pure compression normal to the bond since there is no force of equilibrium that exists to pull apart the two blocks of concrete (overlay and substrate). However, in a tension test where the bond is subjected to pure tension across the bond the full force equilibrium is applied to breaking the bond. Direct shear testing of the bond is difficult to achieve, and will give results that are dominated by surface roughness since a friction force will almost certainly exist. The use of "shear jigs" advocated by some highway departments will give a combination of flexure and shear instead of pure shear. This implies that flexural and indirect tension tests are logical choices.

Concrete subjected to "pure shear" fails by cracking perpendicular to the tension diagonal. Thus, in this thesis, failure is taken to be initiated by maximum tensile stress. Shrive and El Rahman (1985) show how such a failure criterion can explain typical cracking in uniaxial and multiaxial stress states. Their explanation is based on the stress field which develops around the voids in a material. In uniform uniaxial compression, maximum tension occurs on a vertical plane parallel to the direction of compression (when a semi axis of the void also lies in the direction of compression). In this context, the slant shear test can be interpreted as containing a weak plane, off-center from the void, but in the zone of tensile stress at the surface of the void.

Thus, using a tensile failure criteron, flexural and indirect tension tests are logical choices, and the slant shear test might also be acceptable.

3.2.2. Assessment of Mortar and Paint Types of Bonding Agent

A useful bond test should be designed to test both mortar and paint types of bonding agents.

The thickness of the mortar joint is important (Sise (1984)), therefore, the bond tests selected for further evaluation were required to accommodate a relatively precise technique for controlling the bond thickness. The bond surface should not be on a steep slant because the mortar bonding agent should not slide or pool at the bottom of the mould during the vibrations associated with casting.

The requirement of the bonding test to test a "paint" type of bonding agent is much less demanding since depth control is unnecessary and the tendency for the paint to pool at the bottom of the mould is less.

3.3. Tests Selected for Assessment

Four tests were selected for further assessment: the slant shear test, two flexure tests and an indirect tension test. These tests are now described in detail.

3.3.1. Slant Shear Test

The literature survey indicated that of all tests the slant shear test has been used the most extensively by researchers in industry and universities. Thus a slant shear test was evaluated in this program. The specifications issued on slant shear tests vary considerably. The Arizona Slant Shear Test is the best known version. The Arizona Slant Shear Test requires a 152 mm (6'') × 305 mm (12'') composite cylinder with a 60^o to horizontal bond line and is designed to test the effectiveness of epoxy bonding agents in bonding fresh or hardened concrete to hardened concrete. The ASTM specification is similar except that 76 mm (3'') × 152 mm (6'') cylinders are used and mortar replaces concrete in the substrate and overlay. Dixon and Sunley (1983) used a 55 mm × 150 mm slant shear prism for their tests on SBR modified grout. This test is now incorporated into the British Standards as

BS6319. These versions of the slant shear test are not conducive to a precise monitoring of the bond thickness and in the case of the cylindrical tests are somewhat difficult to cast.

The macroscopic state of stress that exists at the bond in the slant shear test is one of compression and shear. If one applies the theory that small voids create tensile stress perpendicular to the field of principal compressive stress (see Shrive and El Rahman (1985)) then the stress state at the miroscopic level becomes one of shear and tension with the principal tensile stresses acting across the vertical axis. The version chosen has the bond line at an angle of 60^o from horizontal similar to Kreigh (1976), Dixon and Sunley (1983), Tabor (1978) and BS6319. A steeper angle can cause casting problems. Test dimensions chosen for the present program are 102 mm (4") × 102 mm (4") × 305 mm (12") and are illustrated in Fig. 3.1.

The angle between the bond plane and horizontal axis affects apparent bond strength, with an increased angle causing a reduction in apparent bond strength. This hypothesis is supported by Shrive and El Rahman's theory since the tensile stress due to voids will be greatest on a vertical plane. Experimental work by Savage (1967) with epoxy resin bonds showed that a 70^o bond angle caused more bond failures than a 60^o bond angle. Sixty degree angles appeared, on limited evidence, to give lower strengths than 50^o angles. As mentioned in the literature survey Rehm and Franke (1982) used Mohr's circle and Coulomb's criterion to predict theoretically the weakest bond plane angle. When Coulomb's criterion is superimposed on the $\tau - \sigma$ plot containing Mohr's circle, the upper left corner of

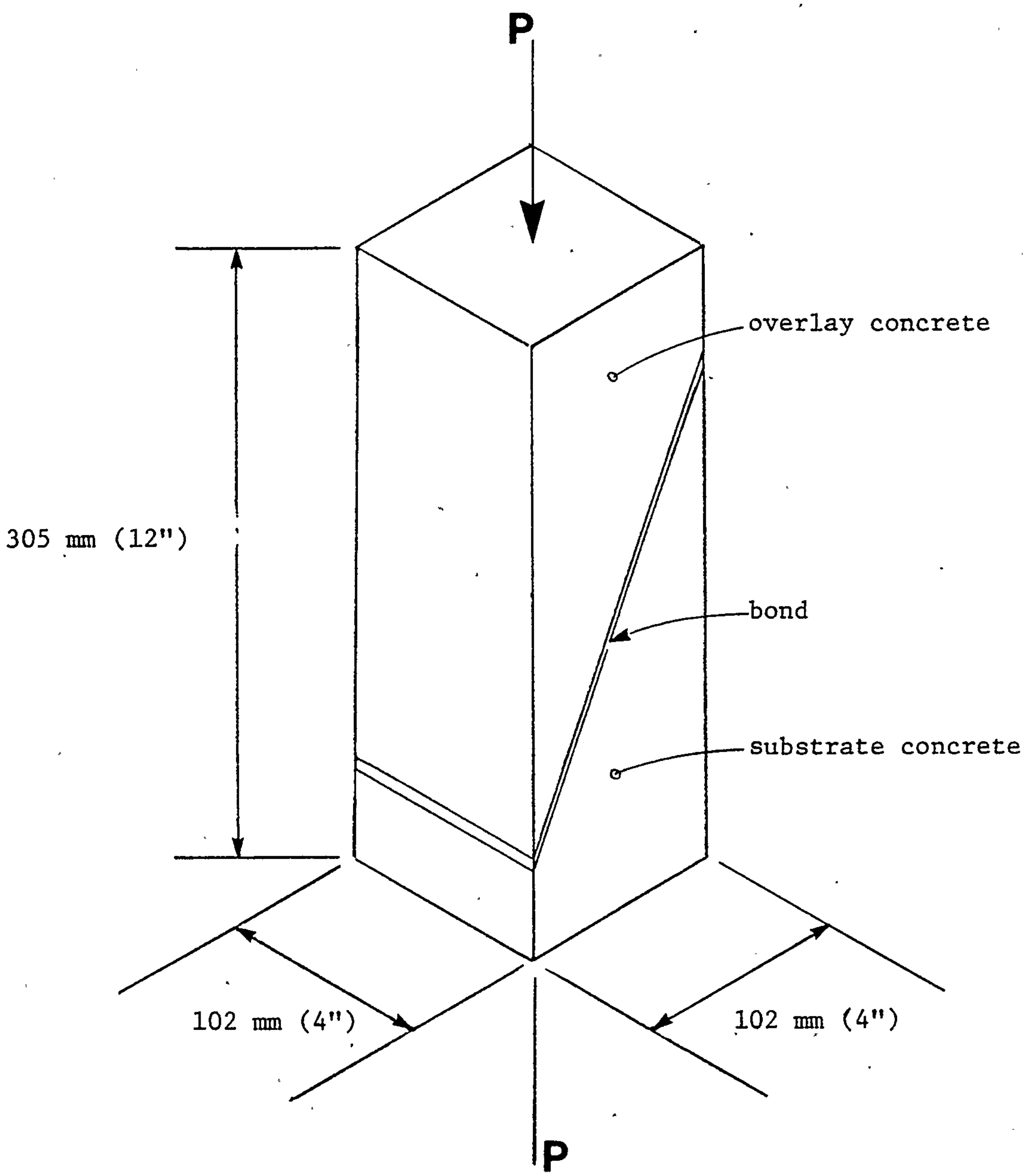


Figure 3.1 Slant shear test

the circle is intersected by the Coulomb line (see Fig. 3.2). Where the distance which is perpendicular to the Coulomb criterion line between the line and Mohr's circle (distance A-B) is largest, slant shear prism strength will be reduced the most.

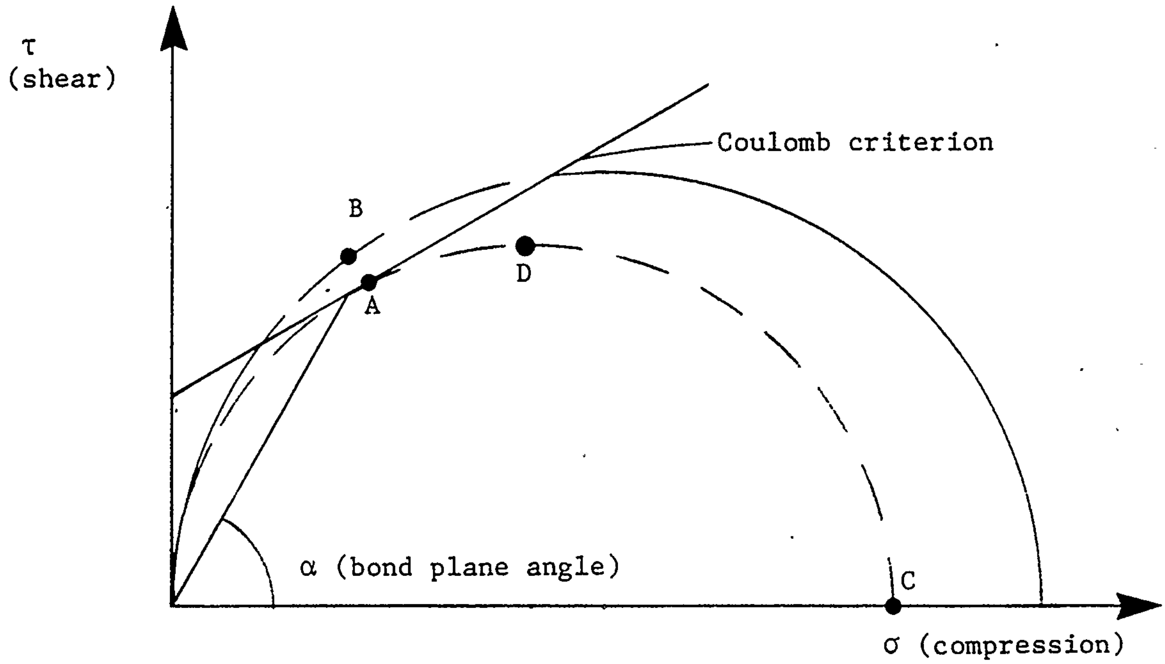


Figure 3.2 Coulomb's criterion and Mohr's circle

The reduction occurs since the Mohr's circle must not cross the Coulomb criterion line for an angle (α), hence, point C and D move closer to the origin. With the parameters of the Coulomb criterion assumed, for a particular bonding agent, Rehm and Franke found the weakest bond plane angle is about 65°.

The height to width ratio of the slant shear prisms is 3. This means that the middle 40% of the prism, including most of the bond region, is subjected to unconfined vertical compressive stresses. The ultimate load using a height to width ratio of 3 provides a better estimate of unconfined stresses in the central zone of the prism than the estimate obtained using a conventional slant shear prism or cylinder with a height to width ratio of 2.

3.3.2. Flexure Tests

The flexure tests chosen for evaluation in this program use beams with bond planes at 45^o and 60^o relative to horizontal (shown in Fig. 3.3). These angles were chosen to determine if exposing bonds to flexural tension and shear stress is a more rigorous test than the slant shear test; providing greater sensitivity to bond strength. Third point loading was used on specimens 305 mm (12") long with 76.2 mm (3") square cross-section. Therefore, the bond was contained in the region of constant moment between the two center loading points. Moss and Batchelar (1975) used a similar test with the bond plane at 30^o to the horizontal to determine the effectiveness of epoxy resins in bonding concrete.

3.3.3. Indirect Tensile Prism

The indirect tensile prism test was used to subject the bond plane to an essentially biaxial stress state with tension directly across (perpendicular to) the bond. In order to facilitate casting a prism was used rather than a cylinder as in the "Brazilian test". Prism dimensions were 102 mm (4") × 102 mm (4") × 356 mm (14"), and a diagram of the test is shown in Fig. 3.4.

3.4. Description of Testing Program Strategy

3.4.1. General

The four tests selected for experimentation were used to determine the performance of two different bonding agents. For each combination of test and bonding

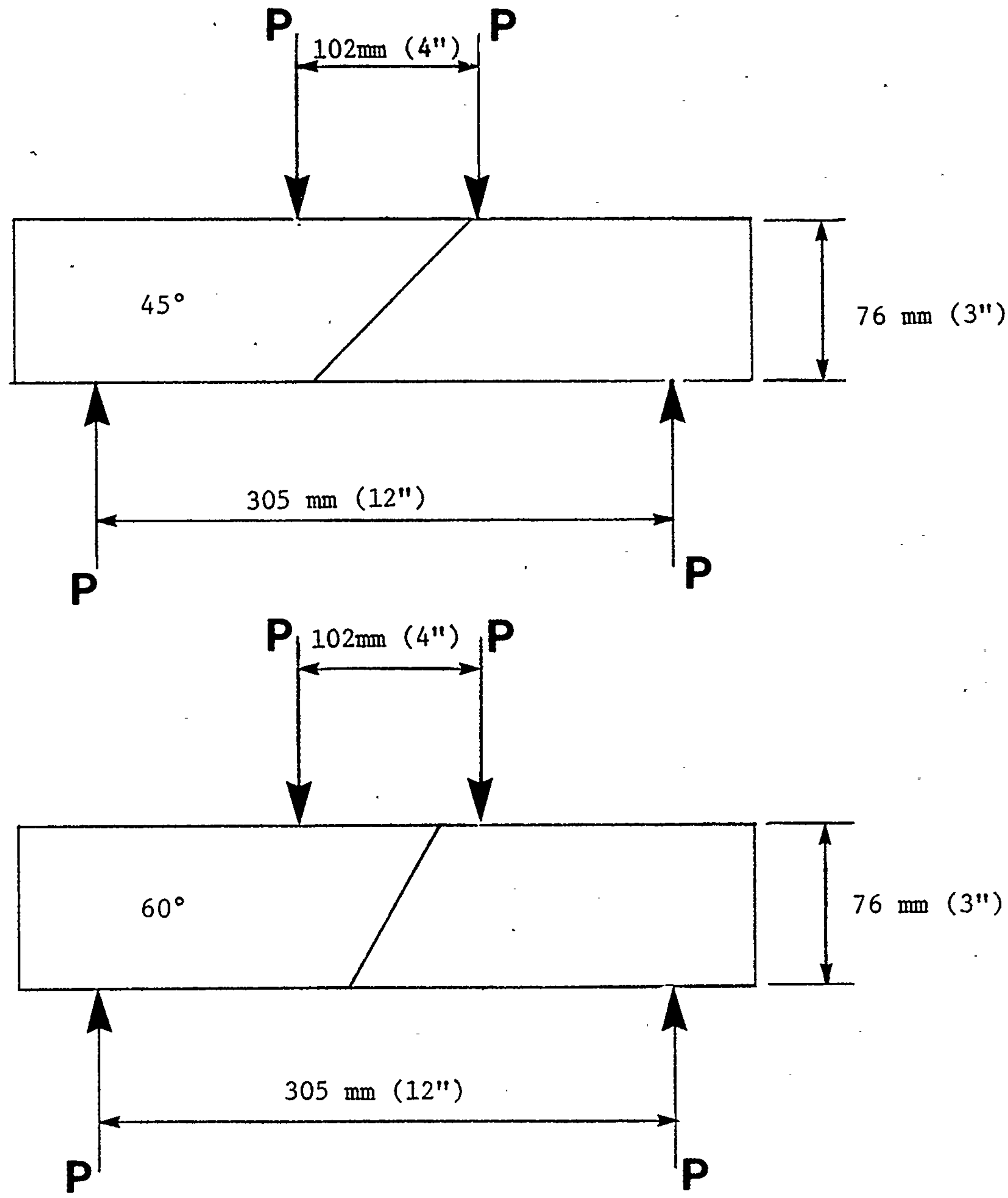


Figure 3.3 Flexure tests

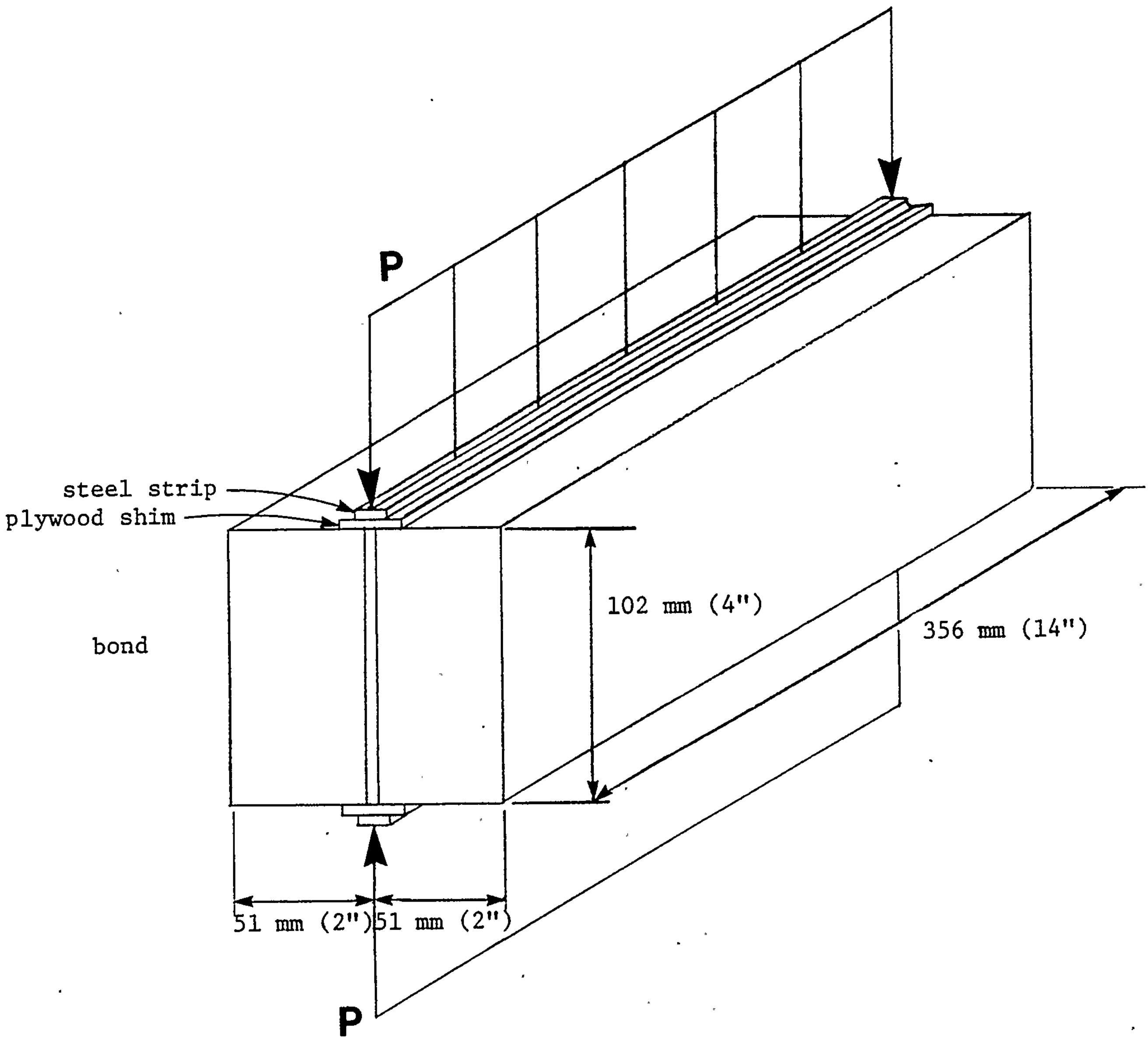


Figure 3.4 Indirect tensile prism

agent 6 composite specimens were cast. It was intended that one of the bonding agents have a moderate to high strength and the other be weak so that the sensitivity of each test to different bond strengths could be observed.

3.4.2. Selection of Bonding Agents

A portland cement mortar with a low water cement ratio (0.35) was chosen for a high strength bonding agent. The proportions of sand and cement were equal by mass. The maximum aggregate size was 2.5 mm, obtained by passing sand with a maximum aggregate size of 4.5 mm through a 2.5 mm sieve. Ordinary type 10 portland cement was used. A mix of similar proportions is widely used by highway departments for bonding concrete overlay to bridges.

A product which contained polyvinyl acetate (PVA) as the active ingredient was used as the low strength bonding agent. The bonding agent was applied in the form of a paint (as opposed to the mixture of the product and portland cement recommended by the manufacturer) to the bond face. This technique is often used in practice. An additional benefit of using the PVA in paint form instead of in a PVA-cement composite, is that the strength contributed by the PVA alone can be gauged.

3.4.3. Curing Conditions

The curing conditions and the bond face surface preparation of the prisms containing the PVA based bonding agent were the same as for the prisms containing the portland cement mortar bond. Curing conditions are discussed further in section 4.2.2. and were determined by the necessity to have strong concrete in order to assess the bond strength adequately. In addition, 28 day strengths are commonly used to gauge strengths, therefore, comparisons can be drawn with greater ease.

3.5. Conclusions

The bond tests which will be evaluated further are a slant shear test, two flexure tests and an indirect tension test. In order to determine which test is most appropriate, each test will be used to evaluate both a weak and a strong bond. The details of the experimental procedure will be described next.

CHAPTER 4

DESCRIPTION OF EXPERIMENTAL PROCEDURE

4.1. Introduction

To evaluate the four tests, an appropriate concrete and mortar mix was designed, and general casting and curing procedures were established. A procedure was developed to compensate for variation between concrete and mortar mixes. Finally, the specific details of the casting, curing and testing procedures for each of the four tests were established.

4.2. General Mixing and Casting Procedure

4.2.1. Concrete and Mortar Mix

The requirements for the concrete used in the base and overlay components of the prisms are:

1. that the mix design is similar to those used in practice;
2. that the concrete be strong enough to expose weak bonds because if the concrete fails at a low load, the bond is never tested;
3. that there is a low batch to batch variation in strength. If the concrete strength varies greatly between batches, a bond of a particular strength could be reflected in test results as a ductile failure in a batch of weak concrete and a brittle failure in a batch of strong concrete.

Depending on the type of the structure, the type of concrete used varies widely. Concretes used in bridge decks often have a low water cement ratio (0.45-0.40 or below). In many types of structures, the concrete will probably have whatever water cement ratio and density were determined to be the most economical while meeting the requirements for strength and durability.

The overlay concrete will have a low water cement ratio and high density if it is applied to a bridge deck. Overlay concrete used to repair structures that have suffered spalling or other deterioration may also be of a low water cement ratio in order to reduce the effects of differential drying shrinkage between the repair and the original concrete. If the overlay concrete is used in a cold joint or to correct a blunder at a construction site, then the concrete may be of the same design as the original concrete.

It was decided to use the same mix for both substrate and overlay for simplicity, and because this is a possible occurrence in practice. A study of the effects of different substrate and overlay concretes on bond might prove useful but is beyond the scope of this project. The mix design is shown in Table 4.1. Aggregate used in this first phase was completely dry which was compensated for by the modified mix design. The water cement ratio for this mix with saturated surface dry coarse and fine aggregate was 0.48. The mix was stiff but had acceptable workability when a vibrating table was used. A 0.0850 m^3 (3 ft^3) mixer was used with a minimum batch size of 0.0283 m^3 (1 ft^3) to ensure proper mixing.

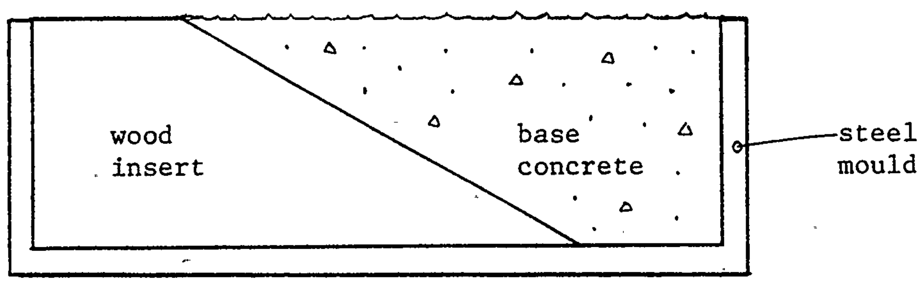
Table 4.1 Concrete Mix Design

	Mass kg/m^3 SSD	Mass kg/m^3 Oven Dry
Cement	368	368
H_2O	176	212
Coarse Aggr.	1242	1217
Fine Aggr.	780	769

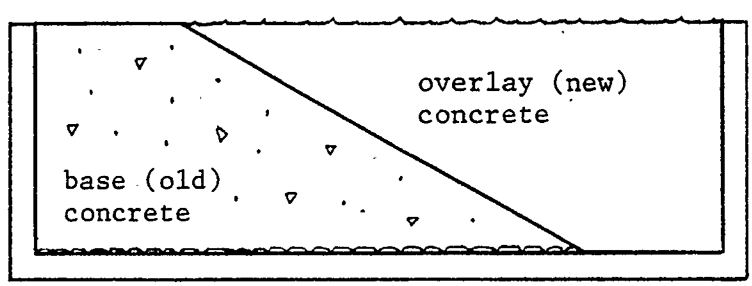
The portland cement mortar mix proportions were described in detail in section 3.4.2. The mortar was mixed in a 0.0283 m^3 (1 ft^3) bowl using a "cake" mixer. Cement was added to sand and mixed at low speed for 1 minute at which time water was added. The mortar was then mixed at medium speed for 3 additional minutes. A typical mortar batch was 0.00566 m^3 (0.2 ft^3).

4.2.2. Casting and Curing

Casting and curing conditions were kept as uniform as possible for the four different types of test specimens. In order to cast the base (old concrete) halves of the composite prisms, wood inserts treated to prevent moisture absorbtion, were placed inside steel moulds, as shown in Fig. 4.1. The geometric control was acceptable. The base halves of the prisms were poured in two layers, each being



a) elevation view of the casting of the base half of the composite prism



b) elevation view of the casting of the overlay half of the composite prism

Figure 4.1 Casting procedure

consolidated with the vibrating table. The base half prisms were cured for the initial 20-28 hours in the steel moulds with the tops covered with plastic tarpaulin. Subsequently, specimens were cured in a room containing 100% relative humidity (RH) for 6 days. After curing, the surface to be bonded was dried by air-blasting, then sandblasted. Each sandblasted surface was inspected visually in an attempt to ensure a consistent surface roughness between all the prisms. The surfaces were air-blasted again in order to remove the dust generated by the sandblasting. Next the prisms were re-inserted, with the bond face facing upwards, into the steel moulds, as depicted in Fig. 4.1. The prisms were orientated in this direction, in order to control the bond layer thickness. The overlay concrete halves of the prisms were cast in one layer and consolidated for a longer period on the vibrating table than the base halves of the prisms, in order to reduce the risk of distorting the bond layer.

When concrete is placed, the solid components of the mix settle and as a result water rises to the top of the cast. The severity of this process is quantified as the bleeding capacity. Little if any water was observed on the cast surface in the first four hours after casting for both base and overlay components. The casting procedure was designed so that cast surfaces of the prisms become the vertical sides of the prisms during testing. As a result, the effect of bleeding on the bond region would be minimal.

When the portland cement mortar bonding agent was used the surface was kept dry and the mortar was applied with a trowel. The depth was kept at approximately 3.2 mm (1/8'') with the aid of a template. However, if the PVA paint bonding agent was used the concrete bond surface was wetted about 5 minutes before the paint was applied.

For the next 20-28 hours the composite prisms were again cured in the steel moulds covered with plastic sheets. At this time the prisms were removed from the moulds and placed in the 100% RH room for 27 days and then tested in the laboratory.

4.3. Description of Batches Cast and the Control Tests

In order to compensate for the variation in strength between individual specimens, six composite prisms were used for both bonding agents (the portland cement and the PVA bonding agents) and in all four test types (slant shear, flexure with bond plane at 45^o and 60^o to horizontal, and indirect tension). In addition six monolithic specimens of each test type were cast and tested.

Out of a typical batch of concrete the following were cast:

1. the base or overlay component of two composite prisms of each test type;
2. six 76 mm × 152 mm (3'' × 6'') concrete batch control cylinders.

In some of the concrete batches monolithic specimens of one or more of the four test types also were cast. By casting specimens of all test types in each batch, the effects of batch to batch variation in concrete strength on the comparison of results among the four different tests were reduced.

Six 51 mm (2'') mortar cubes were used to monitor batch to batch variations in mortar strength.

4.4. Slant Shear Tests

4.4.1. Casting and Curing Procedure

The slant shear prisms used in the experimental program were cast in steel moulds with dimensions 102 mm (4'') × 102 mm (4'') × 305 mm (12'') as mentioned in section 3.3.1. The remainder of the casting and curing procedure is explained in section 4.2.2.

4.4.2. Testing Procedure

All the slant shear prisms were tested in stroke control with a 2000 kN compression testing machine. The loading rate range was selected to ensure that the increase in compressive stress was between 0.14 and 0.34 MPa/s (ASTM C39).

Deformations measured by Linear Variable Differential Transducers (LVDT's) and converted into strains were obtained from 3 of the 6 prisms cast for each of the two bonding agents, using a gauge length of 140 mm (5 1/2''). Two LVDT's were attached to a frame surrounding the specimen, one on each of the sides having the diagonal bond line (Fig. 4.2).

The LVDT's measured a combination of axial deformation and deformation due to shear deformation at the bond line. The bond layer affects the stress distribution in the adjacent concrete, hence, the deformation of that concrete. Thus the shear deformation can not be separated from the axial deformation by simply subtracting the axial deformation of a monolithic control prism from the deformation measured in a composite specimen.

If the LVDT's were placed on the other 2 sides from those shown in Fig. 4.2 the LVDT's would have been at risk during a brittle bond failure. The LVDT frame was attached to the prism by screws that contacted measuring points (similar to demec points) which in turn were cemented onto the prisms (Fig. 4.3). This allowed rapid transfer of the frame between specimens. As a precaution against damage to the frame from sudden brittle bond failure, contact points were not placed at the heel and the top of the bond line (see Fig. 4.3). As a further precaution plywood packing was loosely attached to the prism with fibre tape. The frame was positioned so as to be centered with respect to the bond line (see Fig. 4.3). The LVDT's had +/-2.5 mm travel which was ample for the 140 mm (5.5'') gauge length (2.5mm/140mm = 17900 μ). The LVDT's had a sensitivity of approximately $\pm$ 5 μ.

Stroke/load plots were recorded for the other 3 specimens in each batch.

4.5. Flexure Tests

4.5.1. Specifications Published

Specifications exist for testing concrete in flexure (ASTM C78) using beams of various dimensions, but none exist for bond tests. Therefore, the flexure tests for concrete were applied with slight modifications.

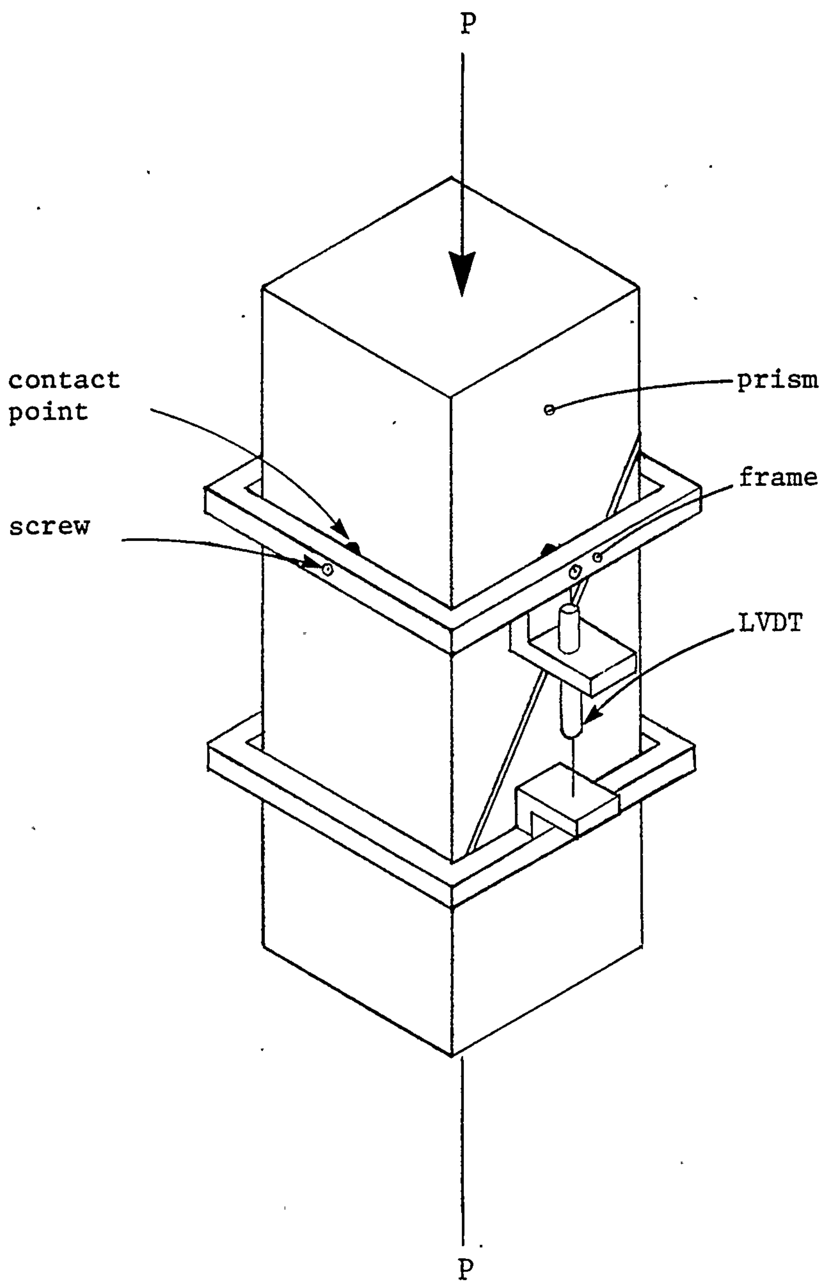


Figure 4.2 LVDT frame on slant shear prism

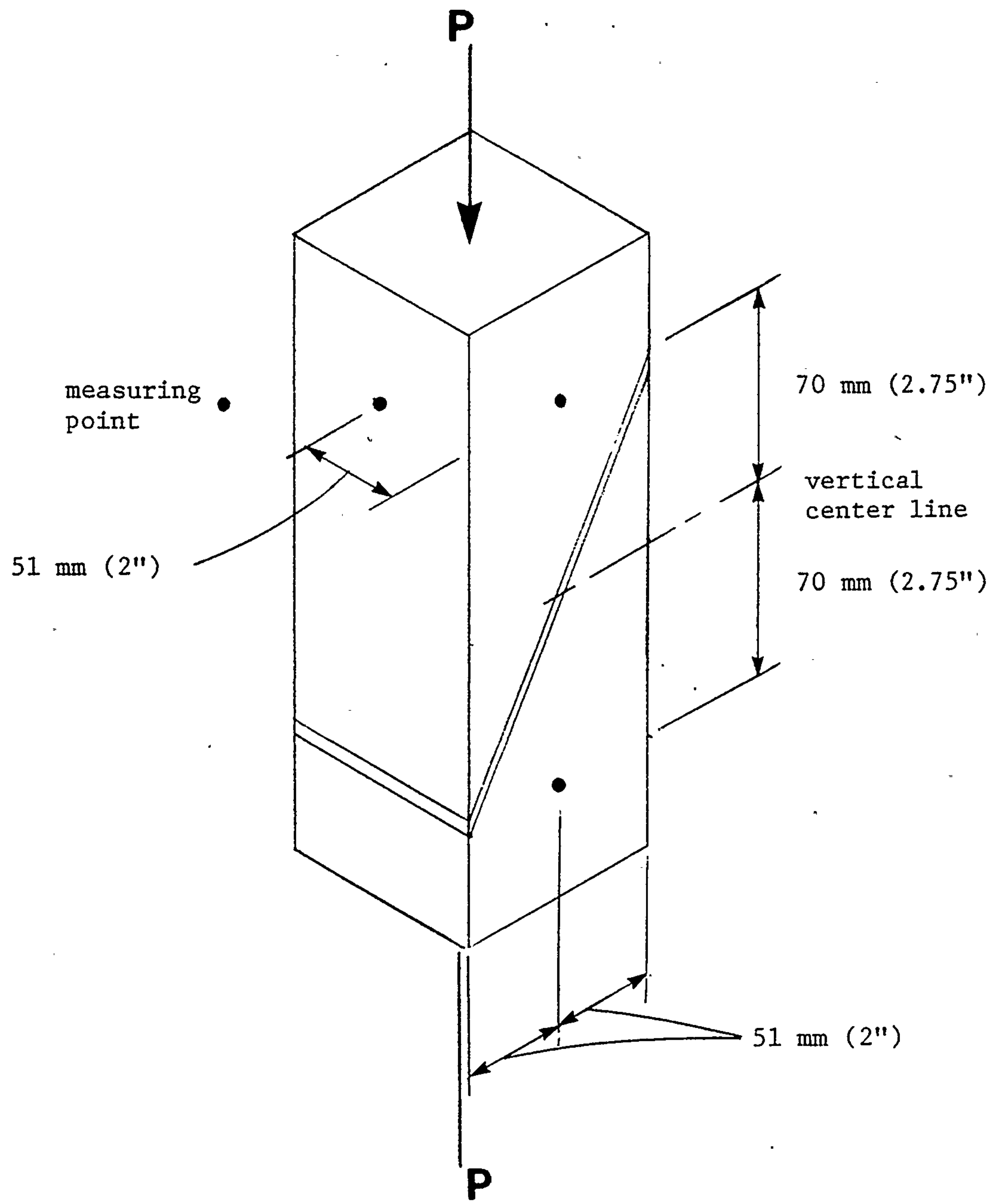


Figure 4.3 Location of LVDT frame contact points

4.5.2. Casting and Curing Procedure

The dimensions chosen for the flexure test specimens were 76 mm (3'') × 76 mm (3'') × 380 mm (15'') with a bonding plane at 45^o or 60^o from the horizontal plane as mentioned in section 3.3.2. These dimensions were chosen to ensure that the bond line would not be adjacent to a loading point. The casting and curing procedure was described in section 4.2.2.

4.5.3. Testing Procedure

A 250 kN hydraulic testing machine equipped with a 3rd point loading frame, 102 mm (4'') between each load point, was used for all the flexure tests. The loading rate was kept in a range between 1.25 kN and 1.75 kN per minute as specified by the ASTM C78 for flexural specimens.

The ultimate strength and a plot of load versus center line deflection (as measured by an LVDT built into the testing machine frame shown in Fig. 4.4) were recorded for each test.

Due to casting procedure requirements it was necessary to load the beams on cast surfaces. The beams were tested in the orientation shown in Fig. 4.5 as this proved to be the most practical configuration for placing the specimens level in the test rig. To assist in keeping the specimens level and contacting the supports and loading points uniformly, plywood shims were used. To ensure that the compression deformation of the shims had minimal effect on the load-deflection plots, the shims were precompressed in another testing machine. An alternative to the use of

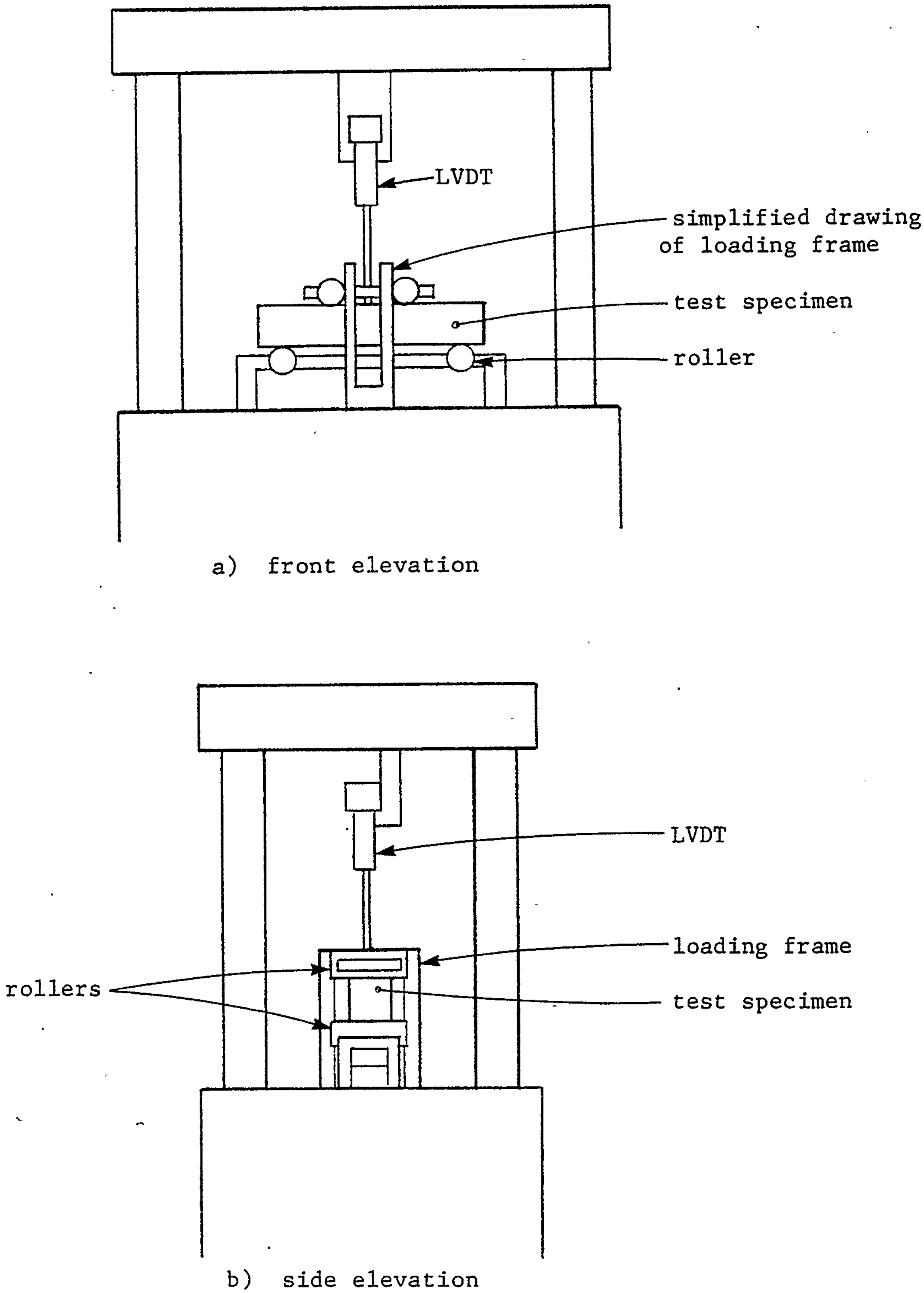


Figure 4.4 Test apparatus and location of LVDT for the flexure tests

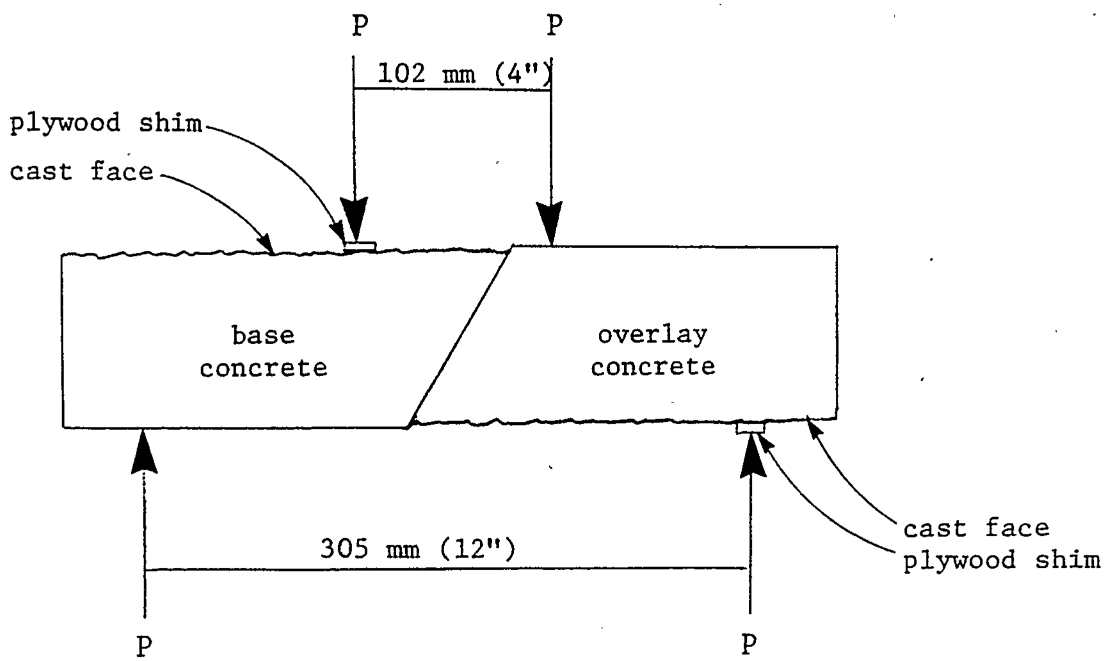


Figure 4.5 Orientation of beams during the flexure test

plywood shims would have been the application of plaster of paris to the regions of the cast face subjected to the point loads. Another alternative, would have been to measure shim deformation during the tests, by attaching an LVDT to each load point where a shim was placed. These alternatives might have produced more accurate deflection results. However, the only purpose of taking deflection readings was to assist in deciding which test type was the most sensitive to different bonds. Ultimately, the selection of the most accurate test was made on the basis of the ultimate load data.

4.6. Indirect Tensile Test

4.6.1. Specifications Published

There appears to be no specification and little published information on an indirect tensile bond test. The loading rate and the concept of using plywood shims were taken from ASTM C496 (Brazilian test).

4.6.2. Casting and Curing Procedure

The dimensions for the indirect tensile test were chosen as 102 mm (4'') × 102 mm (4'') × 356 mm (14'') to match the availability of moulds in the laboratory and to make the test comparable in size to the slant shear and flexure tests. The casting and curing procedure is the same as described in section 4.2.2.

4.6.3. Testing Procedure

A 2000 kN Amsler testing machine was used to test the prisms. Load was applied through a steel strip which contacted plywood packing which in turn transferred the load to the prism as shown in Fig. 3.4. The configuration of packing and steel strip was designed to minimize local stresses while maximizing the tensile stress applied at the bond line. This design process was aided by the use of finite element analysis, described in Appendix A. The loading rate used was 1 kN per second, the same as for the Brazilian test, ASTM C496.

CHAPTER 5

RESULTS AND ANALYSIS

5.1. Introduction

The experimental results involving the four bond tests, procedures of which were described in the previous chapter, are now discussed. The results were used to select the single most appropriate bond test.

5.2. Slant Shear Test

5.2.1. Observations and Comparisons

The individual ultimate strengths, for the control prisms and prisms with either PVA paint or portland cement mortar, are shown in Table 5.1. The average values along with bond prism strength as a percentage of the control are shown in Table 5.2. The variability in results can be seen to be low for the control specimens and the portland cement mortar specimens and high for the PVA paint bond prisms. The most obvious information that the results produce is that the PVA paint is far weaker than the portland cement mortar and monolithic concrete. The strongest PVA bond prism was only 1/3 as strong as the weakest control prism and the average PVA bond strength was 22% of the average of the control prisms. The portland cement mortar bonded specimens had an average ultimate strength of 72% of the monolithic concrete controls.

Table 5.1 Individual Specimen Strengths

TEST	CONTROL		PORTLAND CEMENT		COPOLYMER PVA PAINT	
	Batch(s)	Strength(MPa)	Batches	Strength(MPa)	Batches	Strength(MPa)
SLANT SHEAR (f_c) (MPa)	B6A+	39.06	B3A/B	26.56	B4A/B	6.58
	B6A	42.07	B3A/B	27.78	B4A/B	6.20
	B7A	40.63	B5A/B	30.49	B6A/B	13.66
	B7A	39.04	B5A/B	26.31	B6A/B	9.26
	B9	43.78	B8A/B	34.97	B7A/B	8.12
	B9	43.41	B8A/B	32.57	B7A/B	10.38
45 FLEXURE (f_r) (MPa)	B9	6.13*	B3A/B	4.95	B4A/B	1.95
	B9	5.60*	B3A/B	4.41	B4A/B	1.96
	B9	6.39*	B5A/B	5.43	B6A/B	2.58
	B9	5.32	B5A/B	5.33	B6A/B	2.79
	B9	5.51	B8A/B	5.79	B7A/B	2.77
	B9	5.63	B8A/B	5.12	B7A/B	3.93
60 FLEXURE (f_r) (MPa)	Same as 45 FLEX		B3A/B	4.86	B4A/B	1.21
			B3A/B	4.12	B6A/B	1.26
			B5A/B	4.89	B6A/B	2.12
			B5A/B	5.08	B6A/B	2.07
			B8A/B	5.37	B7A/B	3.12
			B8A/B	4.91	B7A/B	3.03
INDIRECT TENSION (f_t) (MPa)	B5A	3.21	B3A/B	2.34	B4A/B	2.59
	B5A	3.07	B3A/B	3.11	B4A/B	2.20
	B5A	3.44	B5A/B	3.04	B6A/B	2.85
	B6A	2.91	B5A/B	3.31	B6A/B	2.04
	B6A	2.93	B8A/B	3.21	B7A/B	2.33
	B6A	3.22	B8A/B	2.95	B7A/B	2.63

Note: The letter A indicates concrete used to cast the concrete used in the base half of the prisms

The letter B indicates concrete used to cast the concrete used in the overlay half of the prisms.

* Loaded on cast face

For the purposes of this thesis a brittle failure was considered to be one which occurred with a sudden loud noise and a rapid reduction in load from the ultimate. Any other failure was considered ductile. In almost all cases the portland cement mortar bonds failed in a brittle manner and at the base side of the concrete-bond interface (see Fig. 5.1). This indicates that the bond could be weak because of either or both a lack of penetration of the bonding agent into the substrate and a weakening of the substrate due to the sandblasting. There is evidence of high stress adjacent to the bond because vertically orientated cracks exist in the concrete

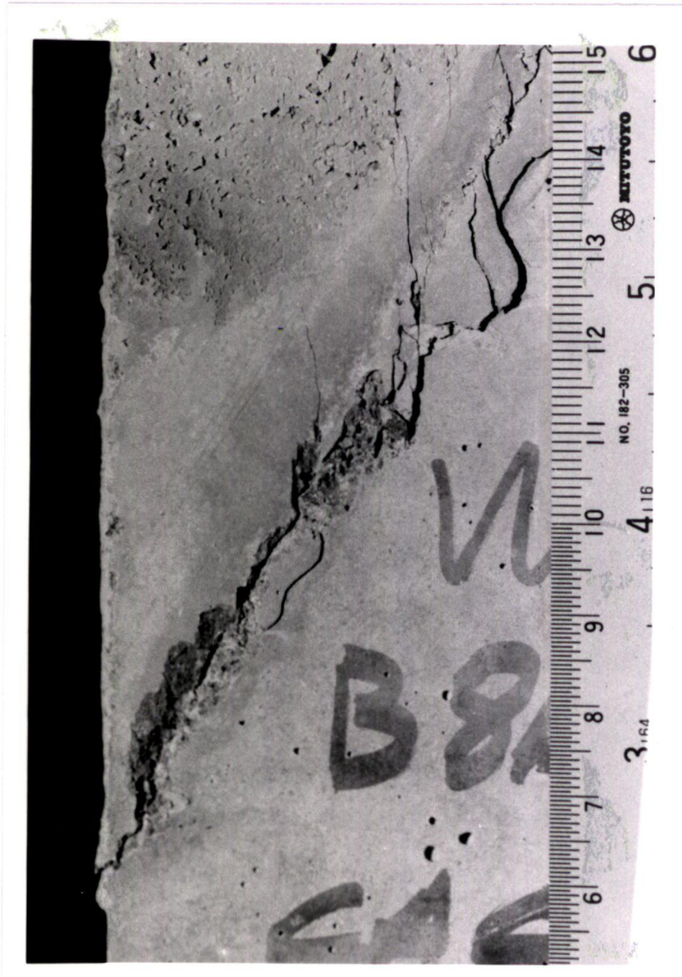


Figure 5.1 Vertical cracks near bond

next to the bond as shown in Fig. 5.1. The PVA bonds, however, failed in a partially ductile manner. Most of the PVA bonded prisms did not debond at ultimate strength but had little residual strength.

The compressive strains of the slant shear prisms measured with the LVDT's yield different results to those strains calculated from the stroke/load plots even after accounting for the effects of testing machine softness. To compensate for this, the strains measured with the LVDT's for each prism are compared only to other prisms in which strain was measured with LVDT's. Likewise, strains calculated using the stroke/load plots are compared only to other strains calculated the same way.

Strains calculated from the stroke/load data were highly varied among individual prisms and did not vary significantly between different bonding agents. The strains determined from the LVDT's did not vary much between individual prisms of a single bond type which indicates these data are more reliable than the stroke/load information. The LVDT strain data in Tables 5.3 and 5.4 show that the control prisms (unjointed) were the most stiff (had the lowest strains), the portland cement bond was significantly less stiff and the PVA bond was clearly the least stiff. The stress/strain data was averaged among three specimens of each bond type and plotted in Fig. 5.2.

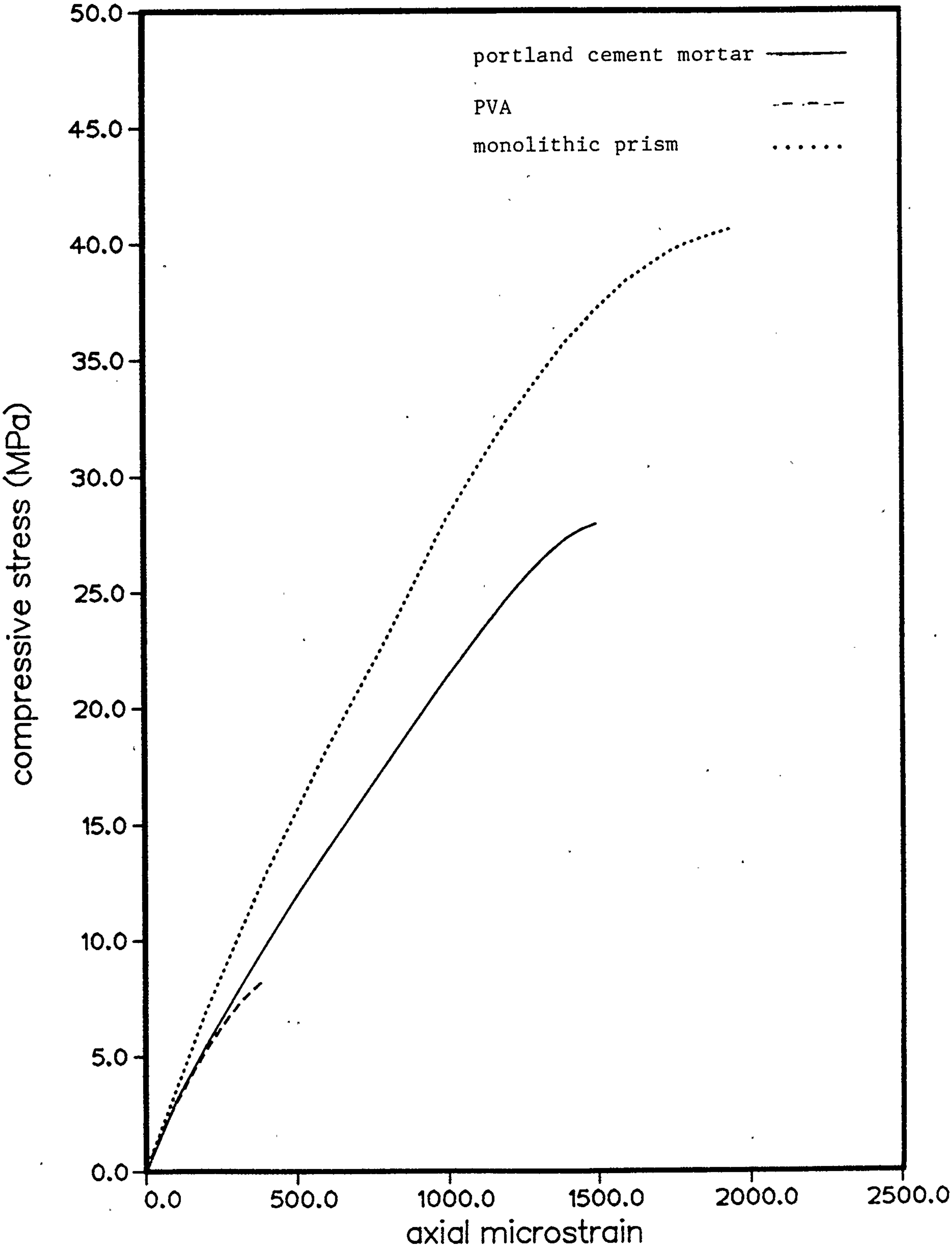


Figure 5.2 Averaged stress/strain curves of slant shear test prisms

Table 5.2 Strengths from the bond tests.
Each value is the average of six specimens.

	Control (MPa)	PC Mortar (Strength and Standard Deviation as a % of Controls, MPa)	PVA (Strength and Standard Deviation as a % of Controls, MPa)
Slant Shear (Prism Compressive Strength)	41.3	29.8 (72%)	9.03 (22%)
Standard Deviation	2.1 (5%)	3.51 (8%)	2.76 (7%)
Flexure-45^o Bond (Modulus of Rupture)	5.76	5.17 (90%)	2.66 (46%)
Standard Deviation	0.41 (7%)	0.47 (8%)	0.73 (13%)
Flexture-60^o Bond (Modulus of Rupture)	5.76	4.87 (85%)	2.14 (37%)
Standard Deviation	0.41 (7%)	0.41 (7%)	0.82 (14%)
Indirect Tension (Tensile Strength)	3.13	2.99 (96%)	2.44 (78%)
Standard Deviation	0.201 (6%)	0.344 (11%)	0.302 (10%)

Table 5.3 Strains at specific stresses (slant shear test).

	Control	PC Mortar	PVA
Stress (MPa)	5 8 20	5 8 20	5 8 20
Strain (μ)	140 237 672	175 312 925	217 - -
Standard Deviation	10 11.5 12.6	5 7.6 23	32

Table 5.4 Strain and deflection data for individual specimens

SLANT SHEAR TEST

COMPRESSIVE STRAIN (μ) (MEASURED AT COMPRESSIVE STRESSES)

SPECIMEN	CONTROL PRISMS 5 MPa	8 MPa	20 MPa	PORTAND CEMENT MORTAR 5 MPa	8MPa	20 MPa	COPOLYMER PVA PAINT 5MPa	8 MPa	20 MPa
1	150	250	685	170	310	945	235	-	-
2	130	230	670	175	305	900	235	-	-
3	140	230	660	180	320	930	180	280	-
4^*	350	461	977	240	353	843	337	454	-
5^*	189	297	826	329	356	866	179	284	-
6^*	271	392	895	265	379	882	288	402	-
AVG (TOTAL)	205	310	786	212	337	894	242	355	
AVG (STRAIN)	140	237	672	175	312	925	217	280	
AVG (STROKE)	270	383	899	278	363	864	268	380	
STD. DEV. (STRAIN)	10	11.5	12.6	5.0	7.6	23	32	-	
STD. DEV. (STROKE)	82	82	76	46	14.2	19.6	81	87	

45° BOND LINE FLEXURE TEST

CENTER LINE DEFLECTION IN mm (MEASURED AT DIFFERENT FLEXURAL STRESSES)

	CONTROL 1.03MPa	2.4MPa	4.5MPa	PORTLAND CEMENT MORTAR 1.03MPa	2.4MPa	4.5MPa	COPOLYMER PVA PAINT 1.03MPa	2.4MPa	4.5MPa
1	0.013^+	0.030^+	0.063^+	0.040	0.085	0.145	0.045	-	-
2	0.019^+	0.041^+	0.076^+	0.021	0.055	-	0.033	-	-
3	0.018^+	0.040	0.073^+	0.025	0.063	0.108	0.063	0.116	-
4	0.018	0.038	0.069	0.036	0.091	0.146	0.017	0.047	-
5	0.018	0.041	0.076	0.024	0.080	0.150	0.034	0.076	-
6	0.018	0.044	0.079	0.061	0.167	0.265	0.039	0.068	-
AVG	0.017	0.039	0.073	0.035	0.090	0.163	0.039	0.077	
STD.DEV.	0.002	0.005	0.006	0.015	0.040	0.060	0.015	0.029	

Table 5.4 Strain and deflection data for individual specimens

60° BOND LINE FLEXURE TEST

DEFLECTION IN mm (MEASURED AT DIFFERENT FLEXURAL STRESSES)

SPECIMEN	CONTROL			PORTLAND CEMENT MORTAR			COPOLYMER PVA PAINT		
	1.03MPa	2.4MPa	4.5MPa	1.03MPa	2.4MPa	4.5MPa	1.03MPa	2.4MPa	4.5MPa
1	0.013^{+}	0.030^{+}	0.063^{+}	0.015	0.051	0.104	0.033	-	-
2	0.019^{+}	0.041^{+}	0.076^{+}	0.023	0.065	-	0.061	-	-
3	0.018^{+}	0.040^{+}	0.073^{+}	0.023	0.065	0.111	0.048	-	-
4	0.018	0.038	0.069	0.034	0.083	0.144	0.053	-	-
5	0.018	0.041	0.076	0.034	0.117	0.221	0.026	0.059	-
6	0.018	0.044	0.079	0.025	0.075	0.133	0.025	0.063	-
AVG	0.017	0.039	0.073	0.026	0.076	0.143	0.041	0.061	
STD.DEV.	0.002	0.005	0.006	0.007	0.023	0.047	0.015	-	

* Calculate from stroke/load plot
$^{+}$ loaded on cast face

5.2.2. Errors

When the base components of the slant shear prisms were reinserted into the moulds the bottom face was slightly misaligned with the bottom of the mould. Also, the location of cast faces on opposite sides of the composite prism made sulphur capping difficult. As a result of these problems some prisms had top and bottom load bearing surfaces which were not completely parallel. However, the spherical seating above the top platen compensated for the absence of parallel bearing surfaces. As well, no significant difference was noticed between prisms with mild slants and those with more severe slants.

A calibration curve used to compensate for testing machine softness in the 2000 kN MTS testing machine was used to convert stroke/load data into stress/strain information. It was thought the calibration curve might be incorrect. The calibration curve was reconfirmed during the testing program, by loading a steel cylinder of known dimensions. As a further check a load cell was loaded by the machine allowing load data from the MTS console to be compared with load cell data. In addition the accuracy of the LVDT responsible for the MTS stroke output was checked by placing a dial gauge between the platens and incrementing the displacement. In both cases, the accuracy of the testing system was confirmed. However, the stroke/load data when converted into stress/strain data were highly variable which suggests the effect of non parallel sulphur caps reduced the accuracy of the calibration curves. The plotter was recalibrated frequently and is an improbable source of error. In addition the stress at the ultimate load was stored electronically by the MTS control console after each test.

The slant shear prisms were nominally 102 mm (4") × 102 mm (4") in cross-section but were actually slightly less than this due to the effect of the cast faces. Several dozen of the prisms were measured and the cross-sections were found to vary from approximately 98 mm to 101 mm from prism to prism and between cross-sections of an individual prism. To compensate for this error, the cross-section was assumed to be 100 mm × 100 mm which meant the actual cross-section area and stress were between approximately 97% and 102% of that assumed. Exact dimensions were impossible to measure due to the nature of cast face.

Between base and overlay sections of the prisms, an offset of between 1 mm and 3 mm existed (see Fig. 5.3). The offset would cause a small stress concentration at the bond line. Since the offset was small relative to the overall dimensions of the prism and the general shape of the offset was similar in each prism, the overall error should be small. As well, the offset error should not affect accuracy in comparisons between different prisms/bonding agents since the offset error is always present.

5.3. Flexure Tests

5.3.1. Observations and Comparisons

The modulus of rupture (f_r) for each monolithic concrete, portland cement bonded, and PVA bonded beam is shown in Table 5.1. Average values of the f_r

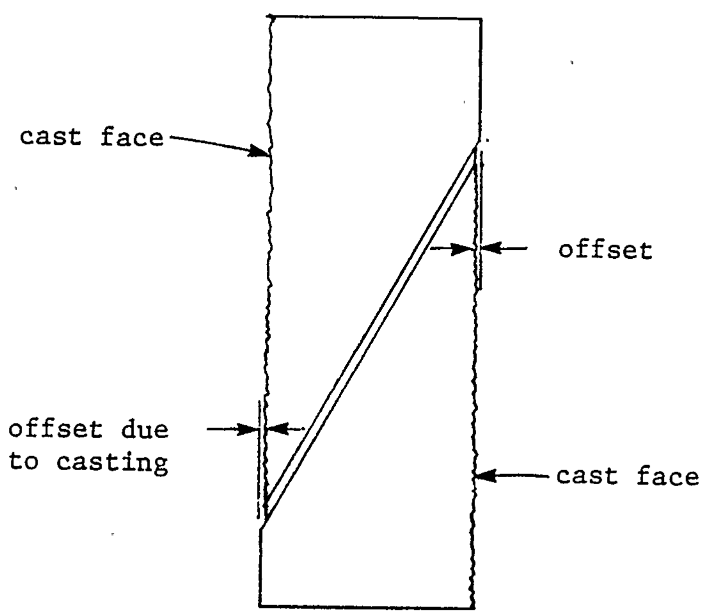


Figure 5.3 Offset error of a slant shear prism

along with the percentage value of the f_r as a proportion of the control beams are given in Table 5.2.

By observing the results, the weakness of the PVA bonded prisms is clearly seen since the average f_r of the composite prisms, as a proportion of the control beam average f_r, was 37% for the 60° bond line test and 46% for the 45° test. The portland cement mortar bonded specimens give average strengths of this bond type which are 85% and 90% of the control beam average f_r for the 60° and 45° tests respectively. In almost all cases the portland cement mortar bonds failed in a brittle manner as described in section 5.2.1., at the bond-substrate interface, as with the slant shear tests. Five of six bonds and three of six bonds failed in a brittle manner during the 60^o and 45^o tests respectively. The PVA bonded beams also failed in a ductile manner, as did the PVA slant shear prisms.

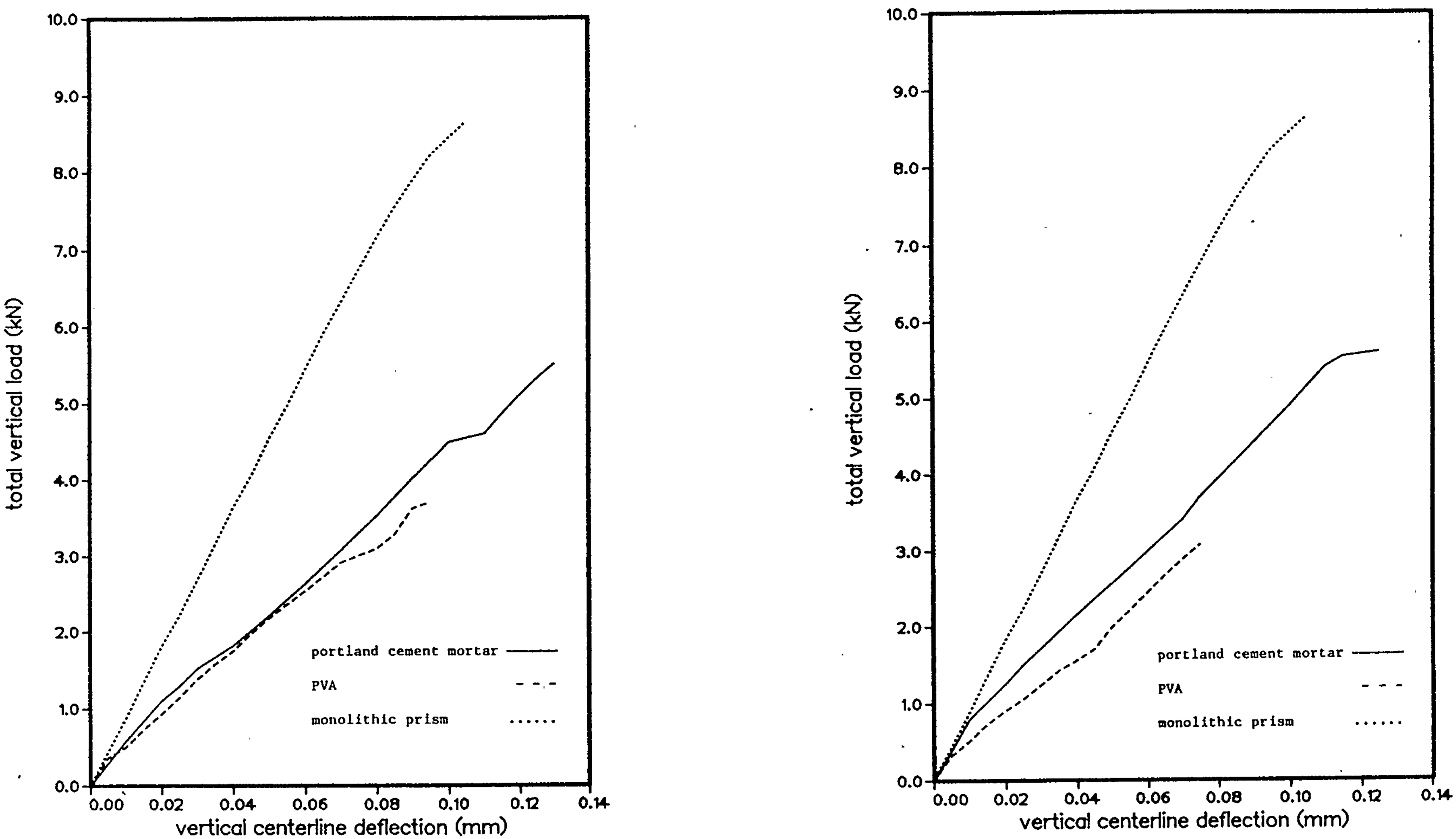
The variability of the PVA bonded beam strength was high for both the 45^o and 60^o tests. Individual specimen strength varied to a much smaller extent when the portland cement mortar bond was tested. The variability was similar in magnitude to the slant shear results.

As shown by the above results, the significant difference between the flexure tests and the slant shear test was the bond strengths. The 45^o bond test gave higher results for both bonding agents than the 60^o bond tests. Both the flexure tests yielded higher bond strengths than the slant shear test.

The center line deflection data were highly variable (see Table 5.4) and thus was of limited usefulness. Average values are shown in Fig. 5.4. The control beam data however were less variable. Lower deflections occurred with the control beams as compared with the composite beams.

5.3.2. Errors

One of the most obvious sources of error in the flexure tests stems from the offset that occurs at the bond line due to the casting procedure as mentioned in section 4.5.3. This offset is more severe (1 mm to 3 mm) on the top surface than on the bottom edge. The bottom edge is subjected to tension and thus more sensitive to stress concentration such as that caused by an offset. The offset will cause



(a) bond at 45° to horizontal

(b) bond at 60° to horizontal

Figure 5.4 Averaged load deflection curves of flexure test prisms a rise in the local stresses.

In order to load the beams at the third points in a uniform manner and to keep the beam level, plywood shims were used as discussed in section 4.5.3. Error in the deflection data might be created if these shims compress and seat themselves under load during the test. This error was compensated for, to the greatest feasible extent, by precompressing the shims in a compression machine and preloading each beam to approximately 0.25 kN.

The LVDT which measured center line deflection was attached to a section of the testing machine which was not under load during the test. However, the vertical rollers, which supported the beams during tests, deflected when the beams were loaded. As a result, the measured center line deflection is not an "absolute" value but contains an error. This error should be constant for a particular load level and should not affect comparisons between specimens or cause high variation in the results. In addition the sole purpose of obtaining deflection data was to assess the performance of the test in evaluating bonds. Ultimately, the selection of the best test was determined on the basis of the ultimate load data. Therefore, the center line deflection data is of limited importance.

The ultimate loads were measured electronically by a load cell and stored in the machine console and the plotter was periodically checked for calibration, therefore, these are unlikely sources of significant error.

5.4. Indirect Tension Test

5.4.1. Observations and Comparisons

The estimated ultimate tensile stress of each prism is displayed in Table 5.1. In estimating the tensile stress, the same equation derived for the Brazilian test was utilized. This equation should yield reliable results since the geometry between the Brazilian cylinder and the tensile prism are the same at the center line (see Fig. 5.5). The difference in geometry between the 2 tests increases with the distance from the bond line. This difference should not cause a significant error since the stresses in these outlying regions are very low.

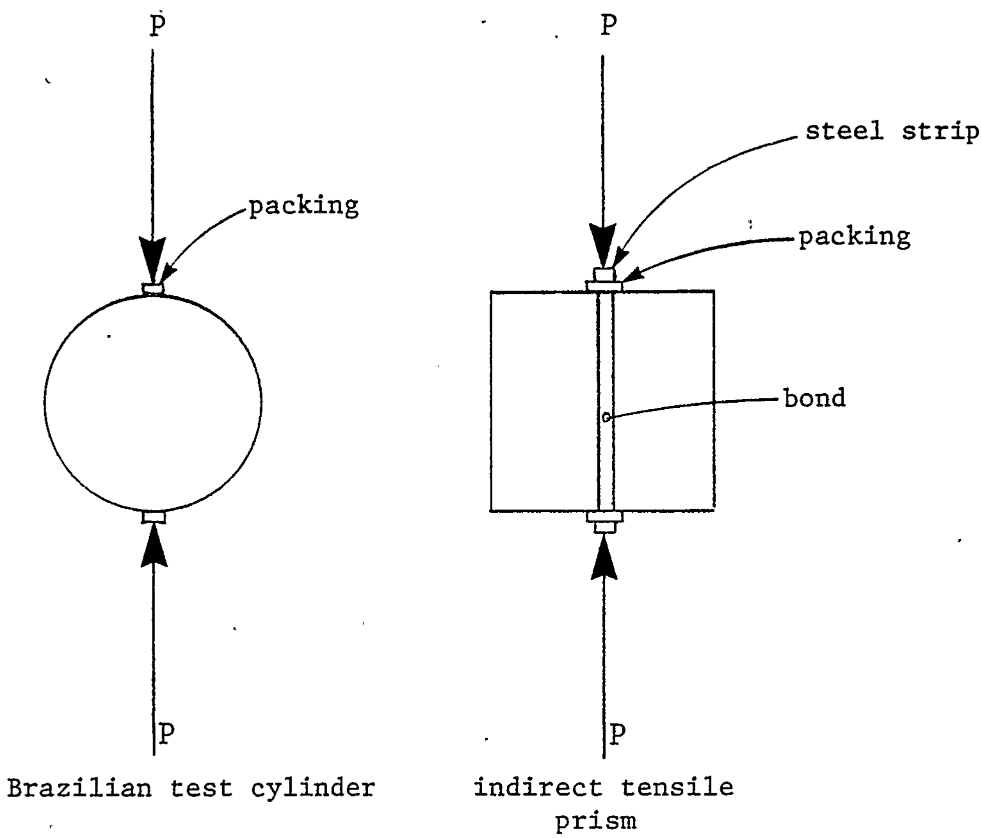


Figure 5.5 Brazilian test cylinder and indirect tensile prism

A comparison between the horizontal stress distribution of the Brazilian test cylinder presented by Wright (1955) and the split tensile prisms as calculated with finite element model is shown in Appendix A. The horizontal stress distributions along the vertical center line of both the indirect tensile prism and the Brazilian cylinder were similar.

Table 5.2 contains average values for the strength of the control, the PVA bonded and portland cement mortar bonded prisms. The ultimate loads for the portland cement mortar bonded specimens were almost as high as for the controls (96%). As well, some of the portland cement mortar specimens did not fail at the bond line. The PVA bond was weaker and ultimate loads for those prisms were only 80% of the control strength. Most of the PVA specimens failed at the bond line, the failure plane was contained within the PVA bonding material.

None of the prisms, with either bonding agent, failed in an "instantaneous" brittle manner as described in section 5.2.1. Many of those that failed at the bond also failed 1-2 cm away on a plane in the substrate approximately parallel to the bond.

The results of individual prisms with the same bonding agent varied less in absolute terms (the standard deviation) when compared with the flexure and slant shear tests. The variation in relation to the difference between average strengths of the different bond types, however, was larger compared to the other tests. Prism strengths with both bonding agents, as a proportion of the control, were much higher than for the slant shear or flexure tests. This makes detection of weak bonds more difficult.

5.4.2. Errors

The bond lines were not at the exact vertical center line of the prisms. This error was reduced as casting experience was gained. The fact that the bond lines were not centered would not be expected to have much effect on the results since stresses at the bond line were much higher than at the outside edges and the packing and metal loading strips were carefully centered over the bond line. This imperfection in symmetry, however, may have had an influence on the observed tendency of a few of the specimens to rotate while under load. The effect of asymmetry on the ultimate load of the prism may not be significant, however, since the gravity forces which exert a net moment on the specimens' longitudinal axes were very small compared to the loads exerted by the testing machine. A more probable cause for error is the packing configuration which concentrates a high load over a small area. Any anomalies in the packing material or in the adjacent concrete and bond areas will have a magnified effect on the test.

5.5. Variations in Control Values

Batch to batch variations in concrete strength cause errors in comparing results since the unjointed control prisms were cast separately.

This was monitored by testing the cylindrical control specimens cast for each batch of concrete. The control specimen average strengths are shown in Table 5.5. The strengths varied from 29.1 MPa to 45.2 MPa. The absolute strength of the

Table 5.5 Average batch control cylinder strengths

Batch	Base		Overlay		Average of Base and Overlay
	Strength and Standard Deviation of Control Cylinders (MPa) (Average of six cylinders).				
	Strength	Standard Deviation	Strength	Standard Deviation	
B3	34.7	1.03	32.2	1.15	33.5
B4	35.8	0.82	35.0	2.99	35.4
B5	41.6	1.13	45.2	1.61	43.4
B6	41.3	1.92	42.2	0.60	41.8
B7	40.5	1.75	40.7	0.75	40.6
B8	43.3	1.40	29.1	1.70	36.2
B9	41.7	0.99	-	-	41.7

bond is more important than the ratio of bond strength to concrete strength since almost all the specimens broke at the bond. Nevertheless, concrete strength will have some impact on bond strength since concrete strength affects the concrete modulus of elasticity. The modulus of elasticity will affect the stress levels at the bond. The concrete strength also influences the bond strength by affecting the condition of the substrate concrete adjacent to the sandblasted bond face.

Variation in bonding mortar strength between batches was minimal. The average compression strength of 52 mm (2'') cubes for each batch is shown in Table 5.6.

Table 5.6 Mortar Cube Strengths

BATCH	STRENGTH (MPa)	STAND DEVIATION (MPa)
B3B	74.2	3.64
B5B	74.0	2.43
B8B	82.6	2.98

5.6. Conclusion

The slant shear test was the most sensitive to different strengths of bonds and also provided results with a low coefficient of variation. As a result, this test was selected to investigate various bond parameters. The effect of the bond parameters will be assessed by two methods: theoretically, by the finite element analysis and practically, by an experimental investigation.

CHAPTER 6

FINITE ELEMENT ANALYSIS OF SLANT SHEAR TEST

6.1. Introduction

One purpose of the finite element analysis of the slant shear test was to study the variation of stress levels at the bond line.

Another purpose of the finite element analysis was to provide an alternative to the experimental investigation into factors influencing bond. The parameters affecting bond strength that were investigated using finite elements were the effect of:

1. bond thickness;
2. modulus of elasticity of the bond material;
3. weakness of the bond material near edges of the bond plane;
4. weakness of the bond material near the center of the bond plane.

The effect of imperfections in the slant shear test was also investigated.

6.2. Explanation of the Computer Program, Finite Element Mesh and the Elements

The finite element program used was FEMSKI written by B.M. Irons and utilizes the frontal solution technique. The program is described in Irons and Shrive (1983). The finite element mesh was designed to optimize the number of nodes and elements used to model the slant shear test while maintaining accuracy in estimating stresses (Fig. 6.1). As a result, small elements were used to model both ends of the bond line. In addition, the elements used to model the bond line (which runs 60^o to horizontal) were separated from the normal rectangular elements by "buffer" elements which were orientated parallel to the bond elements. The buffer elements were intended to decrease errors that would be caused if the narrow bond elements contacted the much thicker rectangular elements directly. The buffer elements also facilitated the variation of the bond thickness with minimal alterations to the mesh.

Several variations of the original mesh were created (mesh 2, 3 and 4) and are shown in Figs. 6.2-6.4. Mesh 2 was used to model stress concentrations due to weakness near the edges of the bond line. In mesh 2 bond weakness was simulated by placing very flexible elements, of modulus of elasticity of 1 GPa, near the edges of the bond line at elements (see Fig. 6.2). Similarly mesh 3 was used to model weakness near the center of the bond line. Mesh 4 was used to simulate the "offset error" (see section 5.2.2.) that occurs due to the casting procedure used.

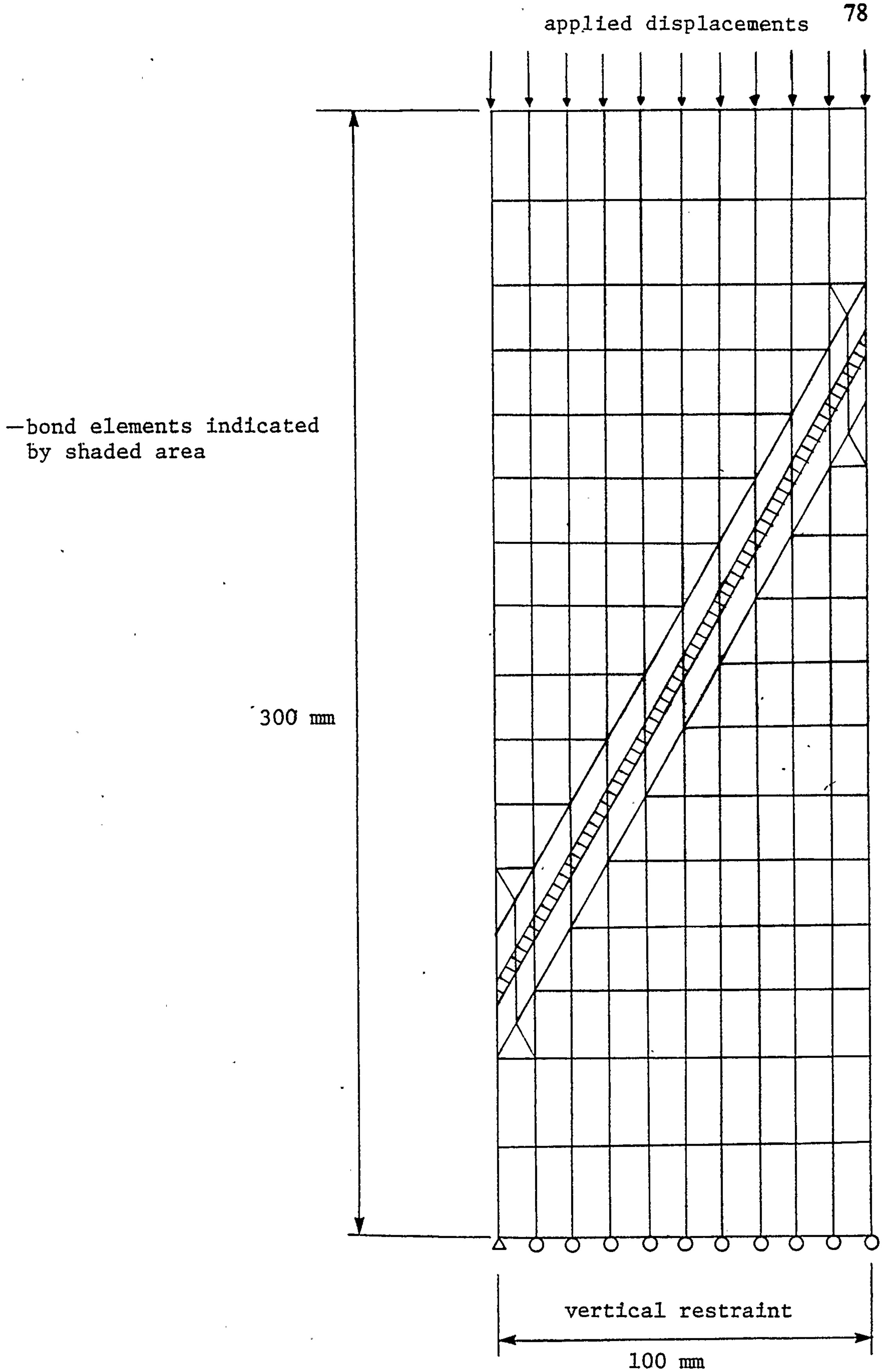


Figure 6.1 Mesh 1: Slant shear test with perfect bond

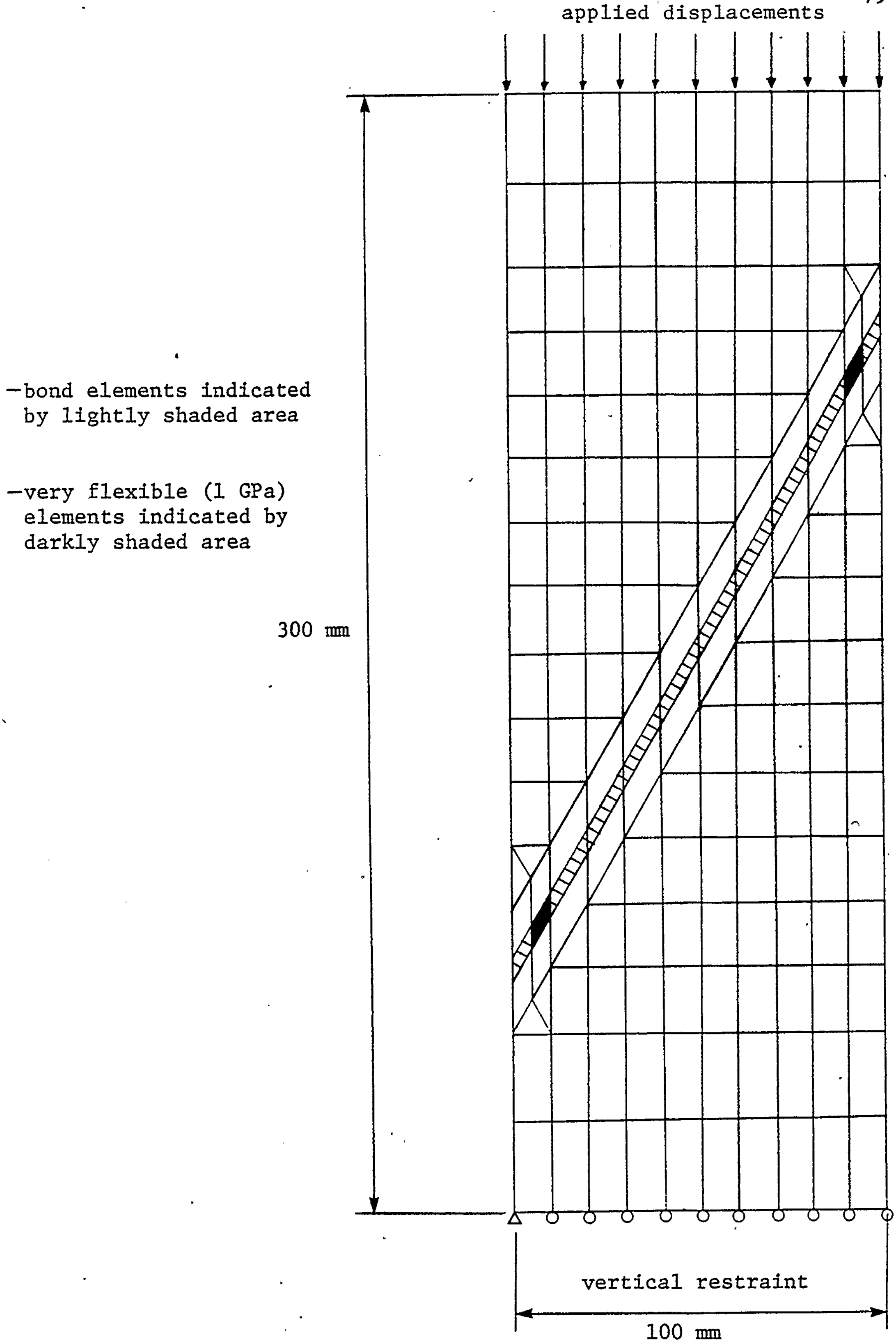


Figure 6.2 Mesh 2: Slant shear test with bond weakness near vertical edges

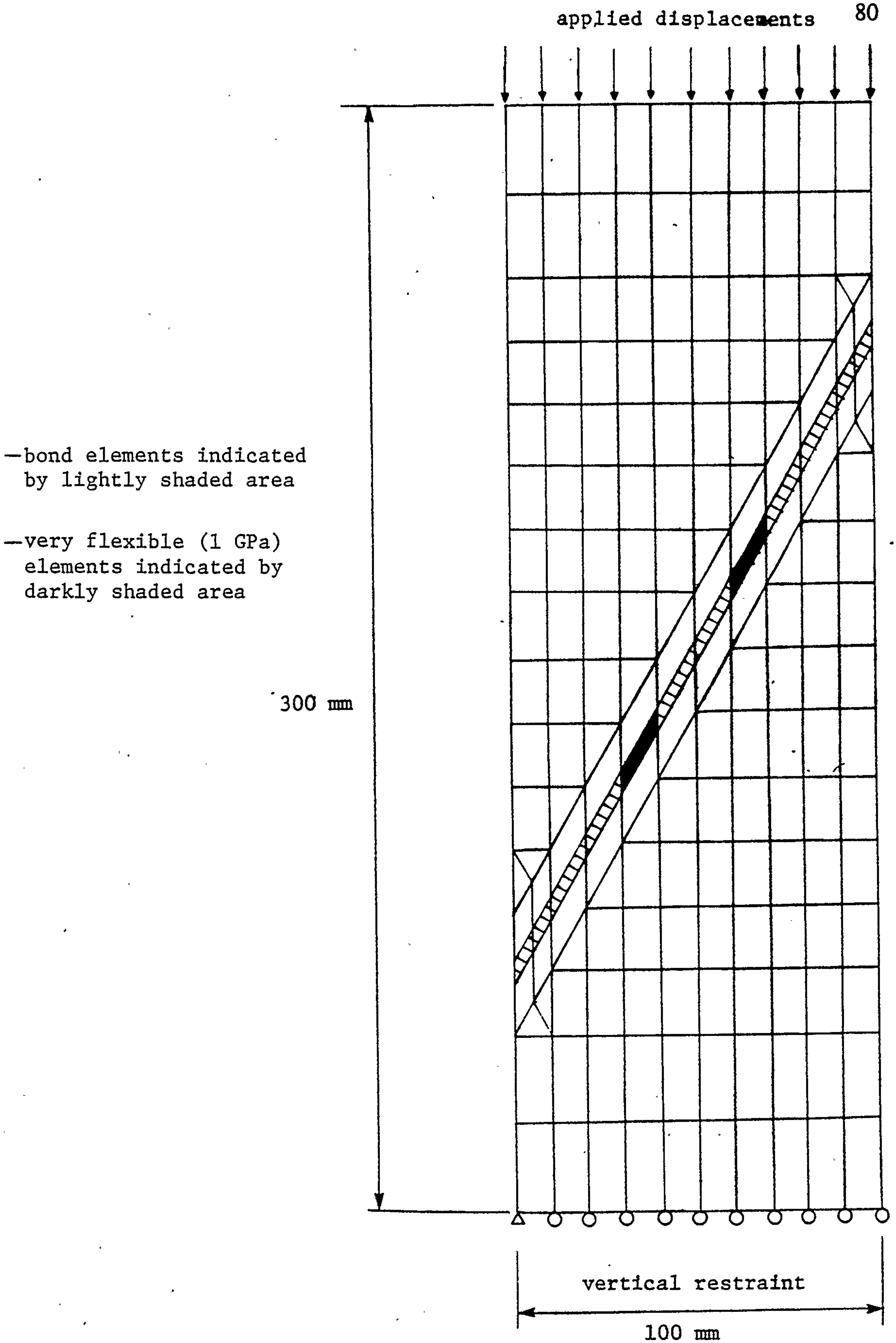


Figure 6.3 Mesh 3: Slant shear test with bond weakness near vertical center line

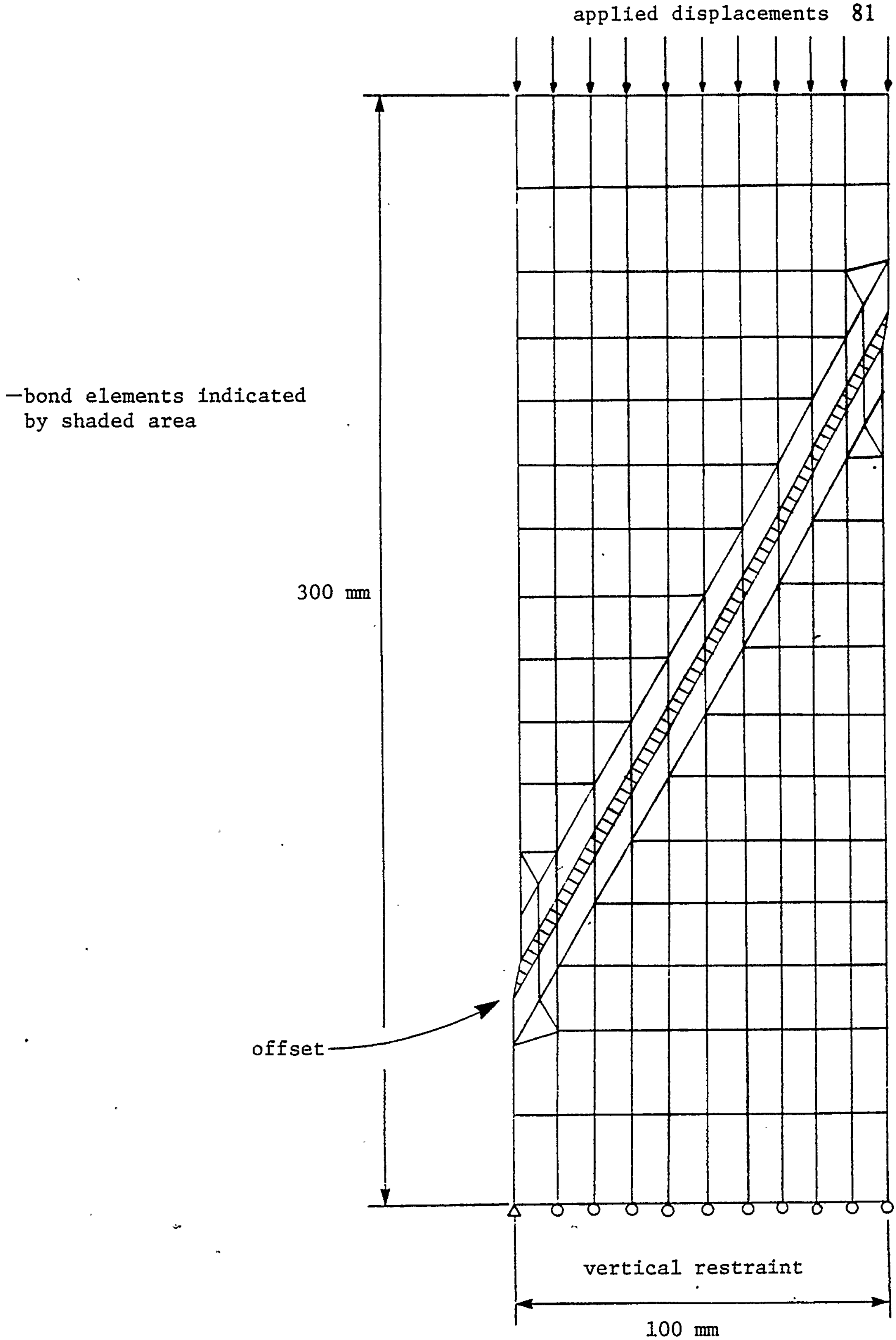


Figure 6.4 Mesh 4: Slant shear test with offset error

The prism model for each mesh was loaded using vertical applied displacements on each of the nodes along the top edge. The prism was laterally restrained at each node on the top and bottom edge, thus simulating the typical boundary conditions present during an actual test. Since the same applied displacement was used to test each combination of mesh and bond type, the total load in each combination varied with that combination's composite stiffness. To eliminate the effect of varying composite stiffnesses on the stresses observed, the stresses for each combination of mesh and bond were multiplied by a factor such that each combination had the same total load.

Wherever possible four-node hybrid quadrilateral elements were used since their performance is superior to isoparametric quadrilaterals and isoparametric triangles (Pian and Sumihara (1984)). Unfortunately, the geometry of the slant shear test was such that a few isoparametric triangular three-node (constant strain) elements were required.

The material properties were chosen so as to be approximately similar to the properties of the materials tested during the experiments. The modulus of elasticity of the concrete was determined using the Canadian Standards Association (CSA) equation:

$$E = 5000\sqrt{f_c'} \tag{6.1}$$

where

$$E = modulus \quad of \quad elasticity$$

$$f_c' = concrete \quad compressive \quad strength$$

and was found to be 33.5 GPa. Similar results were obtained when stress/strain curves measured during the experimental program were used to calculate the secant modulus of elasticity (50% of ultimate strength was used as the reference point).

The dynamic modulus of elasticity could be used instead of the smaller (static) modulus of elasticity previously discussed if the bonds were assumed to fail in a brittle manner. Since the bonds may fail in either a brittle or ductile mode, the static modulus of elasticity was used.

Two mortar moduli of elasticity were used, 10 GPa and 43.5 GPa, with the first value corresponding to a very flexible mortar and the second value corresponding to a very stiff mortar. To obtain a crude estimate of the range of mortar moduli of elasticity that are common, equation 6.1 was used in conjunction with mortar strengths found experimentally (see Table 7.6, Sec. 7.2.3). The 10 GPa value for modulus of elasticity was chosen to be below the lowest value found using equation 6.1 and the experimental data. This value, however, is well within the range of mortar moduli of elasticity used in practice (Shaw (1983)). The 43.5 GPa value for modulus of elasticity was selected since the moduli of elasticity of the strongest mortars calculated using equation 6.1 were of a similar value.

Poisson's ratio ranges between 0.15 and 0.25 for concrete (Neville (1981)). Poisson's ratio was chosen as 0.2 for both concrete and mortar. In some cases the

Poisson's ratio of the mortar will differ from the Poisson's ratio of the concrete, however, this was beyond the scope of this investigation.

6.3. Errors

The most obvious error is the implicit assumption that the concrete and mortar are materials with a linear stress/strain relationship. In addition the bond interfaces are assumed to be completely planar although a small amount of surface roughness obviously exists. If the above limitations are recognized, however, the finite element analysis is still capable of providing useful information.

In order to check for mathematical error in the meshes and to check for program malfunctions, each set of computer results was checked for symmetry. For example, the top left hand side of the prism must always have the same stresses and reactions as the bottom right hand side.

6.4. Results

To gauge the effect of various parameters on stress at the bond, principal stresses in and adjacent to the bond line were plotted (cross-sections A and B, see Fig. 6.5). All compressive and tensile stresses are plotted as a percentage of the gross compressive stress. The gross compressive stress is defined as the total compressive load divided by the area of the horizontal cross section of the prism.

For the 10 GPa bonds, the principal compressive stress in the bond, in some cases, never exceeded 70% of the gross compressive stress (i.e. Fig. 6.6a). Vertical equilibrium appears to be violated but this is not the case. Equilibrium is

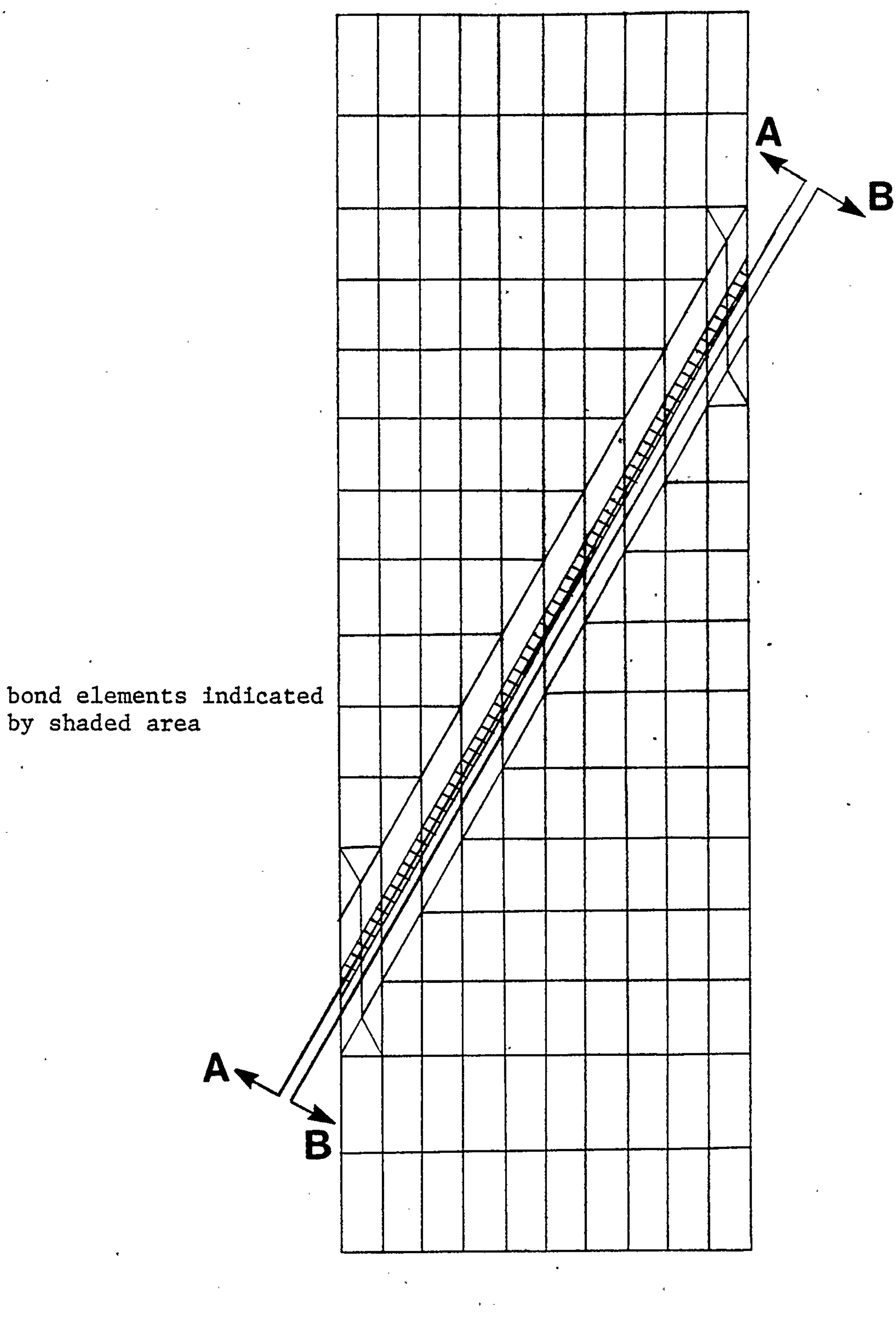


Figure 6.5 Location of cross-sections where stresses were examined

maintained by a shearing force acting on the bond plane (the bond plane has twice the area as the prism cross-section used to calculate the gross compressive stress from the applied load or displacement). The following example, based on the 3 mm, 10 GPa bond stress data at section A, confirms the above argument.

The gross compressive stress was 34 MPa and the maximum and minimum principle stresses in the bond averaged 23.8 MPa (compression) and 5.5 MPa (tension) respectively. The former stress is at 104^o to the horizontal. Therefore, the stress normal to the bond plane and shear stress along the bond were 8.7 MPa (compression) and 14.6 MPa respectively. Fig. 6.6 shows the total force transferred through the bond layer is equal to the gross compressive stress multiplied by the prism cross-section. Therefore, vertical equilibrium is satisfied.

The stress distribution across the bond line is extremely uniform. For example the maximum principal stress at the bond for a 43.5 GPa, 3 mm thick bond varies by less than 6% if the bond is assumed to be perfect. This lack of large variation in stresses exists for all the bonds investigated using the model of the slant shear test with a flawless bond (mesh 1).

A bond layer which is less stiff than the adjacent concrete will try to expand laterally when compressed by a normal load, but will be restained by the concrete. As a result, small lateral compressive and tensile stresses will develop in the bond material and the concrete respectively. There will also be shear at the bond interface. The shear will be of greatest magnitude a few millimeters from the vertical sides of the prism. The shear induced by this mechanism on one side of the

$$\sum F_y\!:\!F_y = \sigma_y' \cos 60^o\ (A/cos60^o)$$
$$+\ \tau_{x'y'}' \sin 60^o (A/cos60^o)$$
$$= \sigma_y' A + \tau_{x'y'}' \sqrt{3}\, A$$
$$(8.7\ MPa)A + (14.6\ MPa\ \sqrt{3})A$$
$$= (34\ MPa)A$$
$$= gross\ \ compressive\ \ load$$

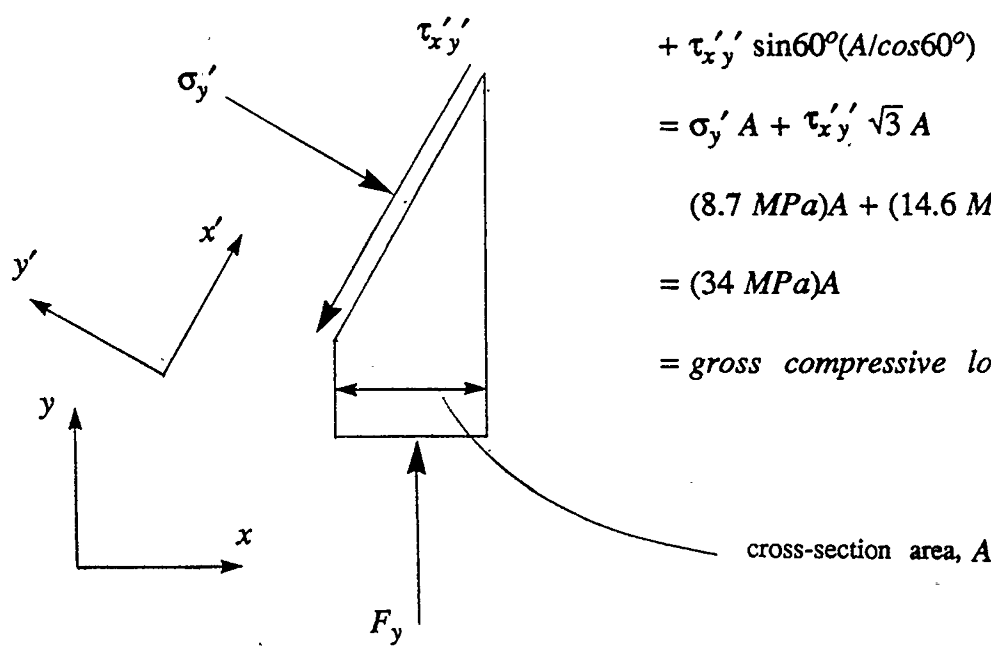


Figure 6.6 Stresses on bond plane

vertical center line of the prism will have the opposite magnitude to shear on the other side of the center line.

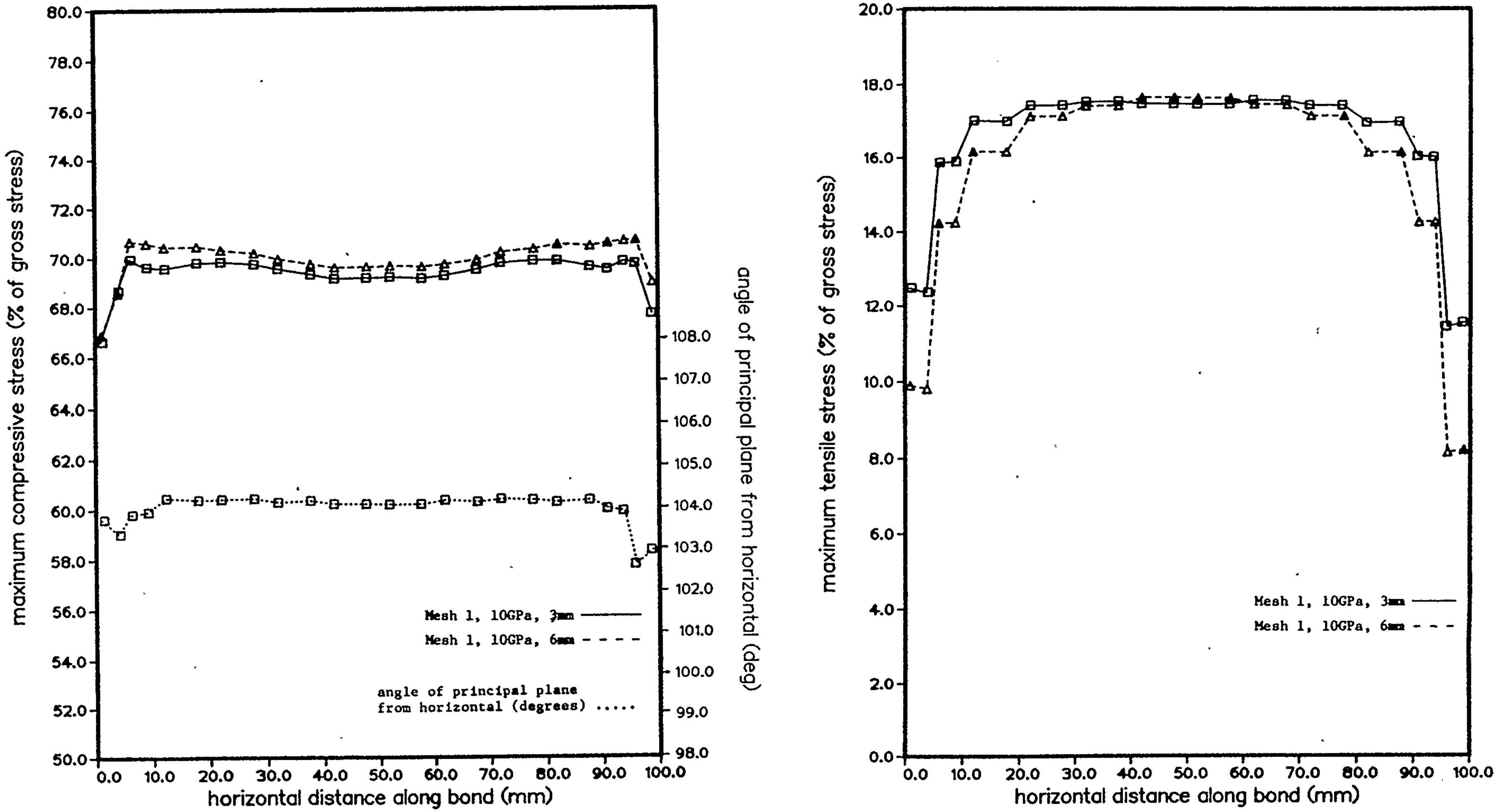
When a bond layer is stiffer than the adjacent concrete, the bond will try to expand laterally when compressed to a lesser extent than the concrete. Therefore, tensile and compressive stresses will exist in the bond material and the concrete respectively. Again, shear will exist at the bond interface.

The shear caused by the difference in lateral deformation of the bond material and the concrete results in high (or low) principal stresses in the bond and the adjacent concrete near the edges of the prisms. These stresses are particularly noticeable in plots of stresses at and adjacent to the 10 GPa 3 mm bond line. This concept is logical since the difference between the modulus of elasticity of the 10 GPa bond and the concrete is greater than the difference between the modulus of elasticity of the 43.5 GPa bond and the concrete.

6.4.1. Effect of Bond Thickness on Stress

The influence of thickness on stress in the bond in linear elastic materials can be seen in Figs. 6.7 and 6.8. The maximum tensile and compressive stress in the bond appear to drop insignificantly with increased bond thickness, contrary to the experimental results and other research which indicate that thick bonds are weaker than thin bonds (Sise (1984)).

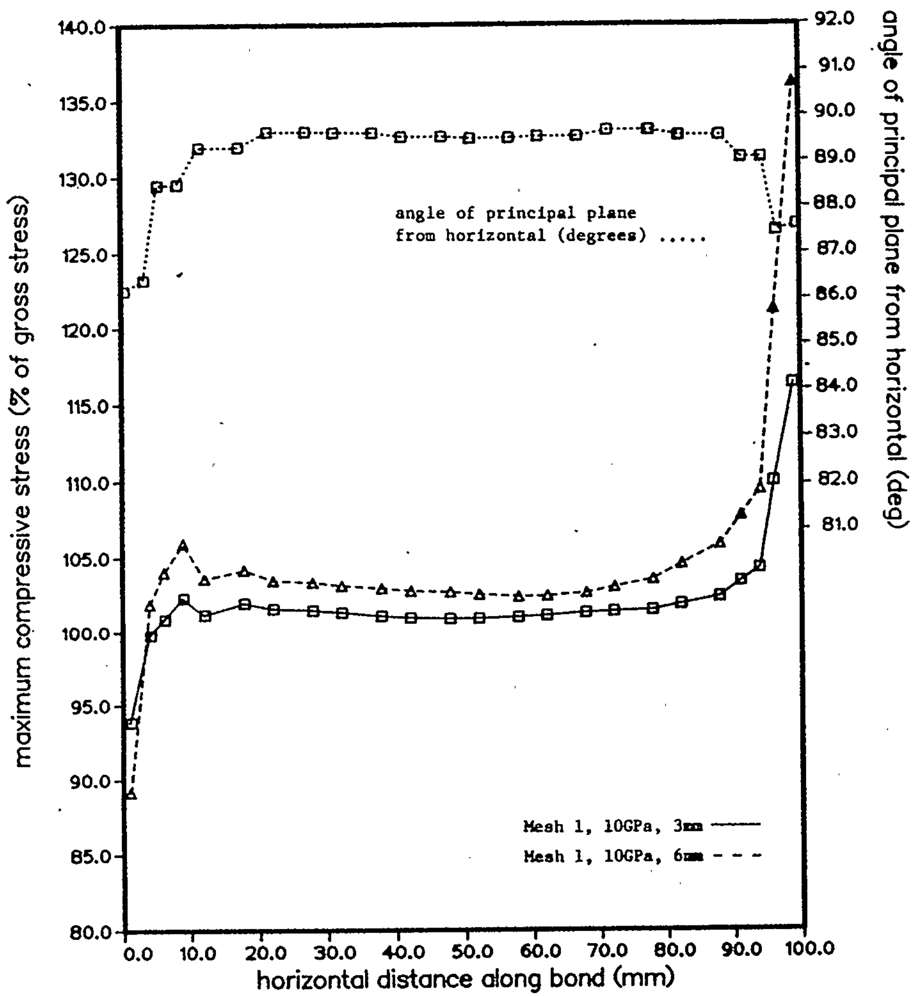
The tensile stresses in the concrete adjacent to the bond line (cross-section B, Fig. 6.5) were slightly lower with the 6mm thick, 10 GPa bond compared to the 3 mm thick, 10 GPa bond (Fig. 6.6). However, the compressive stresses near the 6mm thick, 10 GPa bond were as much as 17% greater than the compressive stresses near the 3 mm thick, 10 GPa bond. The stress level adjacent to the 43.5 GPa bond did not vary significantly with bond thickness except that the tensile stress was higher with the 6 mm bond (Fig. 6.8). Evidence of high stresses adjacent to the bond was also observed during the tests in the form of vertically orientated cracks. These cracks changed direction a few millimeters away from the bond, to run parallel to the bond and are shown in Fig. 5.1.



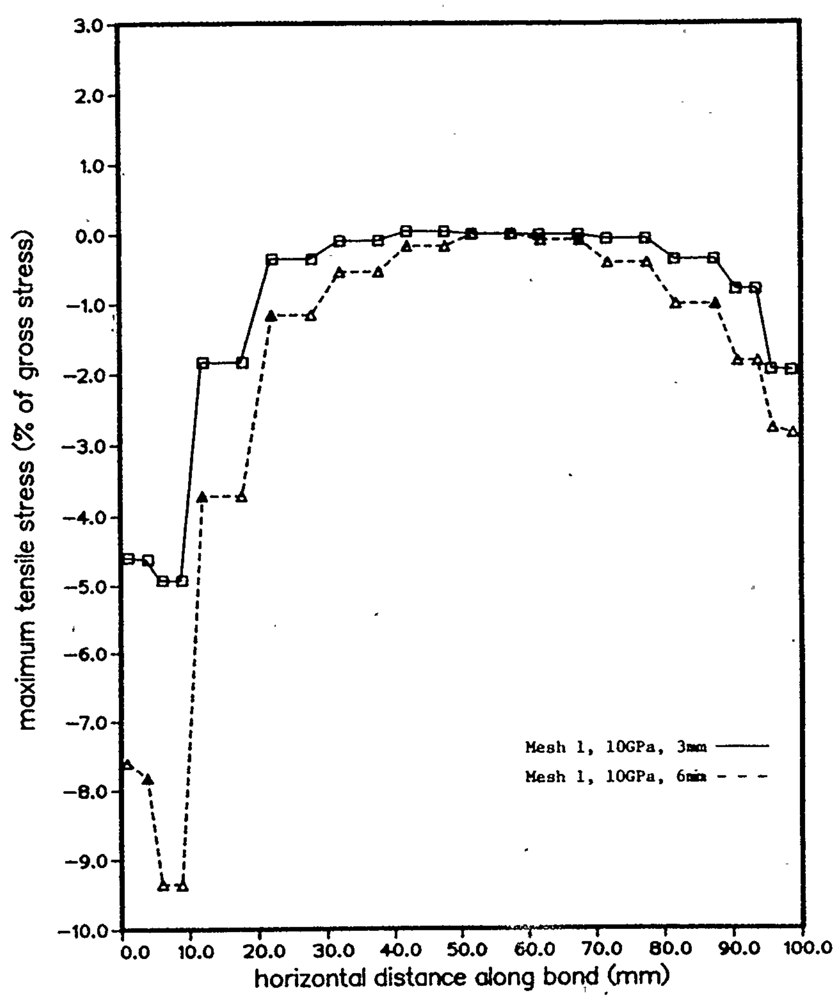
(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

Figure 6.7a,b Effect of bond thickness on stress in and adjacent to a 10 GPa bond.

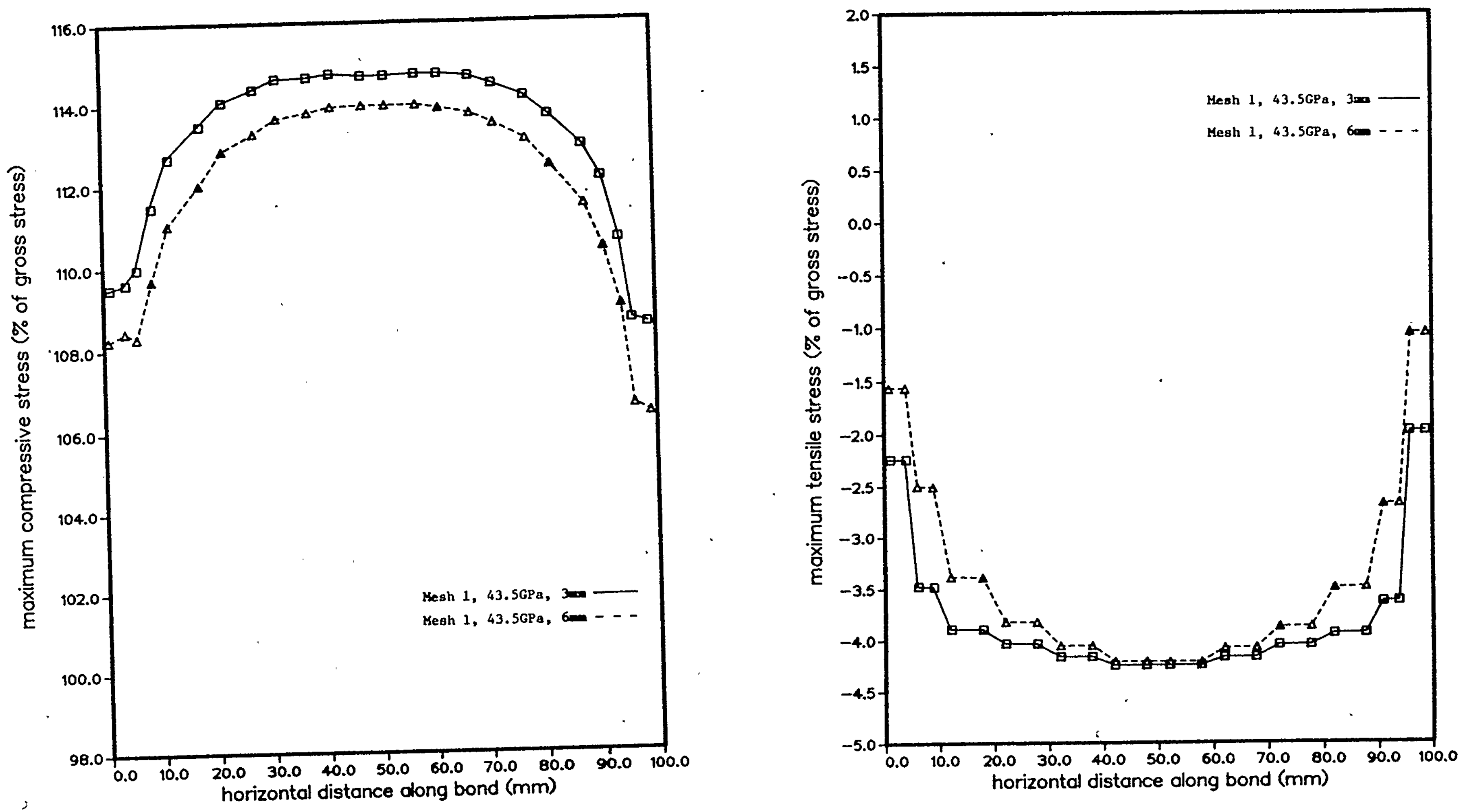


(c) principal compressive stress adjacent to the bond



(d) principal tensile stress adjacent to the bond

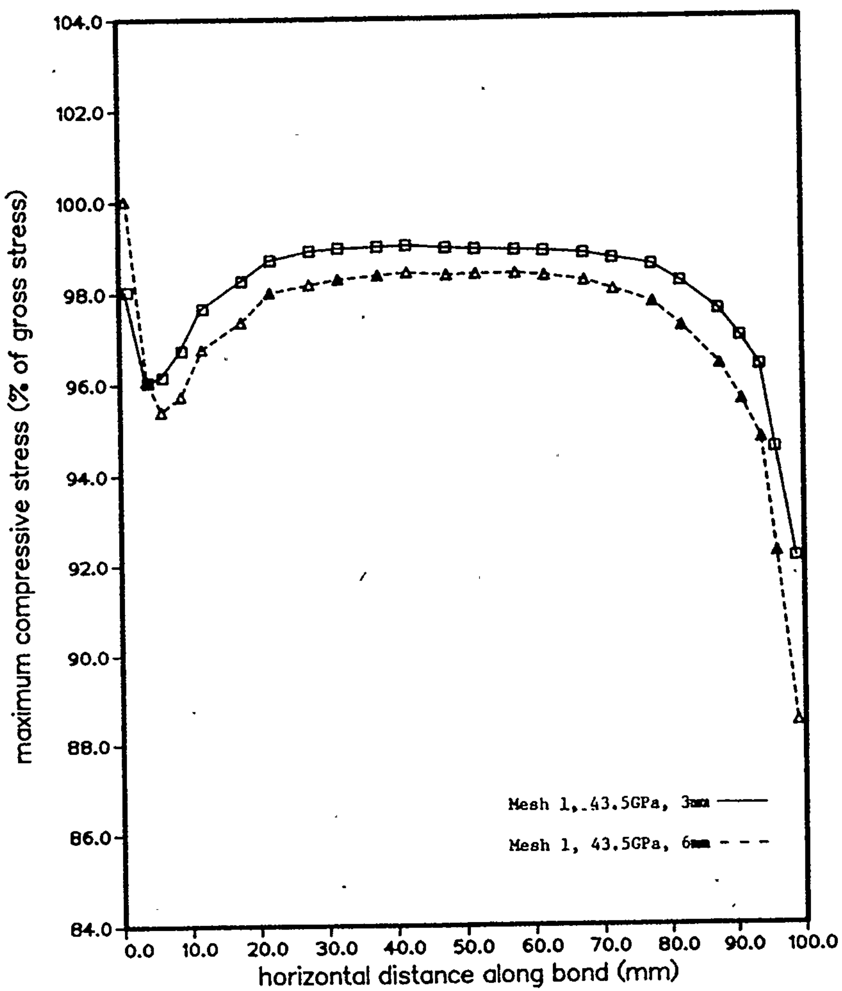
Figure 6.7c,d Effect of bond thickness on stress in and adjacent to a 10 GPa bond.



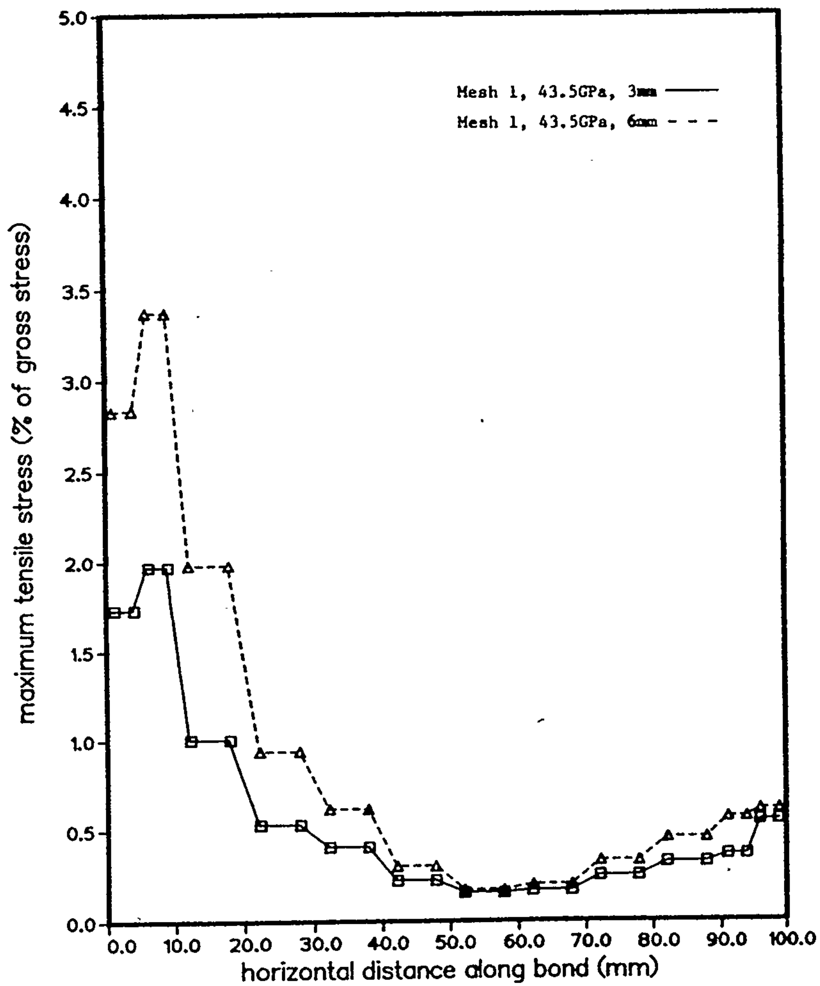
(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

Figure 6.8a,b Effect of bond thickness on stress in and adjacent to a 43.5 GPa bond.



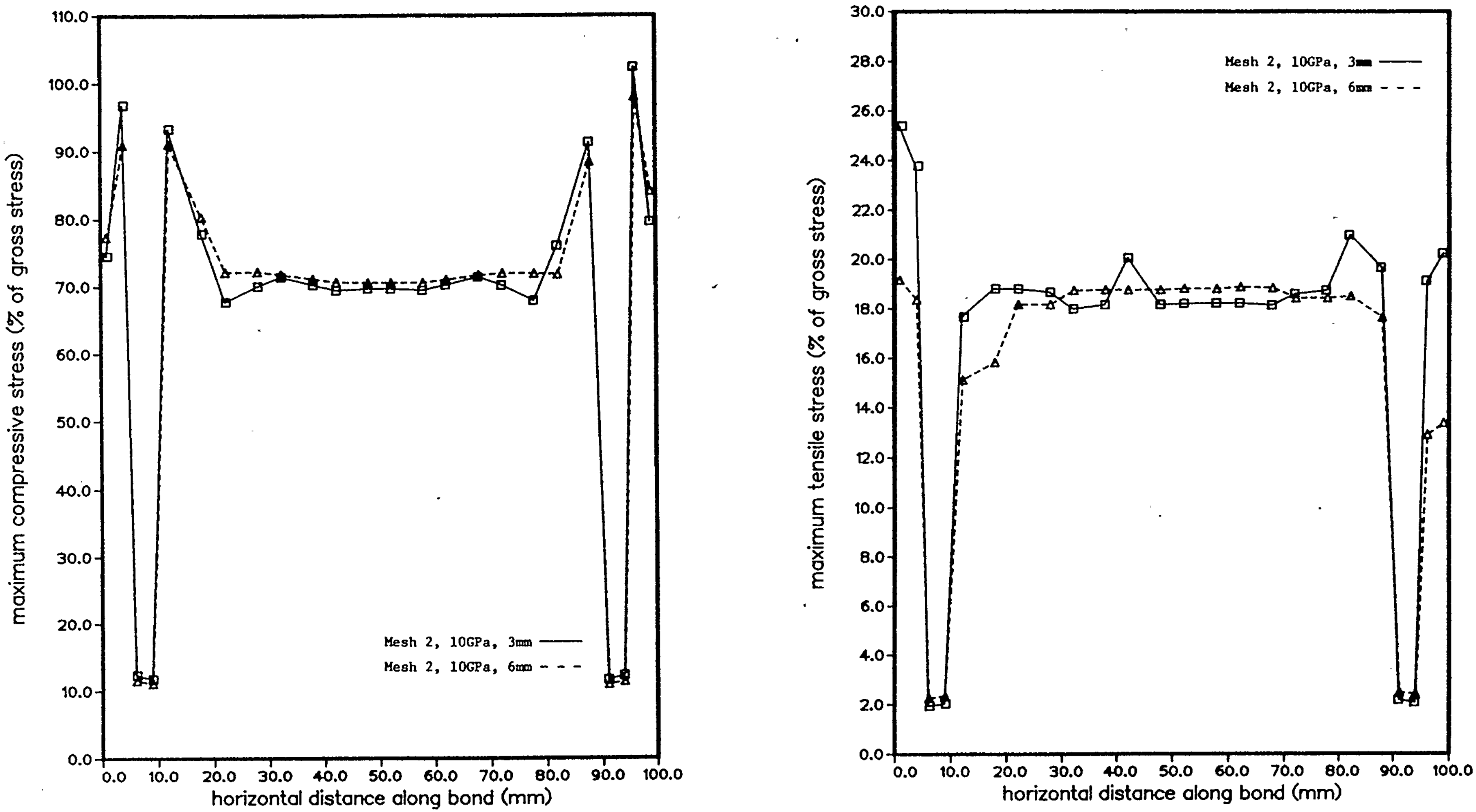
(c) principal compressive stress adjacent to the bond



(d) principal tensile stress adjacent to the bond

Figure 6.8c,d Effect of bond thickness on stress in and adjacent to a 43.5 GPa bond.

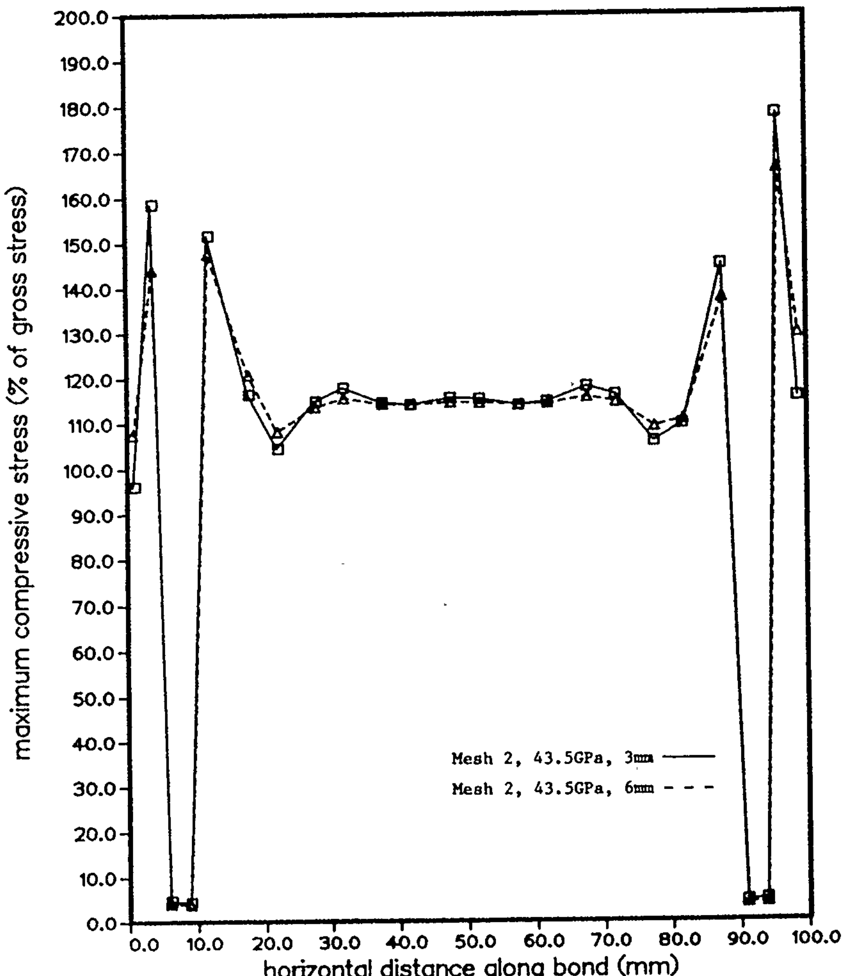
Finite element mesh 2, which contained a bond material which had weaknesses near both edges of the prism, was also used to investigate the effect on stress levels caused by different bond thicknesses (Figs. 6.9-6.10). Again the detrimental effect of increased bond thickness on stress inside the bond was not evident. However, the effect of bond thickness on the compressive stress near the bond, induced by the zones of bond weakness, was very noticeable. In mesh 2, the maximum compressive stress next to a 6 mm thick, 10 GPa bond was more than 60% greater than the 3 mm thick, 10 GPa bond modelled by the normal mesh (mesh 1) (see Fig. 6.11). When mesh 2 was used, the maximum compressive stress in the 3 mm thick, 10 GPa bond was only 32% greater than the maximum compressive stress adjacent to the same bond simulated by mesh 1 (Fig. 6.12). Similarly, the maximum compressive stress next to the 6 mm thick, 43.5 GPa bond modelled by mesh 2 was 27% greater than the corresponding stress next to the 3 mm thick, 43.5 GPa bond represented by mesh 1 (Fig. 6.13). In contrast, the maximum compressive stress next to the 3 mm thick, 43.5 GPa bond, when mesh 2 was used, was only 21% greater than the maximum compressive stress adjacent to the same bond simulated by mesh 1 (Fig. 6.14). The maximum tensile stress near the 6 mm thick bonds modelled by mesh 2 was approximately 7% of the gross compressive stress. This stress was approximately twice as large as the maximum tensile stress adjacent to the 3 mm thick bonds modelled by mesh 2.



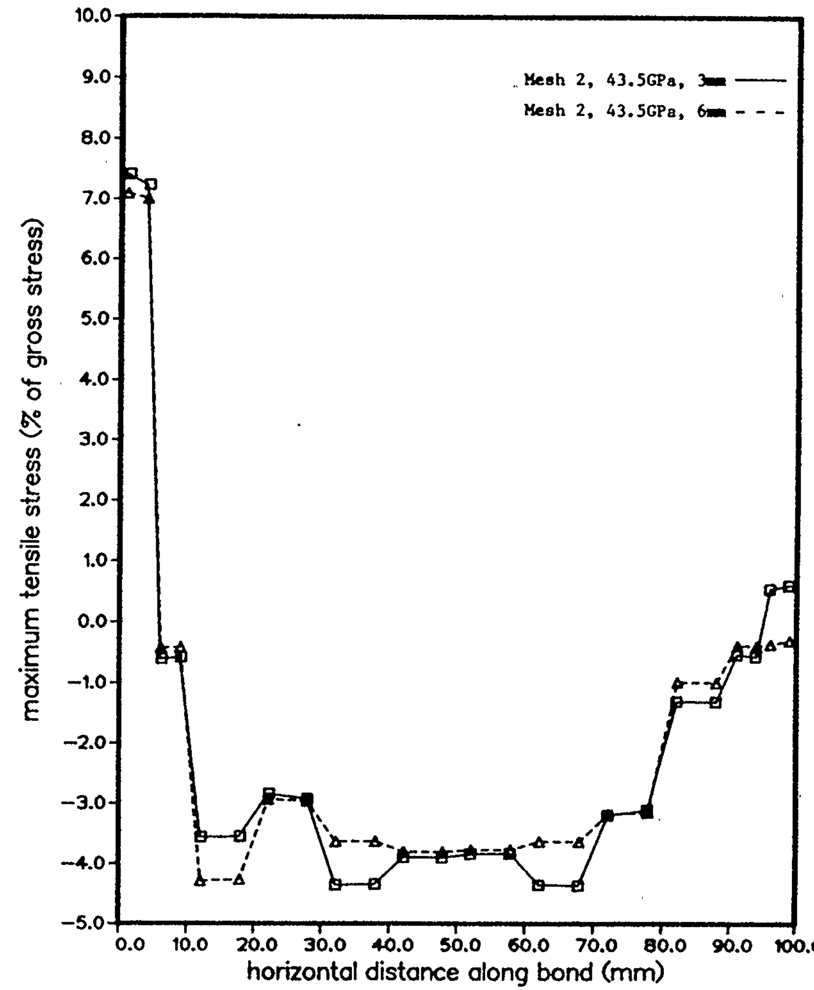
(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

Figure 6.9 Effect of bond thickness on stress in a 10 GPa bond with weakness near edges.



(a) principal compressive stress in the bond



(b) principal tensile stress in the bond

Figure 6.10 Effect of bond thickness on stress in 43.5 GPa bond with weakness near edges.

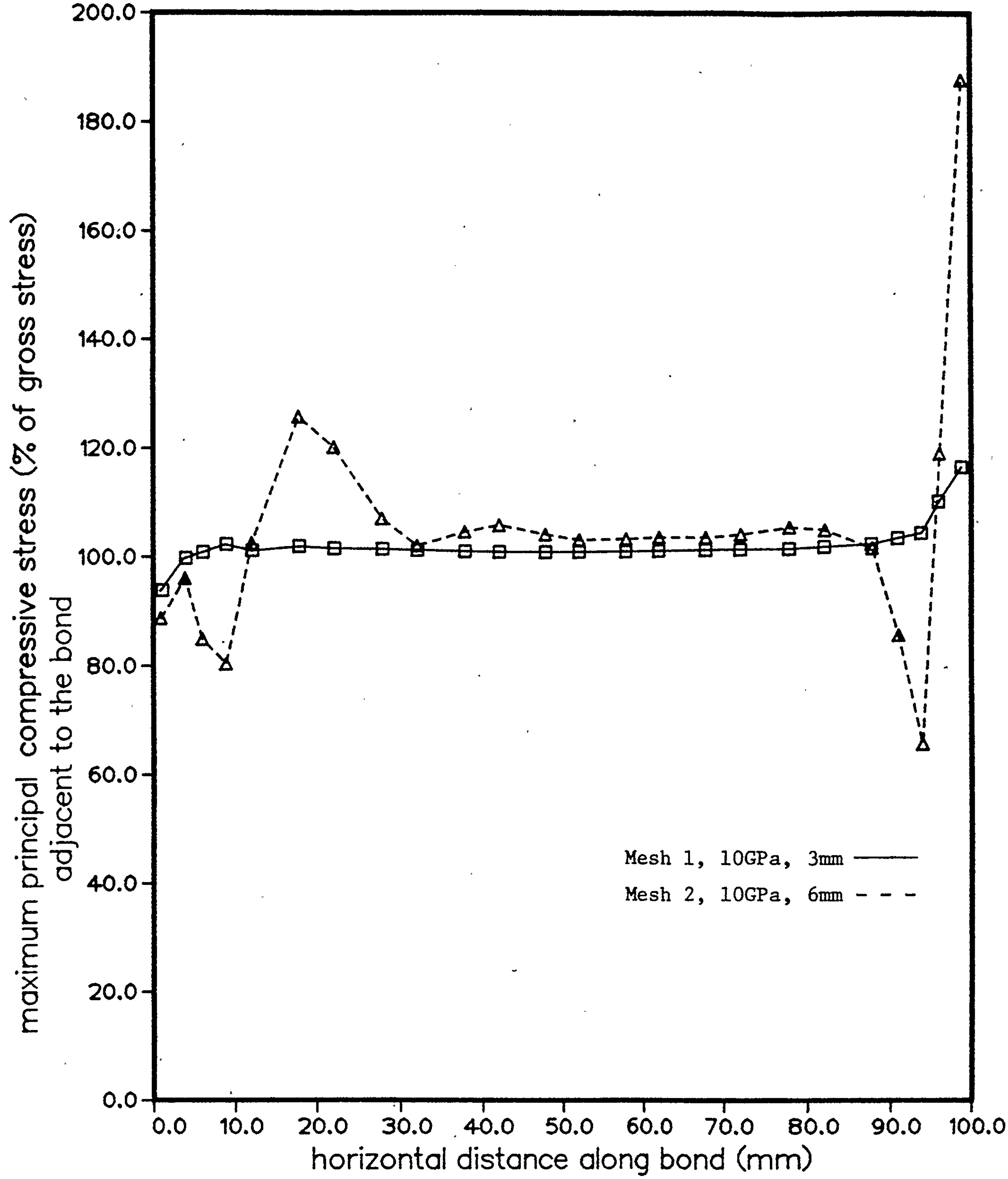


Figure 6.11 Comparison between a 10 GPa 6 mm bond with a weakness near edges and a perfect 10 GPa 3 mm bond.

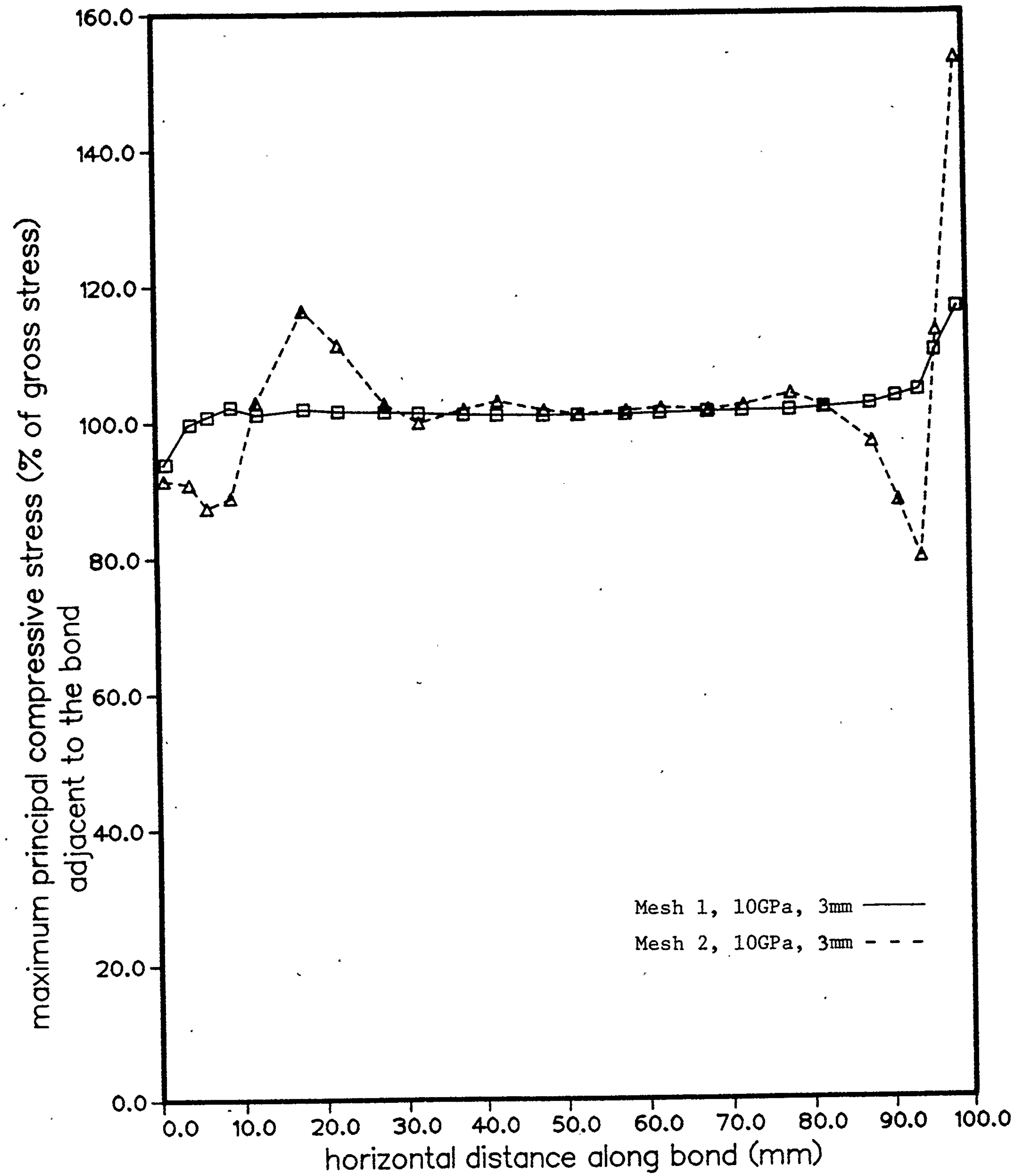


Figure 6.12 Comparison between a 10 GPa 3 mm bond with weakness near edges and a perfect 10 GPa 3 mm bond.

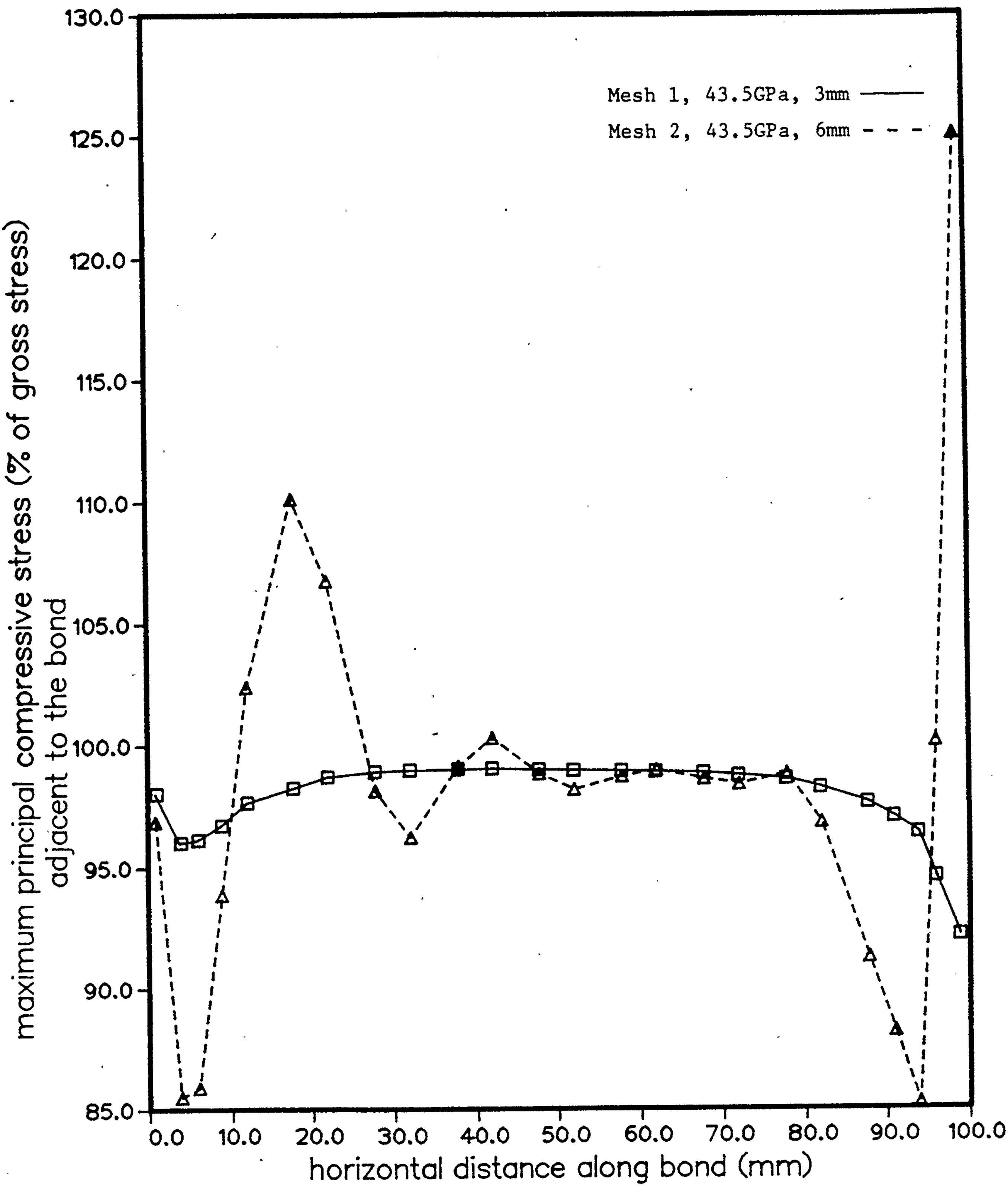


Figure 6.13 Comparison between a 43.5 GPa 6 mm bond with weakness near edges and a perfect 43.5 GPa 3 mm bond.

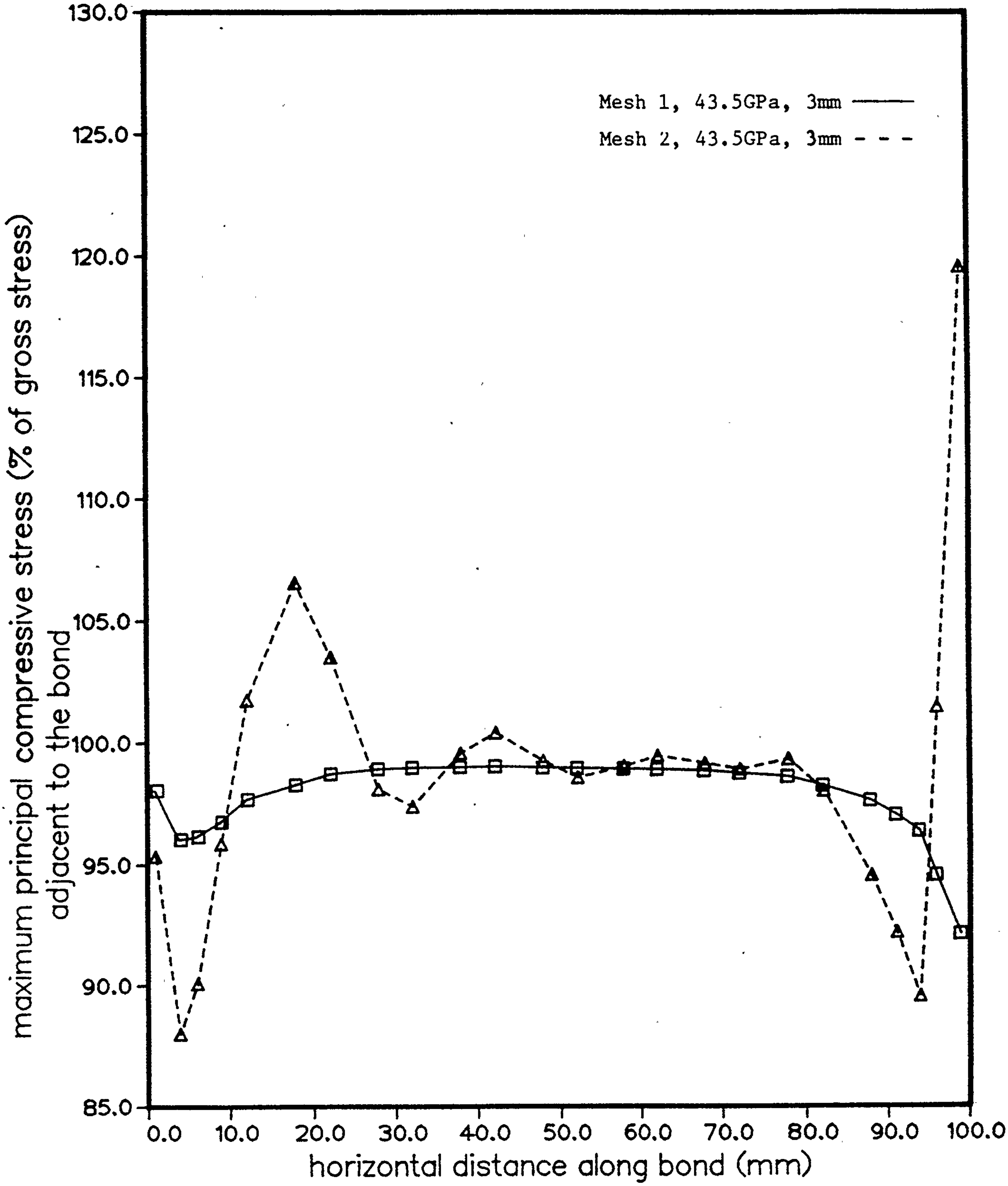


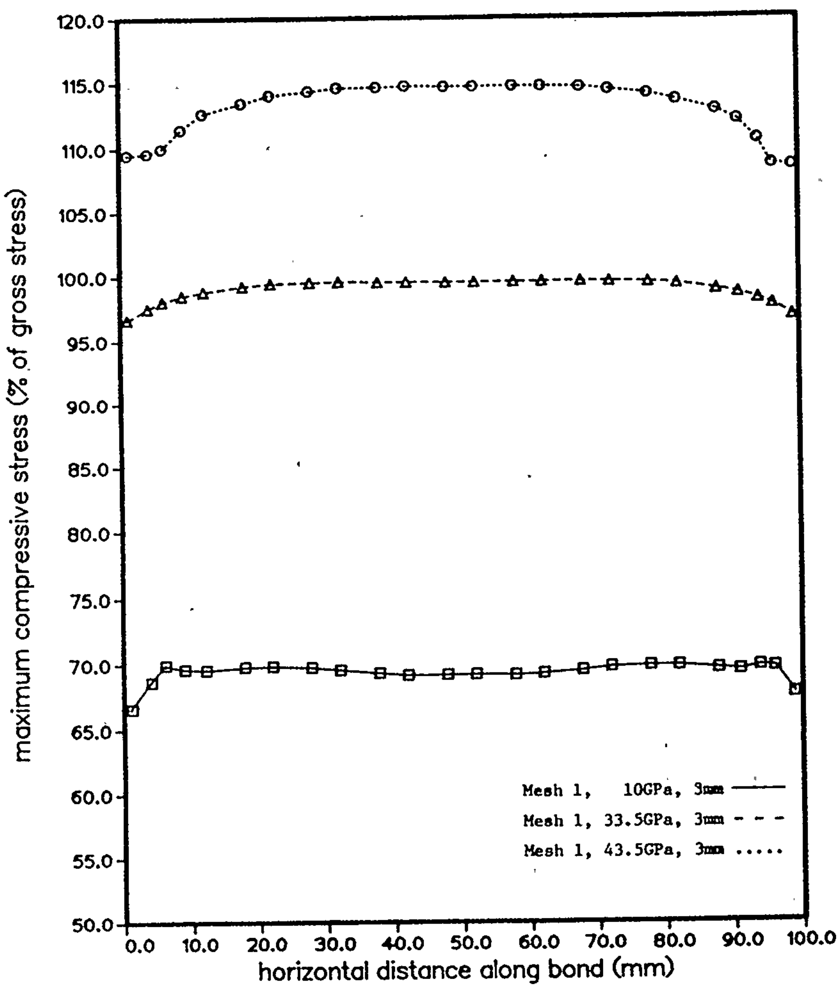
Figure 6.14 Comparison between a 43.5 GPa 3 mm bond with weakness near edges and a perfect 43.5 GPa 3 mm bond.

6.4.2. Effect of Bond Material Modulus of Elasticity on Stress

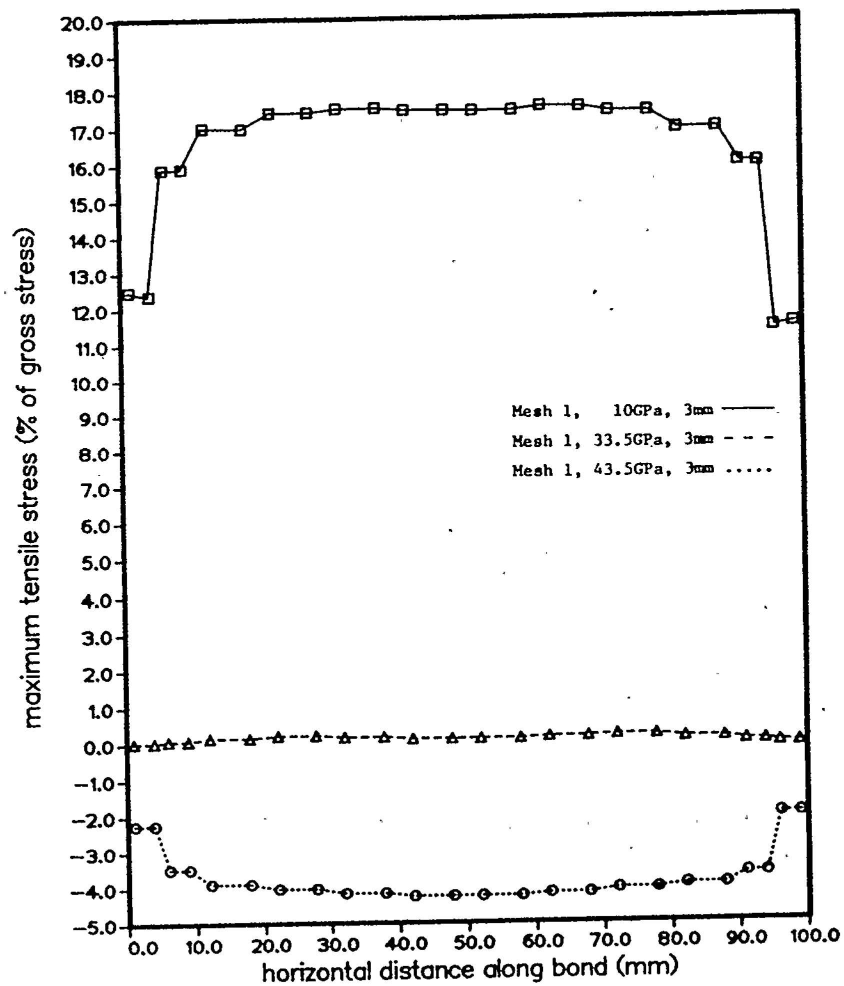
The effect of different bond material moduli of elasticity on bond stress levels was significant. The stress in the model of a normal prism containing 3 mm thick bonds of different stiffnesses is shown in Fig. 6.15. The maximum compressive stress of a normal prism (mesh 1) for the 10 GPa bond material was 70% of the gross compressive stress, for the 33.5 GPa bond material was 100% of the gross compressive stress, and for the 43.5 GPa bond material was 114% of the gross compressive stress. The maximum tensile stress, however, was highest in the 10 GPa bond material (18% of the gross compressive stress). The 33.5 GPa bond (a monolithic prism) and the 43.5 GPa bond had no tensile stress at the bond.

The maximum compressive stress adjacent to the bond varies inversely with bond stiffness for the 3 mm bonds. The maximum compressive stress was 116% of the gross compressive stress for the 10 GPa bond, and 99% of the gross compressive stress for the 43.5 GPa bond (Fig. 6.16). The maximum tensile stress, although small, is highest near the stiff bond (2% of the gross compressive stress).

The same relationship between stresses and bond material stiffness occurred when meshes 2-4, which simulated flaws in the bond or test prism, were used. Maximum tensile stresses occurred in the 10 GPa bond models while maximum compressive stresses occurred in the 43.5 GPa bond models (Figs. 6.17-6.19). Both the compressive stresses and the tensile stresses near the bond were larger for the soft bond material (10 GPa) compared with the stiff bond (43.5 GPa) (Figs. 6.20-6.22).

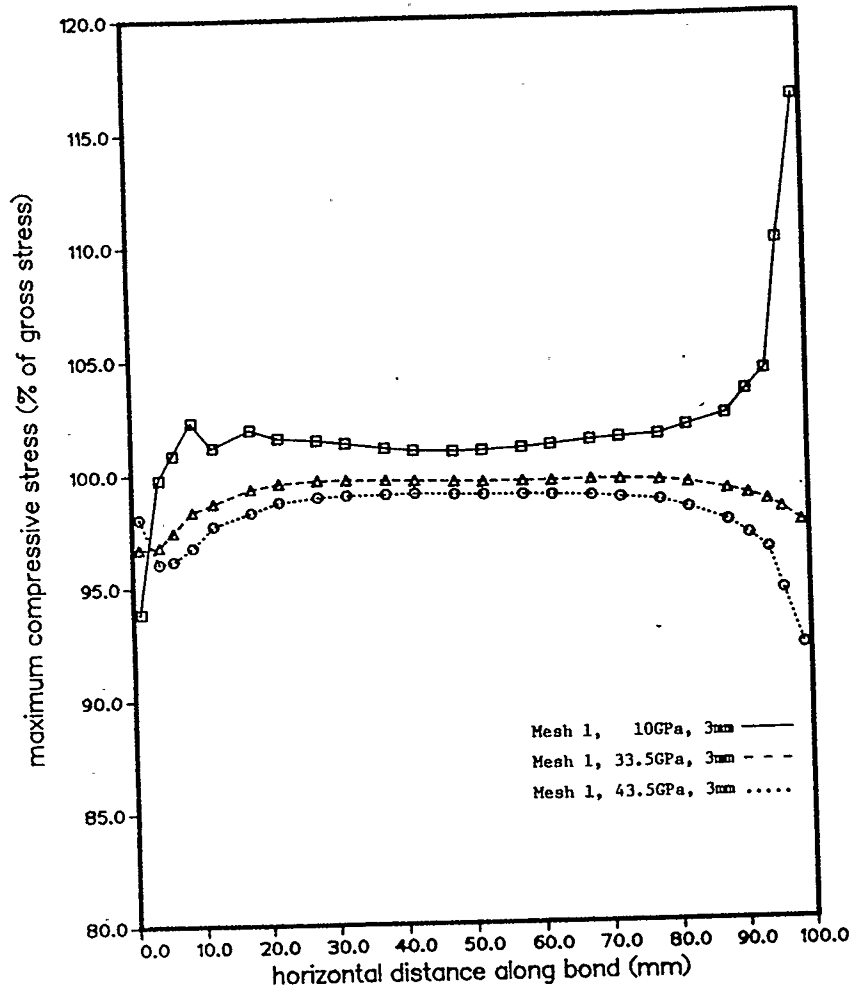


(a) principal compressive stress in the bond

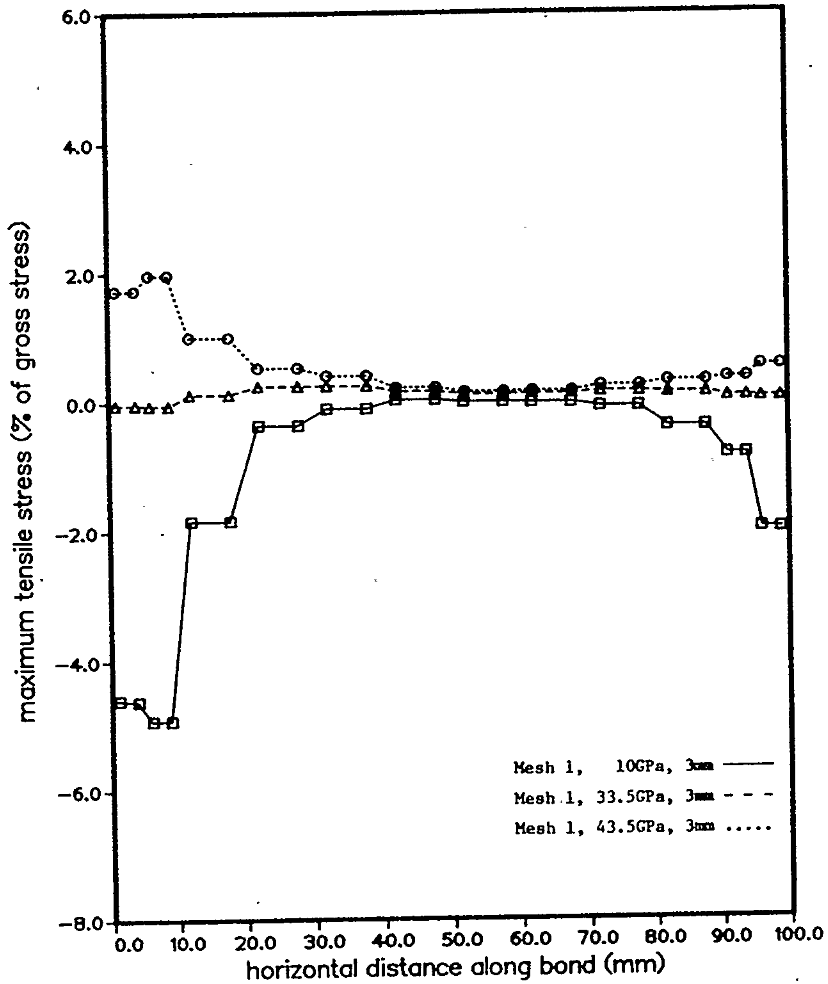


(b) principal tensile stress in the bond

Figure 6.15 Effect of bond modulus of elasticity on stress in a 3 mm bond.

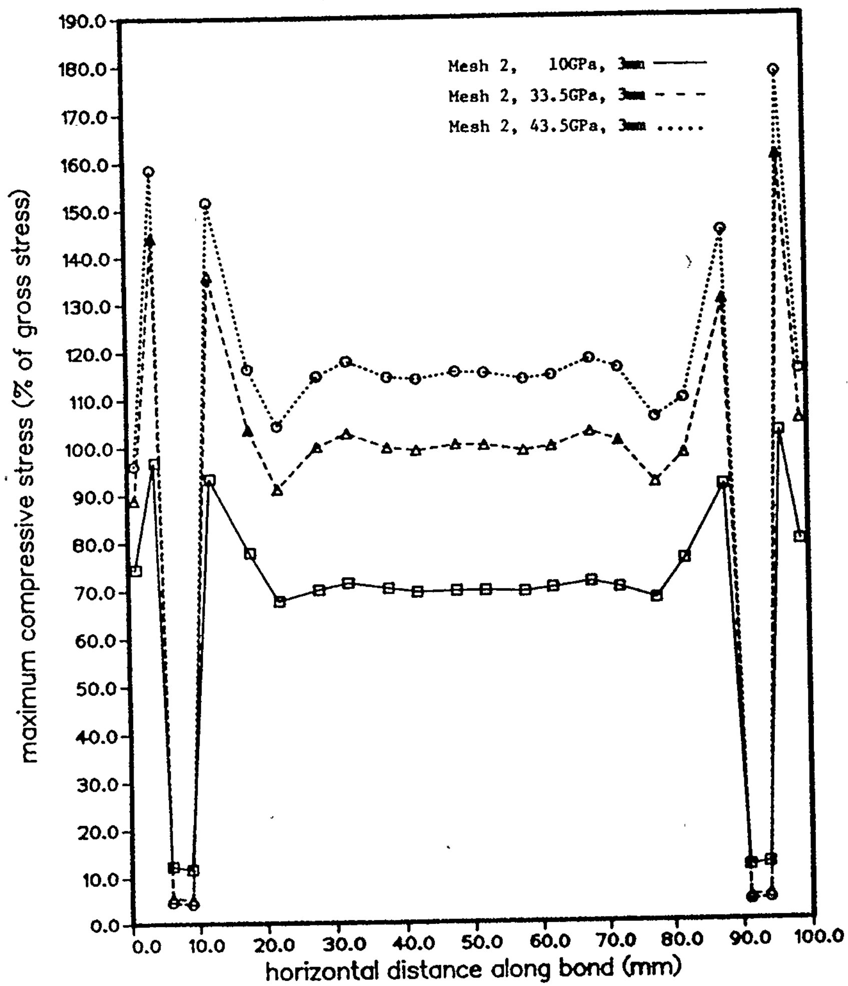


(a) principal compressive stress adjacent to the bond

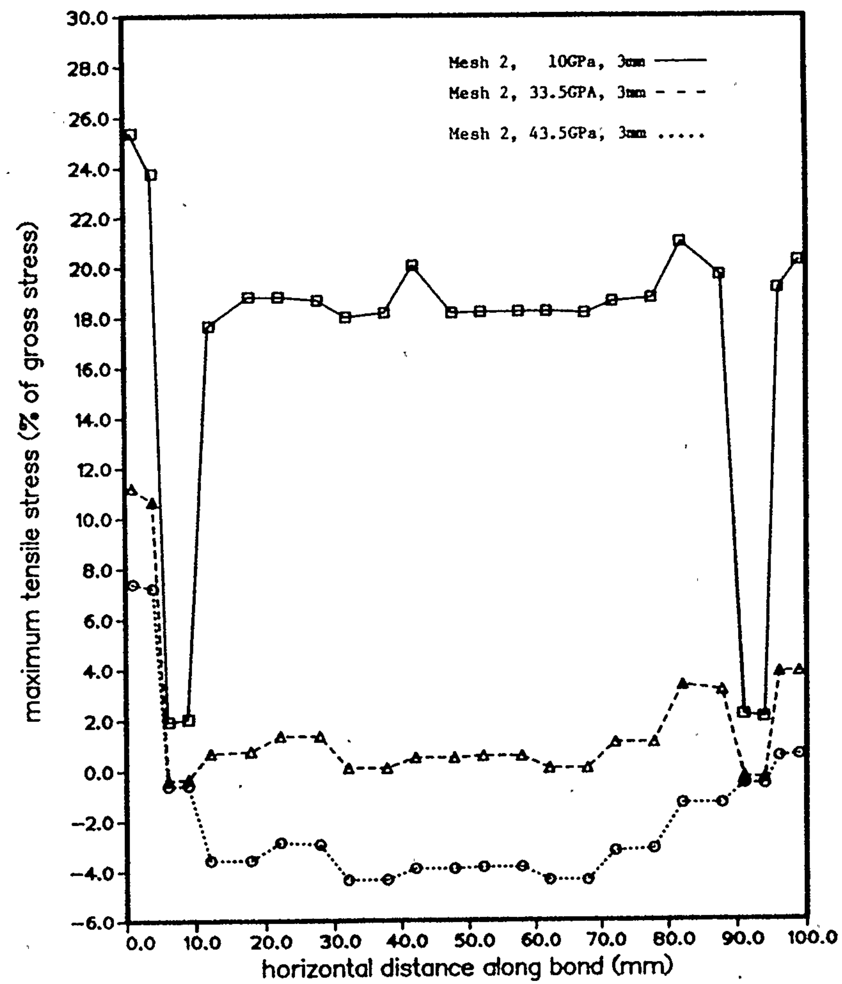


(b) principal tensile stress adjacent to the bond

Figure 6.16 Effect of bond modulus of elasticity on stress in concrete adjacent to a 3 mm bond.

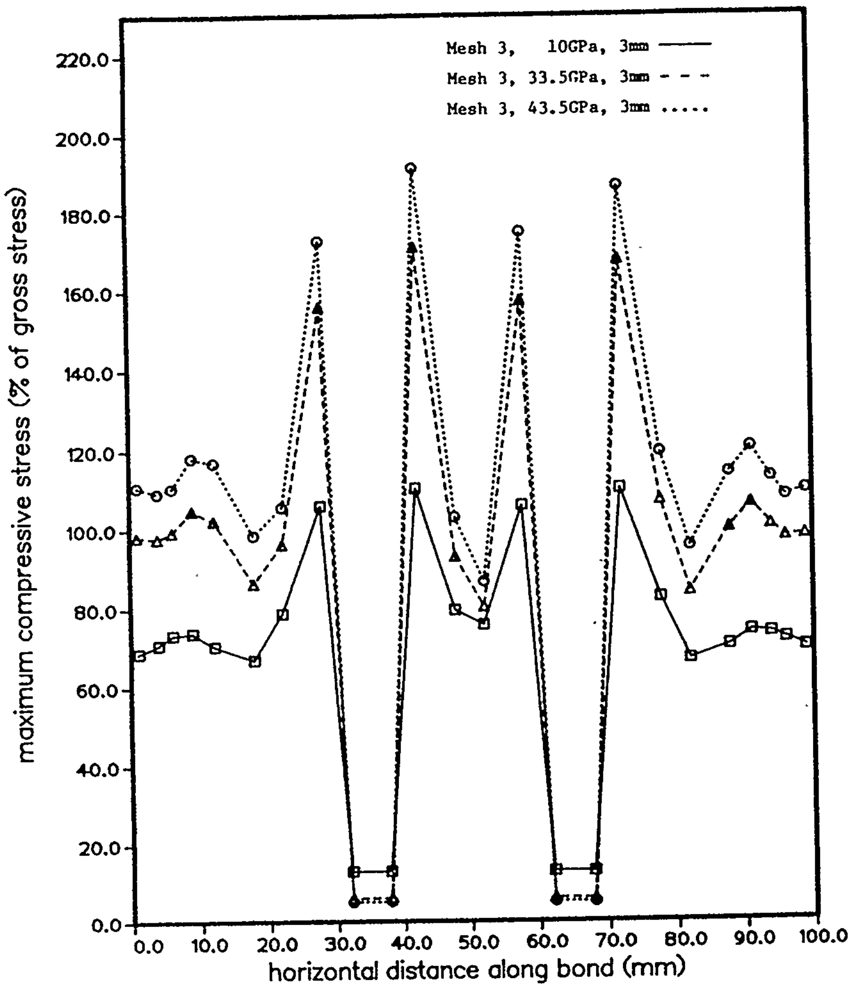


(a) principal compressive stress in the bond

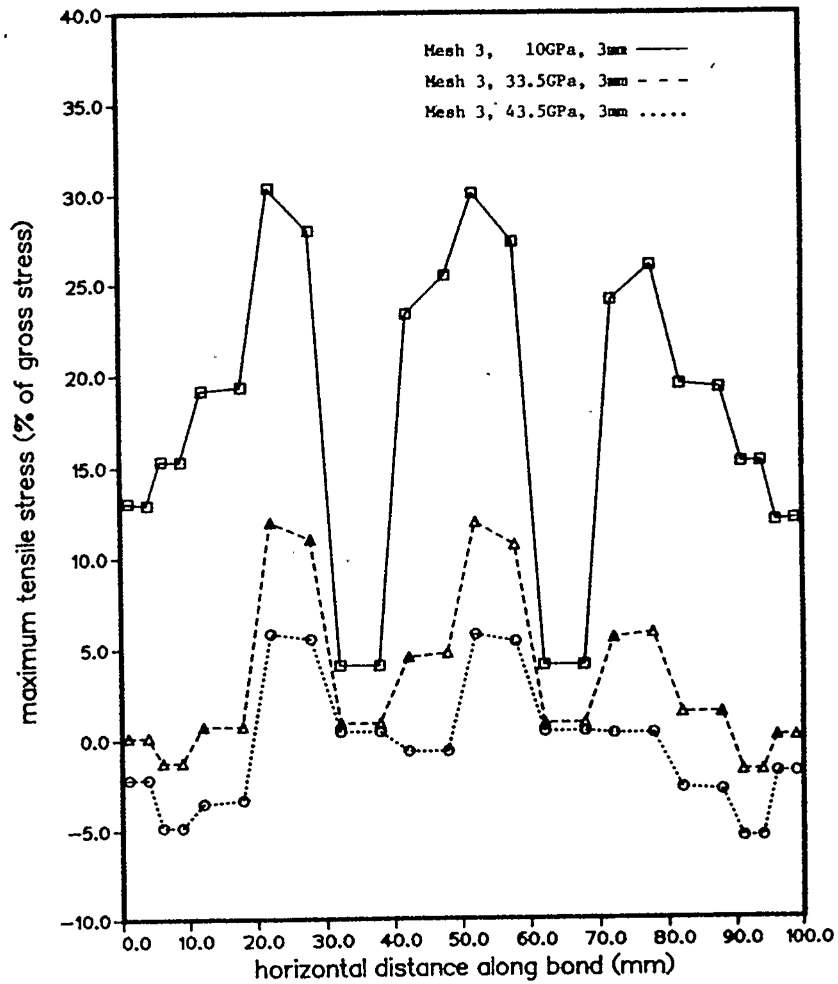


(b) principal tensile stress in the bond

Figure 6.17 Effect of bond modulus of elasticity on stress in a 3 mm bond with weakness near edges.

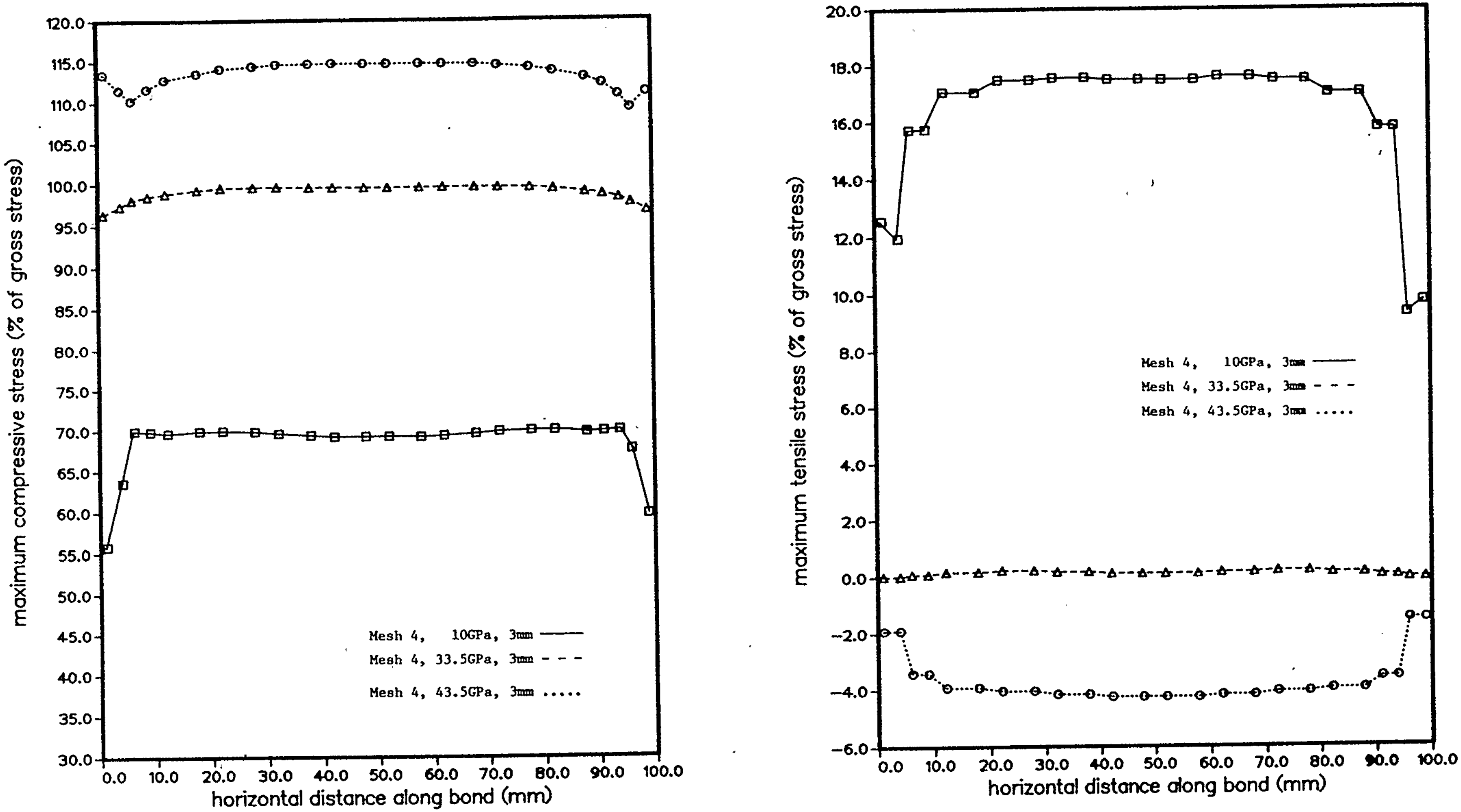


(a) principal compressive stress in the bond



(b) principal tensile stress in the bond

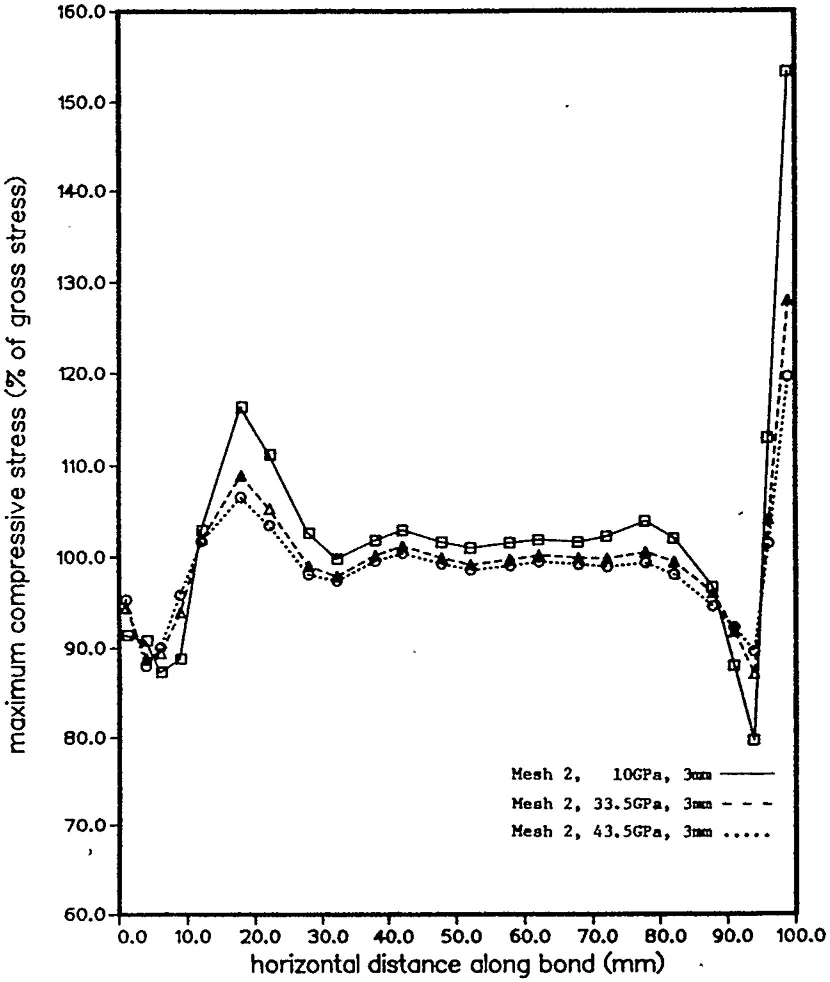
Figure 6.18 Effect of bond modulus of elasticity on stress in a 3 mm bond with weakness near the center.



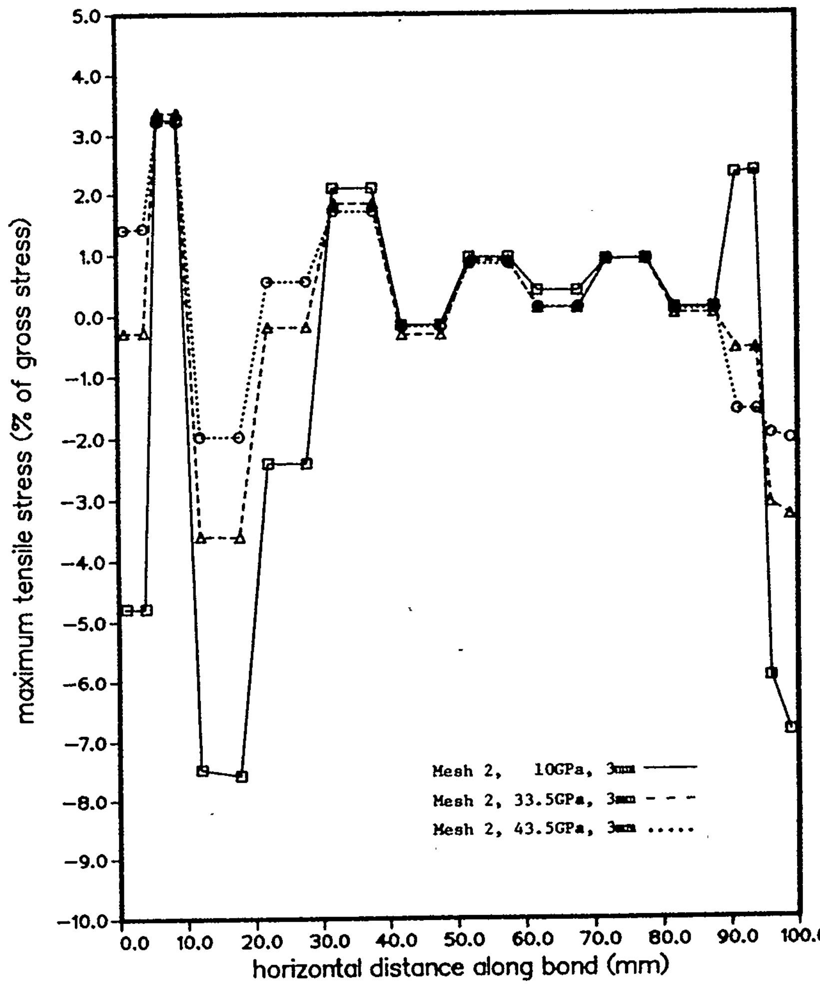
(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

Figure 6.19 Effect of bond modulus of elasticity on stress in a 3 mm bond with offset error.

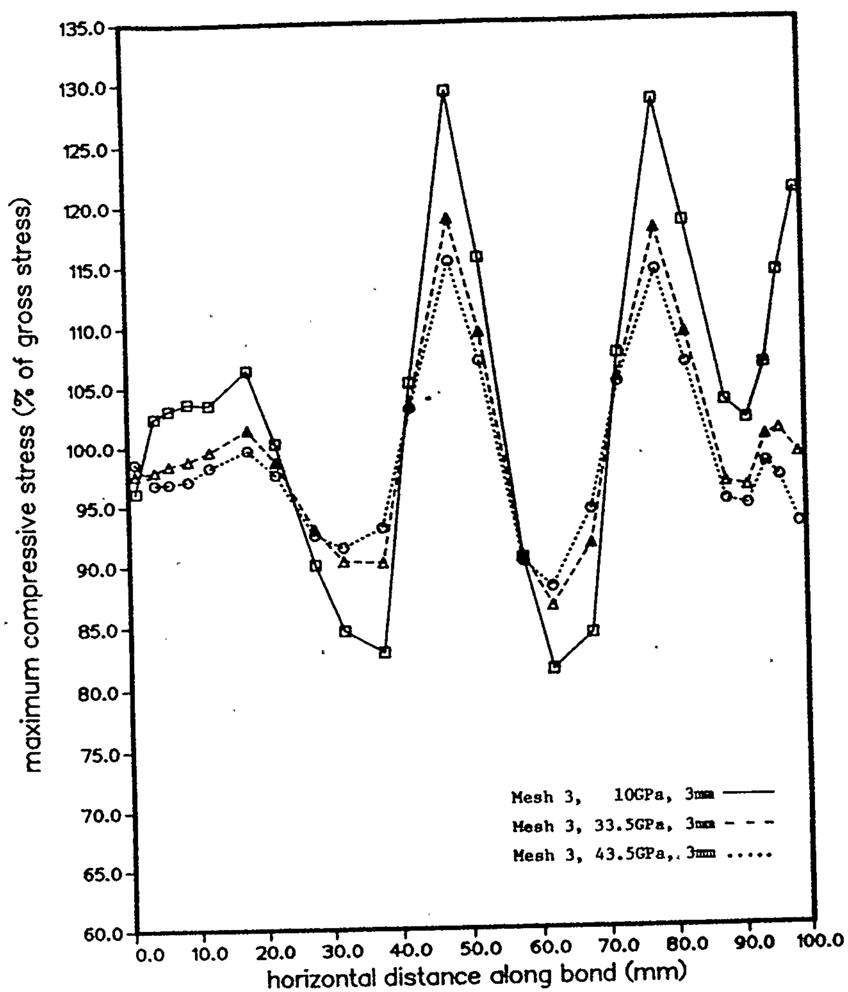


(a) principal compressive stress adjacent to the bond

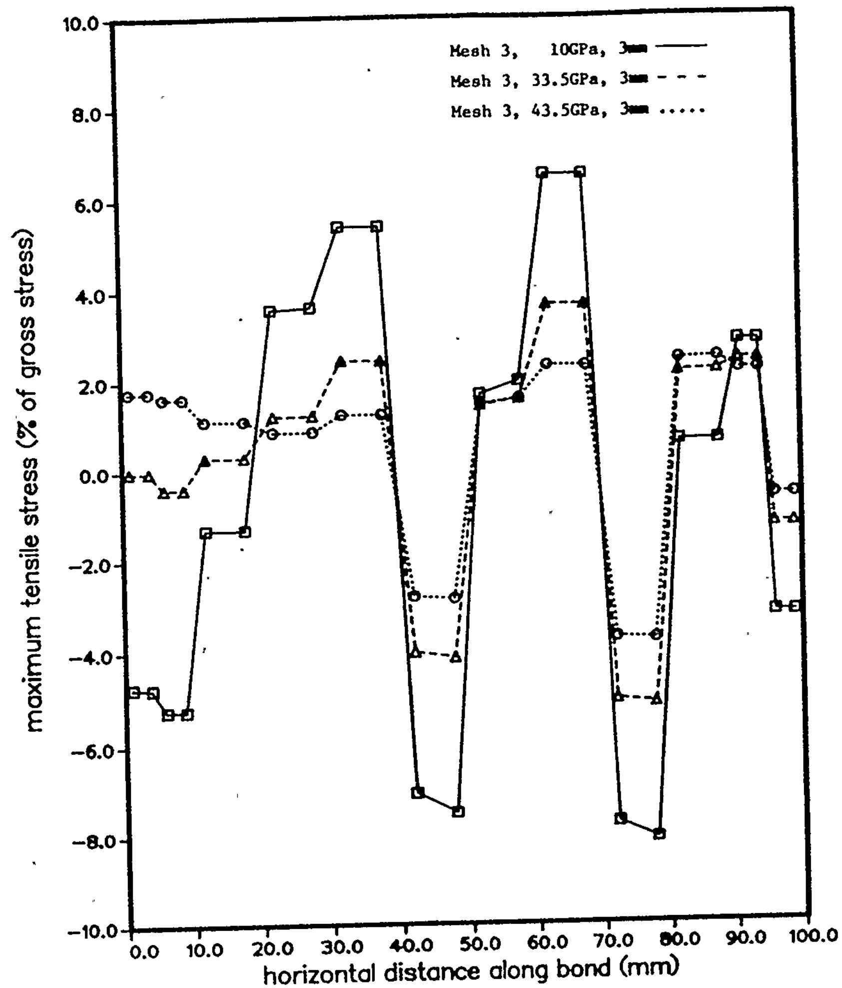


(b) principal tensile stress adjacent to the bond

Figure 6.20 Effect of bond modulus of elasticity on stress in concrete adjacent to a 3 mm bond with weakness near center edges.

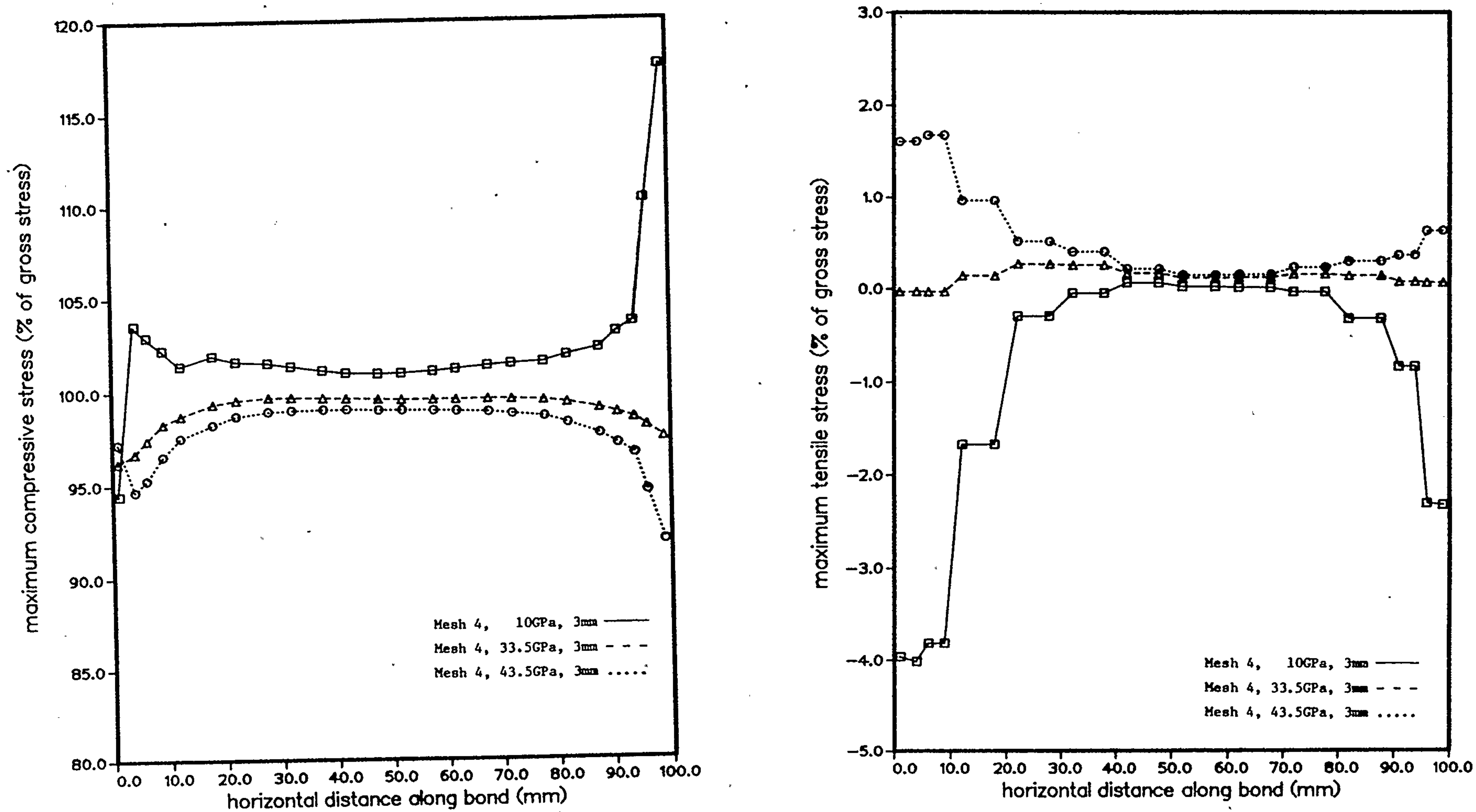


(a) principal compressive stress adjacent to the bond



(b) principal tensile stress adjacent to the bond

Figure 6.21 Effect of bond modulus of elasticity on stress in concrete adjacent to a 3 mm bond with weakness near the center.



(a) principal compressive stress adjacent to the bond

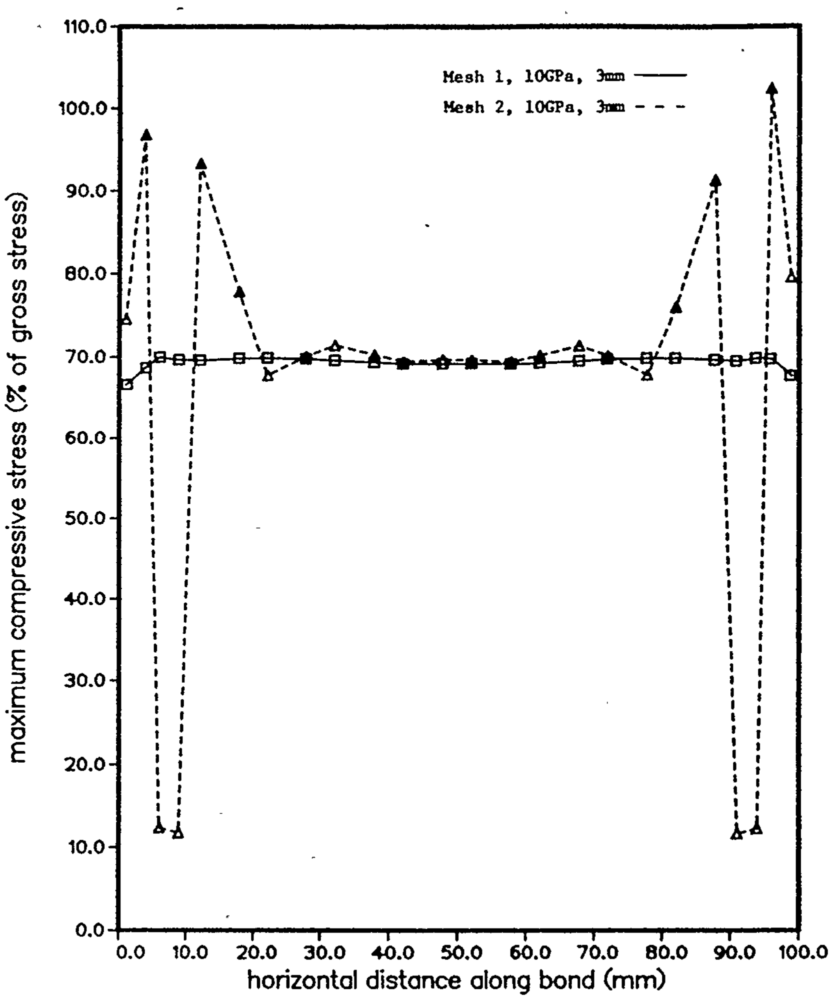
(b) principal tensile stress adjacent to the bond

Figure 6.22 Effect of bond modulus of elasticity on stress in concrete adjacent to a 3 mm bond with offset error.

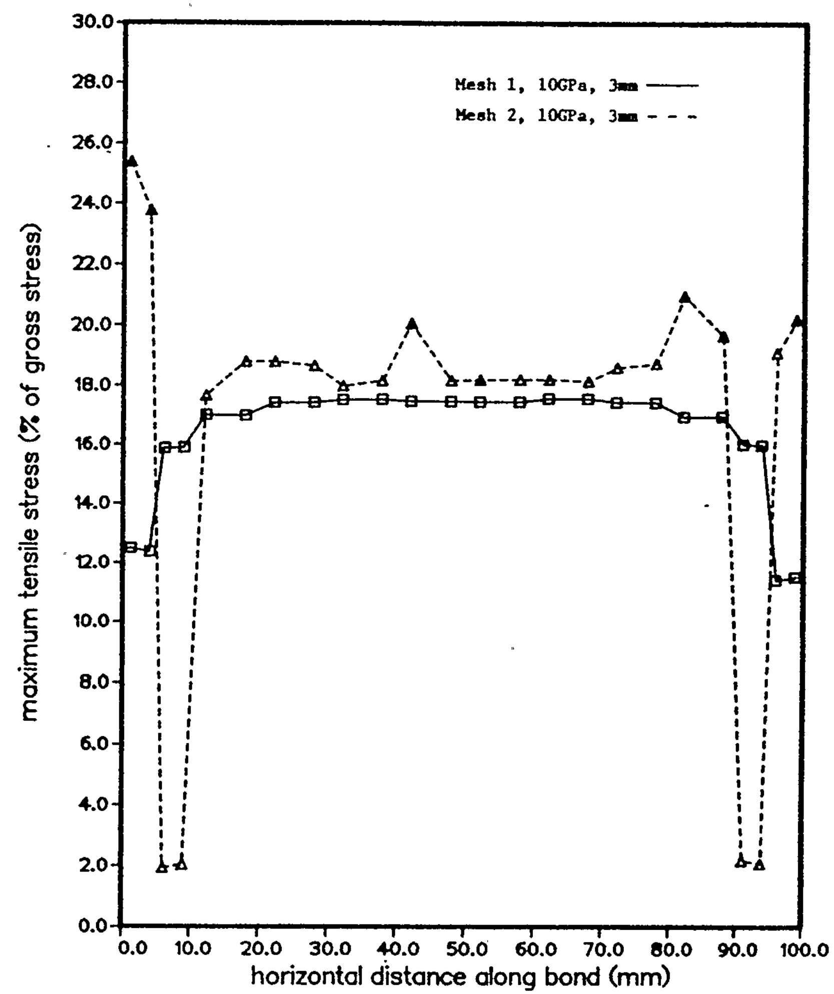
6.4.3. Effect of Regions of Bond Weakness on Stress

As mentioned earlier the effect of flaws near the edge and near the center of the bond line were modelled by meshes 2 and 3 respectively. The discussion in this section is limited to 3 mm bonds since the 6 mm bonds were discussed previously. The maximum compressive stresses, as expected, occurred adjacent to the flaws for both mesh types and all bond moduli of elasticity. The maximum compressive stress in the 10 GPa bond was approximately 45% and 55% higher for mesh types 2 and 3 respectively, compared to the normal mesh (see Figs. 6.23-6.24). The maximum compressive stress in the 43.5 GPa bond increased approximately 55% and 65% for mesh types 2 and 3 respectively compared to the normal mesh. Tensile stresses were also higher for both mesh types 2 and 3 compared to the normal mesh for all bond moduli of elasticity (Figs. 6.25-6.26).

Compressive stresses adjacent to the bond were highest near the regions of bond weakness. Compared to the normal mesh, the maximum compressive stress next to the 3 mm thick, 10 GPa bond was approximately 32% and 11% larger for mesh types 2 and 3 respectively (Fig. 6.27). Maximum compressive stresses next to the 43.5 GPa bond modelled by meshes 2 and 3 were much lower than the maximum compressive stress adjacent to the 10 GPa bond (Fig. 6.28). The maximum compressive stress next to the 3 mm thick, 43.5 GPa bond was approximately 21% and 16% larger for mesh types 2 and 3 respectively, compared to the compressive stress in the same bond modelled by mesh 1.

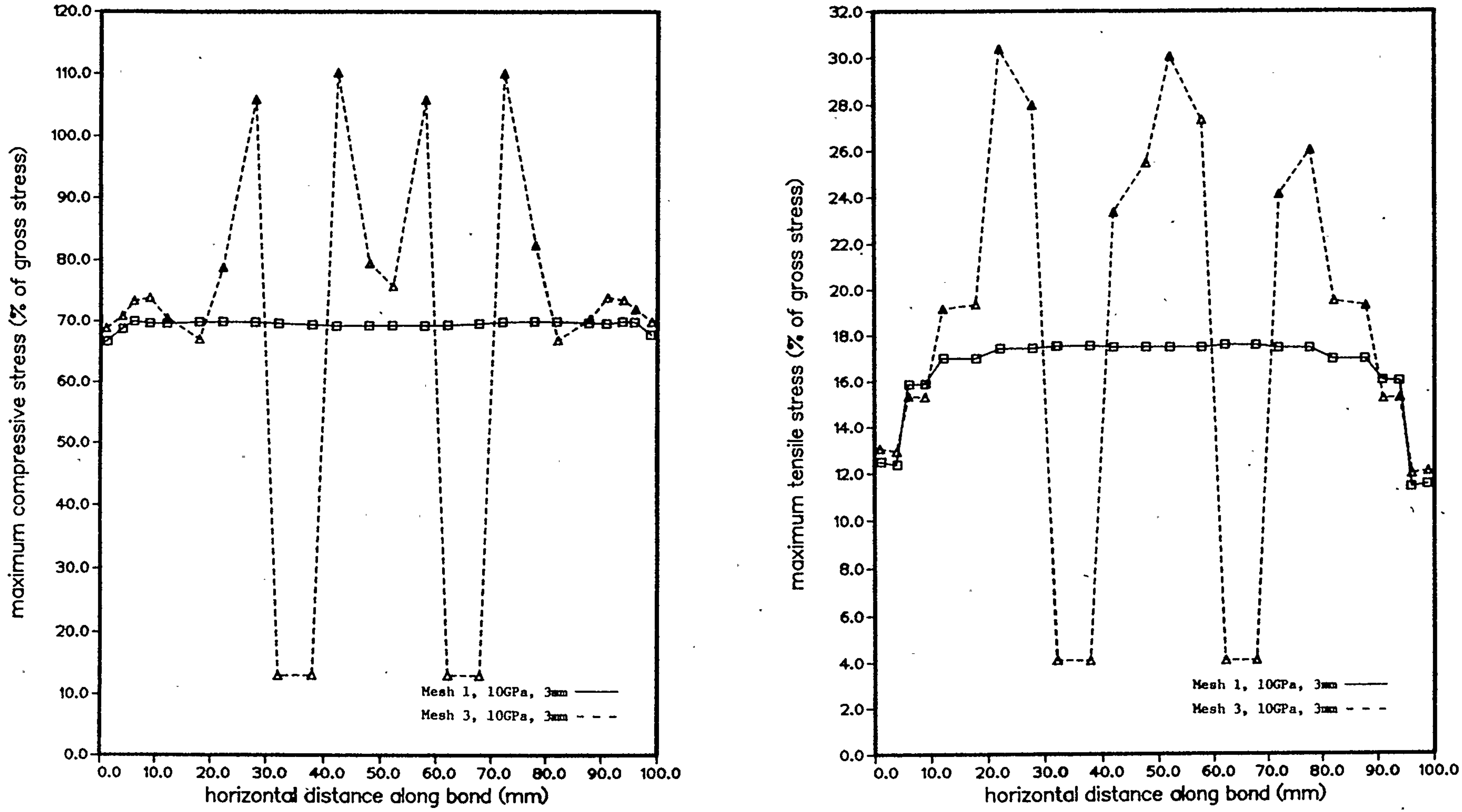


(a) principal compressive stress in the bond



(b) principal tensile stress in the bond

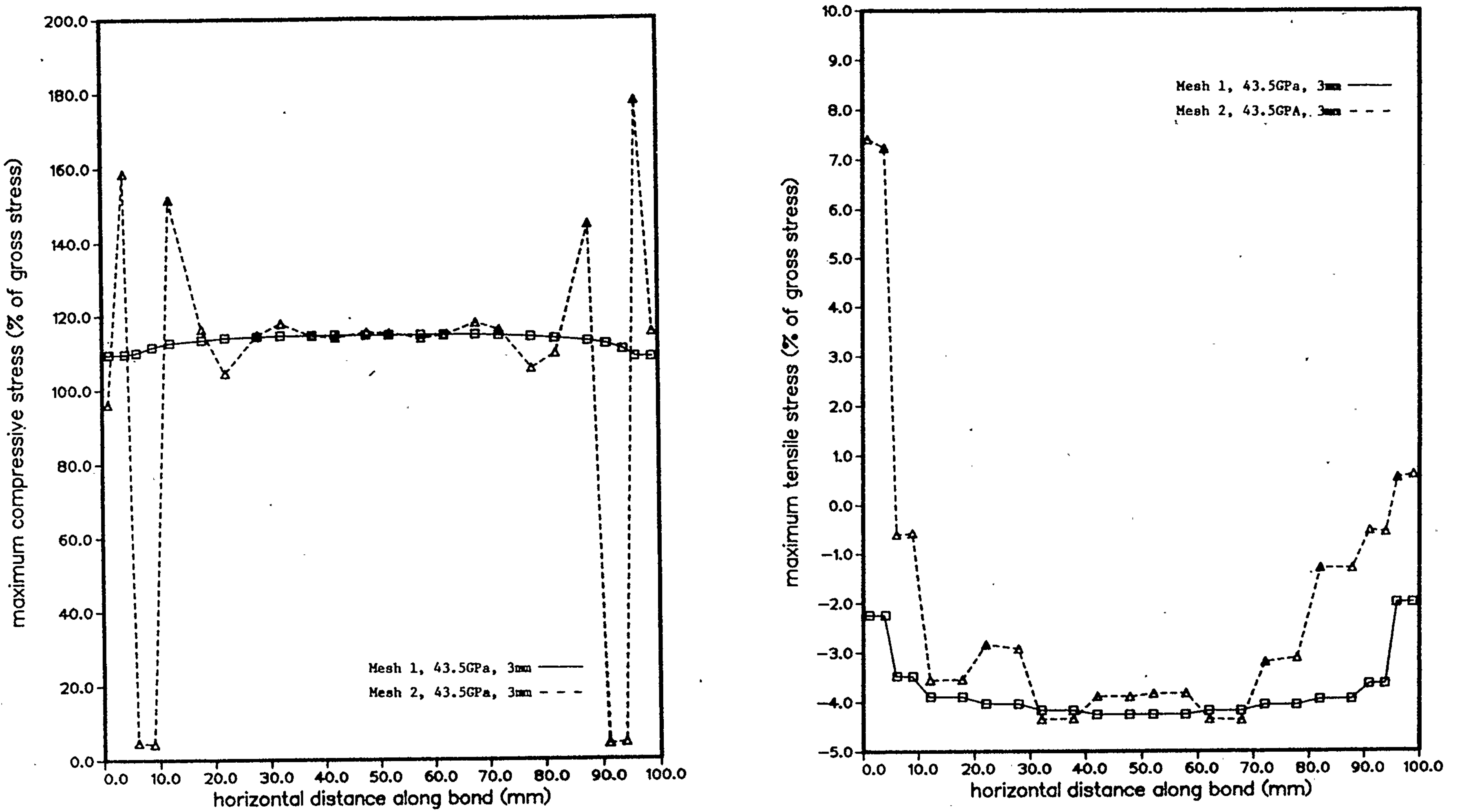
Figure 6.23 Effect of bond weakness at edges on stress in 10 GPa, 3 mm bond.



(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

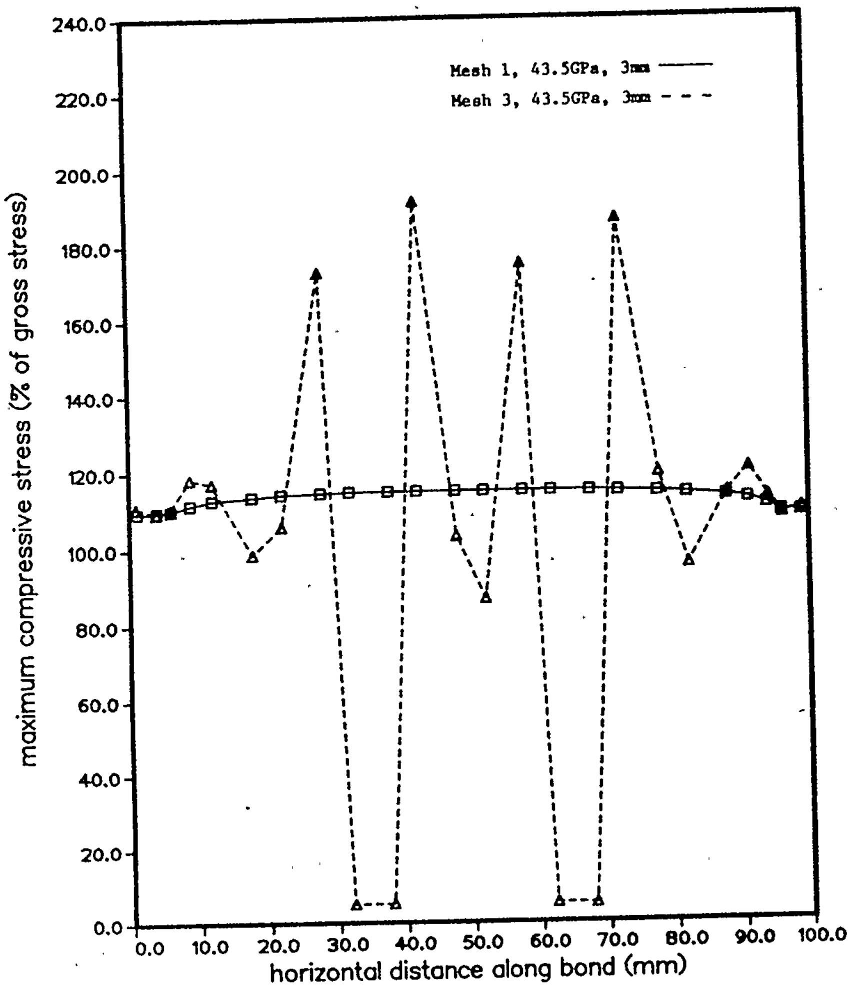
Figure 6.24 Effect of bond weakness near center on stress in 10 GPa, 3 mm bond.



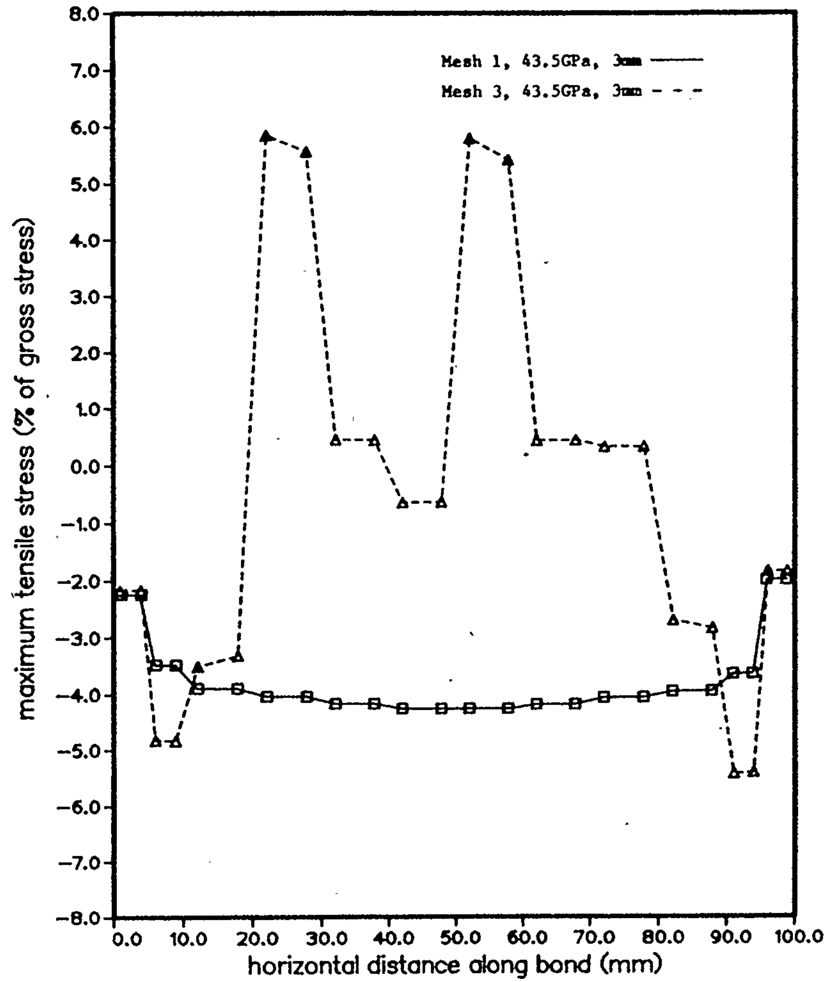
(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

Figure 6.25 Effect of bond weakness at edges on stress in 43.5 GPa, 3 mm bond.

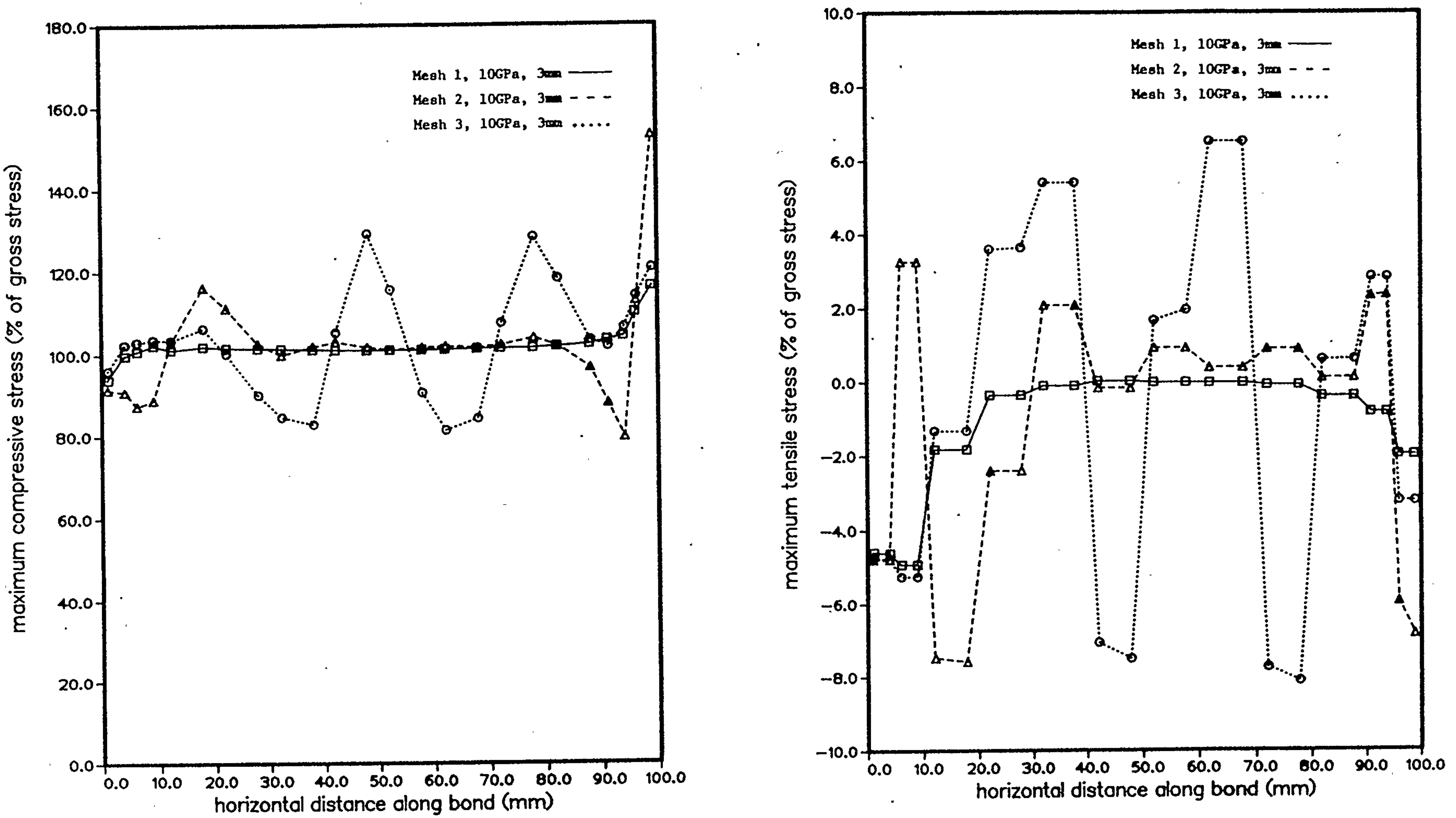


(a) principal compressive stress in the bond



(b) principal tensile stress in the bond

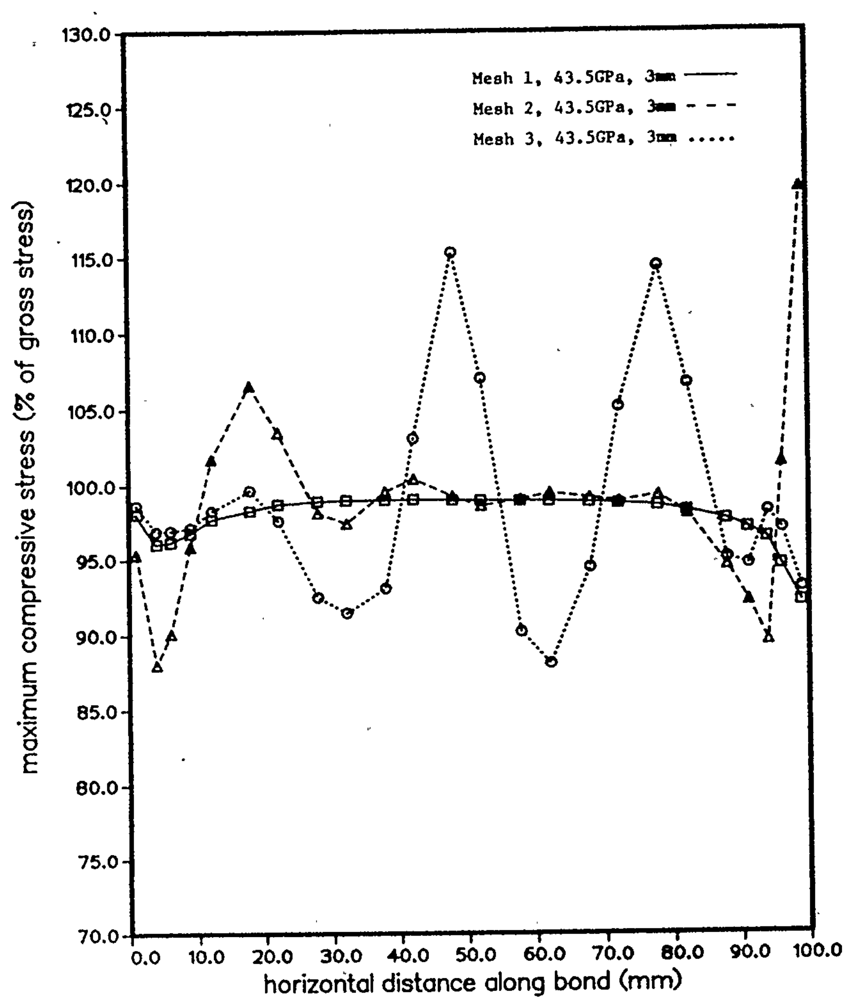
Figure 6.26 Effect of bond weakness near center on stress in 43.5 GPa, 3 mm bond.



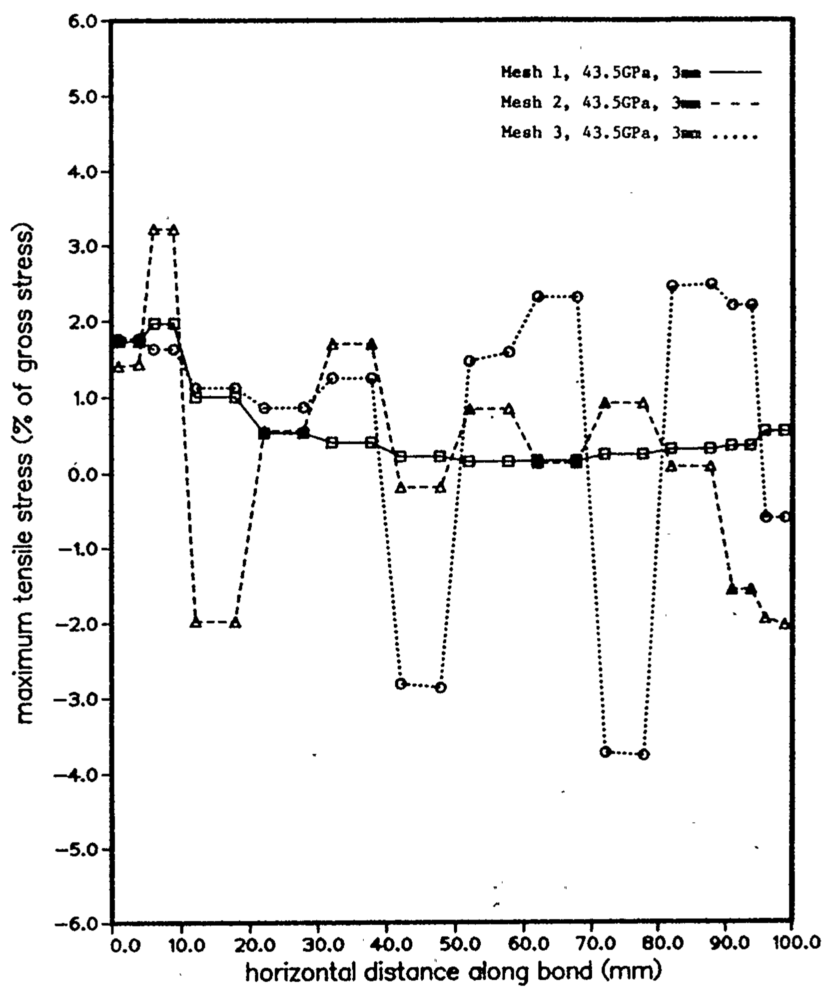
(a) principal compressive stress adjacent to the bond

(b) principal tensile stress adjacent to the bond

Figure 6.27 Effect of bond weakness on stress in concrete adjacent to a 10 GPa, 3 mm bond.



(a) principal compressive stress adjacent to the bond



(b) principal tensile stress adjacent to the bond

Figure 6.28 Effect of bond weakness on stress in concrete adjacent to a 43.5 GPa, 3 mm bond.

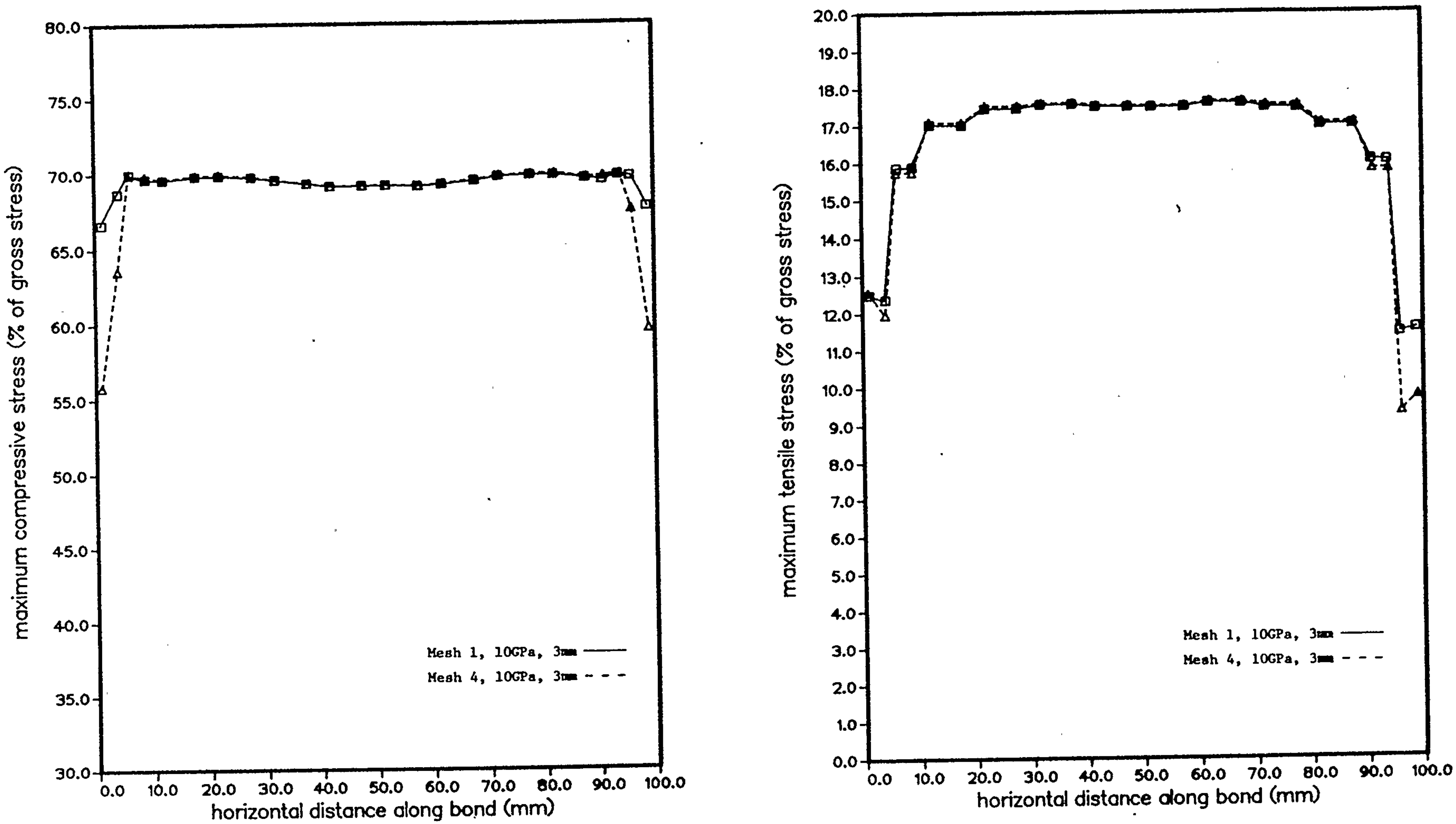
For most bonds analysed using meshes 2 and 3 the tensile stresses adjacent to the bond were higher compared to the stresses in the corresponding bonds modelled by mesh 1 (Figs. 6.27-6.28). However, the largest maximum tensile stress adjacent to the bonds modelled by meshes 2 and 3 was only 7% of the gross compressive stress.

6.4.4. Effect of Casting Procedure on Slant Shear Test Stresses

The effect of a slight "offset" between the base and overlay components of the prism (see also section 5.2.2.) was modelled using mesh 4. The offset appears to affect stresses at the bond line to a very small extent (Figs. 6.29-6.30). The compressive stresses at the edge of the 10 GPa and 43.5 GPa bonds are about 10% lower and 5% higher respectively compared to the normal mesh. Tensile stresses were affected almost imperceptibly. Compressive and tensile stresses adjacent to both the 10 GPa and 43.5 GPa bonds were not affected by the presence of the "offset error" (Figs. 6.31-6.32).

6.5. Conclusions

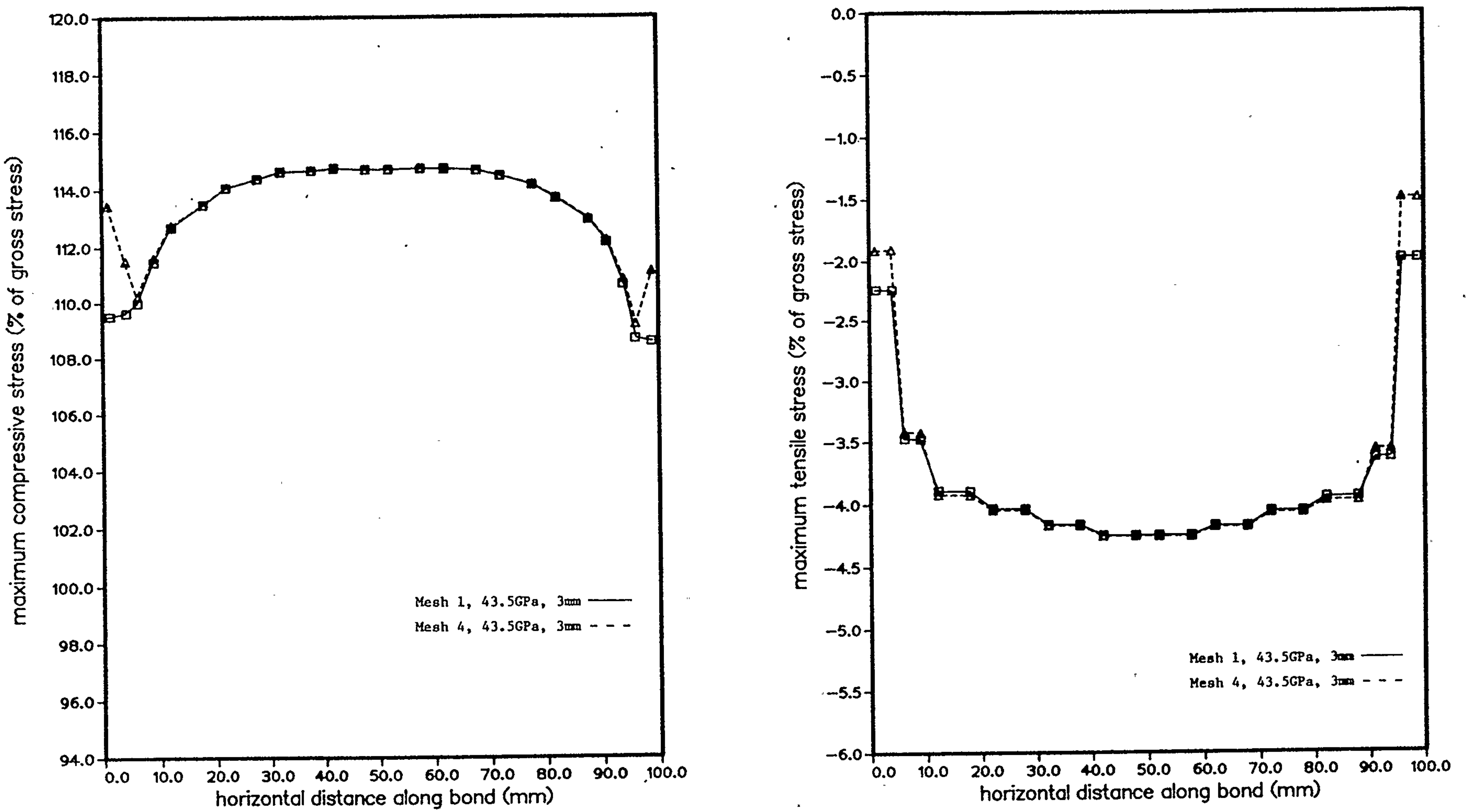
Stress levels were almost uniform across the bond when a bond of uniform mechanical properties was analyzed. Weakness of the bond materials near edges of the bond plane or near the center of the bond plane significantly raises the maximum stress along the bond line. In addition, stress levels varied to a large degree (50%) when bond material weaknesses were studied. Bond materials with a stiff modulus of elasticity created far higher principal compressive stresses at the bond



(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

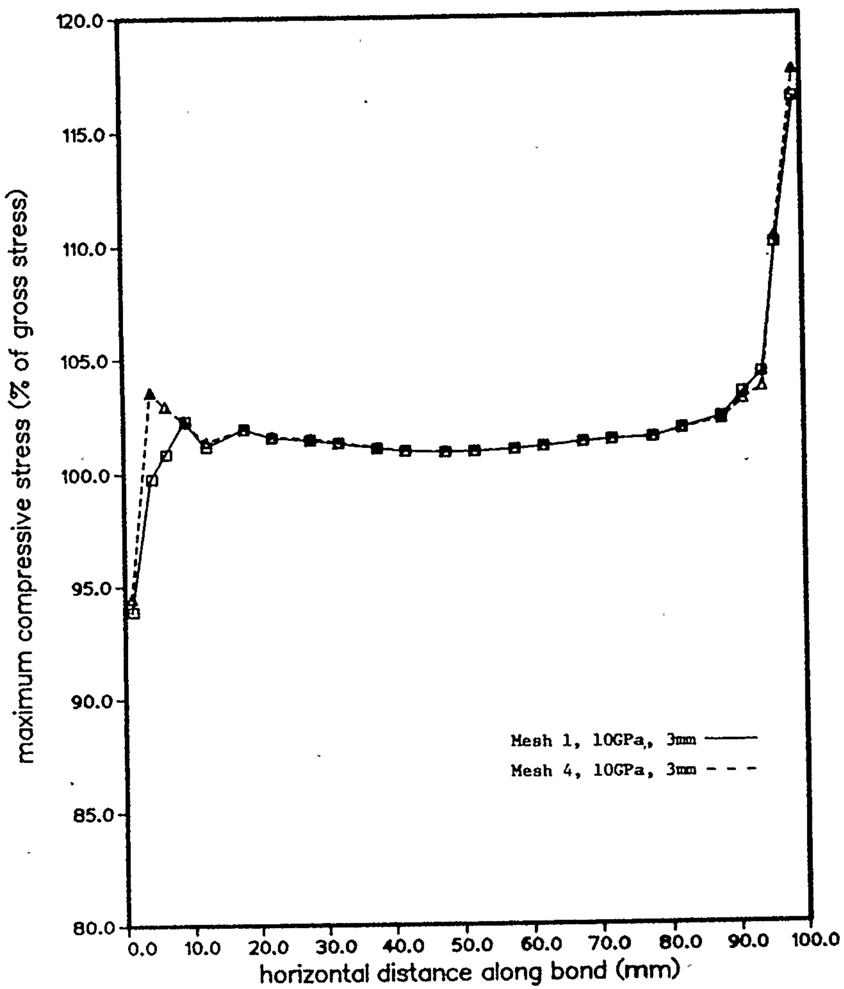
Figure 6.29 Effect of offset error on stresses in a 10 GPa, 3 mm bond.



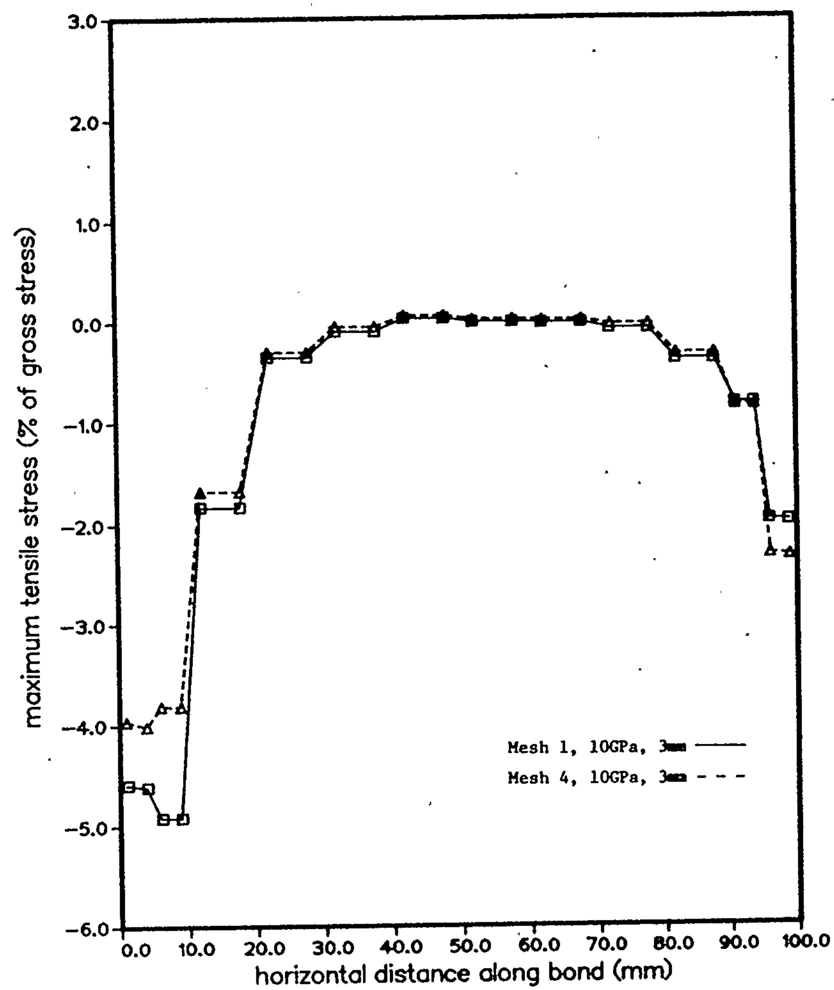
(a) principal compressive stress in the bond

(b) principal tensile stress in the bond

Figure 6.30 Effect of offset error on stresses in a 43.5 GPa, 3 mm bond.

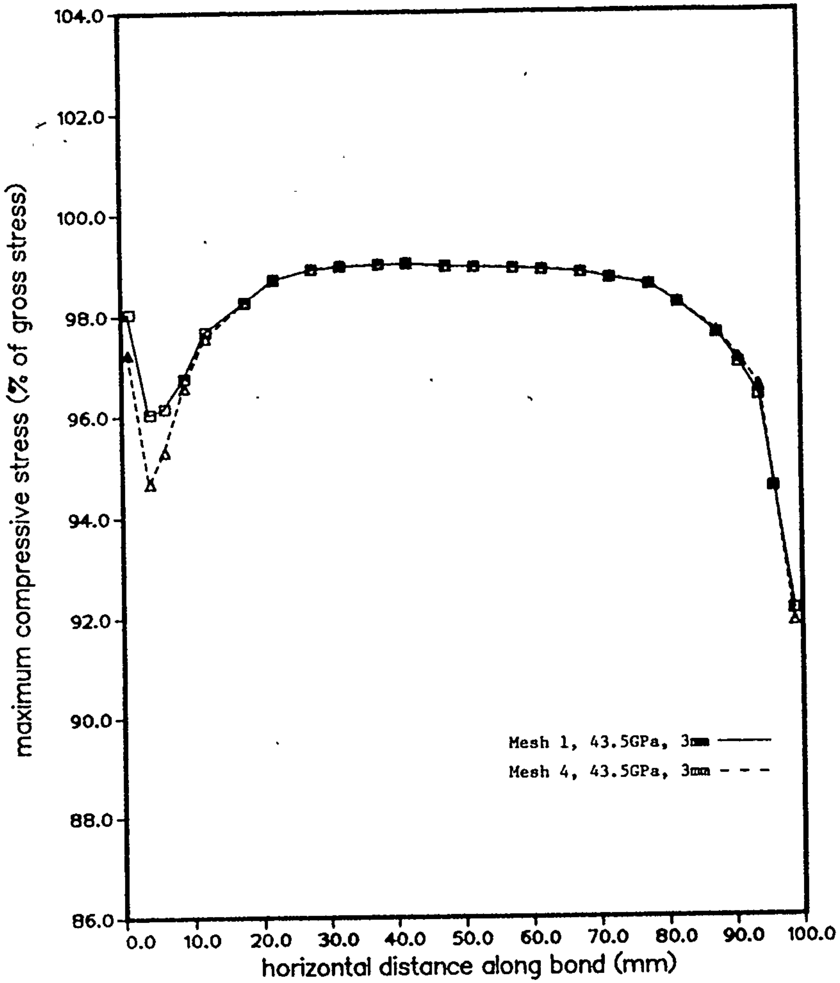


(a) principal compressive stress adjacent to the bond

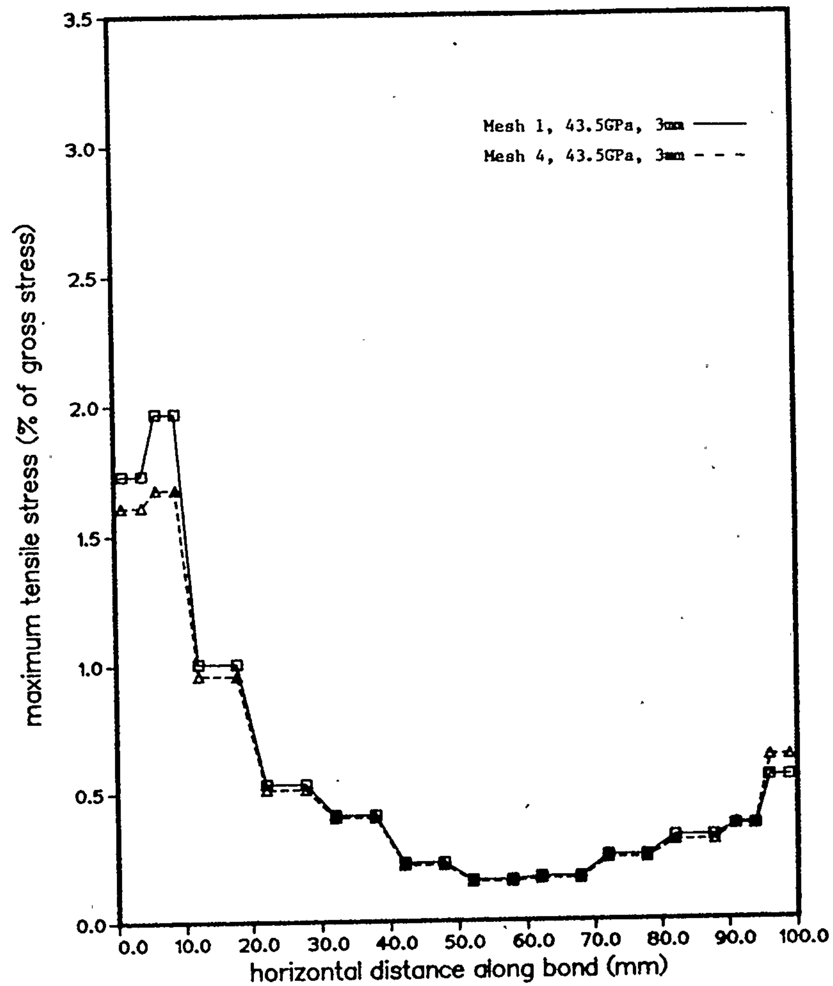


(b) principal tensile stress adjacent to the bond

Figure 6.31 Effect of offset error on stresses in concrete adjacent to a 10 GPa, 3 mm bond.



(a) principal compressive stress adjacent to the bond



(b) principal tensile stress adjacent to the bond

Figure 6.32 Effect of offset error on stresses in concrete adjacent to a 43.5 GPa, 3 mm bond.

line than a bond material with a flexible modulus of elasticity. Increased bond thickness was observed to increase stress in the adjacent concrete. Bond thickness did not increase stress levels in the bond itself. The "offset error" of the slant shear test does not significantly affect test results.

CHAPTER 7

RESULTS AND ANALYSIS OF BONDS USING THE SLANT SHEAR TEST

7.1. Testing Program and Procedure

The second method of bond assessment, experimental investigation, is now discussed. The slant shear test, which was previously selected as being the most appropriate, was used to investigate experimentally the effects of the following parameters on bond strength:

1. the water cement ratio of the portland cement mortars;
2. the thickness of the bond layer;
3. the effect of various curing conditions;
4. the effect of wetting the surface of the hardened concrete before application of the portland cement mortar bonding agent;
5. the effect of delay between mixing a copolymer PVA bonding agent, and its application to hardened concrete.

The procedure was unchanged from that described in Chapter 4 with minor exceptions. The exceptions included the replacement of the wooden mould inserts with steel inserts, and the use of steel templates with a plastering trowel to control the thickness of the bond layer. These changes improved geometric control. Since the results described previously are not compared with the results of this chapter, minor changes in the testing program were expected to reduce the variability of the results. Most of the PVA bonded prisms were cured in 50% relative humidity for the last 14 days before testing. When the base components of PVA bonded prisms were cast, the associated control cylinders were tested at age 35 days (the same time as the prisms) in order to match the curing conditions with that of the prisms. Finally, 8 composite prisms were cast for each bond type, as opposed to 6 in the previous test series.

7.2. Observations and Results

7.2.1. Strengths

The average ultimate strength and standard deviation for each type of bond is given in Table 7.1. Also included in Table 7.1 is a description of each bond and the curing conditions. Individual bond strengths and control specimen strengths are given in Appendix B.

The differences between one bond and another were analysed statistically using a modified version of the *t* statistic (from Walpole and Myers (1978)). The equations are shown in Appendix C. The results of the statistical analysis are shown in Table 7.2. Mode of failure and batch control strengths are given in Table 7.3.

Table 7.1 Details of bonds, curing conditions and bond strength using slant shear tests (average of eight tests).

Bond (Designation)	Active Ingredient	Thickness (mm (ins))	Water Cement Ratio of Bond Mortar	Curing Period after 24 hrs (Days) 100% RH/ 50% RH	Avg. Compr. Strength (MPa)	Stand. Dev. (MPa)
B10	No Bonding Agent			27/0	43.5	2.90
B11	PC	4.8 (3/16)	0.35	27/0	45.1	0.75
B12	PC	6.4 (1/4)	0.35	27/0	34.9	5.57
B13	PC	3 (1/8)	0.35	27/0	44.4	1.79
B14	PC	3 (1/8)	0.40	27/0	41.7	1.23
B15	PC	3 (1/8)	0.32	27/0	31.5	1.05
B16+	PVA	Paint	-	13/14	20.2	1.87
B17+	PVA	Paint*	-	13/14	17.4	1.31
B18+	PVA	3 (1/8)	0.20	13/14	31.9	4.77
B19+@	PVA	3 (1/8)	0.20	13/14	30.2	4.34
B20+	PVA	3 (1/8)	0.22	13/14	26.1	2.03
B21+@	PVA	3 (1/8)	0.22	13/14	26.4	2.36
B22+	PVA	3 (1/8)	0.22	27/0	20.9	1.84
B23+	PC	3 (1/8)	0.40	27/0	46.0	3.36

PC portland cement
\+ substrate was wetted
* 2 coats
@ PVA pot life expired

Table 7.2 Test for statistical significance.

Bonds Compared	Parameter Varied	Mean Strength of First Bond (MPa)	Mean Strength of Second Bond (MPa)	Significant Difference (Y = Yes, N = No)	Highly Significant
B11:B12	4.8 mm:6.4 mm* (3.16":1/4")	45.1	34.9	Y	Y
B13:B11	3.2 mm:4.8 mm* (1/8":3/16")	44.4	45.1	N	N
B15:B13	0.32:0.35+	31.5	44.4	Y	Y
B13:B14	0.35:0.40+	44.4	41.7	Y	Y
B14:B23	Dry:Wet%	41.7	46.0	Y	N
B16:B17	Coats of PVA	20.2	17.4	Y	Y
B18:B19	No Delay:Delay	31.9	30.2	N	N
B20:B21	No Delay:Delay	26.1	26.4	N	N
B18:B20	0.20:0.22+	31.9	26.1	Y	Y
B20:B22	Curing	26.1	20.9	Y	Y

* thickness
\+ water-cement ratio
% surface moisture condition

Table 7.3 Mode of failure and batch control strength.

Bond	At Bond (# of Prisms)	Not at Bond # of Prisms)	Ductility of* Failure Brittle (# of Prisms)	Ductile (# of Prisms	Strength of Control Cylinders (MPa) Base	Overlay
B10	7	1	6	2	44.4	41.5
B11	1	7	1	7	45.0	41.0
B12	8	0	8	0	43.0	44.7
B13	4	4	4	4	42.5	44.2
B14	0	8	0	8	41.5	36.6
B15	4	4	0	8	41.0	27.9
B16	8	0	8	0	53.3	49.6
B17	8	0	8	0	56.0	52.2
B18	8	0	8	0	55.3, 53.3	51.2, 48.6
B19	8	0	8	0	55.3, 53.3	51.2, 48.6
B20	8	0	8	0	51.3, 51.1	43.6, 52.4
B21	8	0	8	0	51.3, 51.1	43.6, 52.4
B22	8	0	8	0	48.4	45.0
B23	8	0	8	0	48.6	48.6

* Any specimen which produced a sudden loud noise and experienced a rapid reduction in load within approximately one second of the ultimate load was considered brittle. Any other specimen was considered ductile.

A significant difference occurs at the 95% confidence level whereas a highly significant difference is deemed to occur at the 99% confidence level.

The most obvious fact reflected in the data is the difference in strength between the bonds containing PVA and the bonds containing portland cement mortar. As with the first series of tests, almost all the portland cement mortar bonds were stronger than the PVA bonds - only 2 PVA bond types had similar strengths. The strongest PVA mortar bond B18 had a strength of 31.9 MPa compared to the weakest portland cement mortar bond B15 of 31.5 MPa. Other portland cement mortar bonds all had strengths of greater than 40 MPa.

The effect of thickness on portland cement bonds with a 0.35 water cement ratio can be gauged by comparing the ultimate loads of B11, B12 and B13. The results show the 3.2 mm (1/8") (B13) and the 4.8 mm (3/16") (B11) bond were stronger than the 6.4 mm (1/4") (B12) bond. This result was found to be statistically very significant. In addition, the 6.4 mm (1/4") specimens all failed at the bond line (Table 7.3). This is unlike the other thicknesses where failure occurred mainly outside the bond area indicating bond strength as good as, or better than, the concrete. The detrimental effect of increased bond layer thickness has been noted before in masonry such as in Sise (1984). There has been no explanation of this phenomenon to date.

The influence of the water cement ratio is less clear. Water-cement ratios used in the portland cement based mortar were 0.32, 0.35 and 0.40, with bond thickness maintained at 3.2 mm (1.8"). The ultimate compressive stress for the

0.32 water cement ratio bond (B15) was on average 12.9 MPa lower than for the 0.35 water cement ratio bond (B13) and 10.2 MPa lower than for the 0.40 water cement ratio bond (B14). The statistical analysis in Table 7.2 shows that this is a very significant difference in both cases, but it should be kept in mind that the overlay concrete for the B15 specimens had unusually low strength. Nevertheless, failure occurred at the bond 4 times, unlike the B14 specimens where failure always occurred away from the bond. Therefore, it appears a very low water cement ratio will cause a reduction in bond strength. A similar relationship has been found in masonry bonds. Very low moisture contents in masonry units cause the units to absorb moisture from the adjacent mortar layers. Therefore, the moisture in the mortar bonds is reduced. Sise (1984) has documented that masonry bond strength is reduced if the masonry units (and thus the mortar) have less than the optimal moisture content.

The effect of prewetting the substrate prior to application of a portland cement bond layer was studied using batch B23. The bond in B23 was 3.2mm (1/8") thick and a 0.40 water cement ratio portland cement mix was used. Comparing B23 to B14 (which is identical except for the substrate treatment), the wet substrate may be seen to improve the strength slightly. The improvement was calculated to be significant but not highly significant (see Table 7.2). This is in disagreement with earlier findings by Felt (1967) who found the dry surface slightly superior when using a "direct shear jig" test. Warris (1967) also found that a dry surface produced a stronger bond when tested by a pull-off type test. However, Tyson

(1977) reports surfaces being wetted for bridges in Virginia. As well, the Kansas Department of Transportation recommends prewetting the surface and has supporting empirical data (Portland Cement Association (1980)).

The effect of using a PVA paint as a bonding agent is also shown in Table 7.1. Paint exposed to 14 days of moist curing and a further 14 days at only 50% relative humidity, produced ultimate compressive strengths of only slightly above 20 MPa (B16). With batch B17 a first coat of paint was allowed to dry on the substrate before a final coat was applied. The curing conditions were the same as with batch B16. A reduction in composite prism ultimate strength resulted, an average strength of only 17.43 MPa was obtained. The statistical calculations show that this is a very significant difference compared to the batch B16 results. Dixon and Sunley (1983) found a more drastic drop in strength for an SBR bonding grout applied in a similar manner.

The PVA modified cement mortars yielded higher bond strengths than the paints. With a water cement ratio of 0.2 and cured 14 days at 100% relative humidity and 14 days at 50% relative humidity, an average composite compressive strength of 31.9 MPa was obtained (B18). The mortar at this water cement ratio had poor workability. Increasing the water cement ratio to 0.22 while keeping all other factors constant produced prisms with a lower average strength of 26.10 MPa which is a very significant difference according to statistical analysis. It should be noted that the maximum water cement ratio recommended by the supplier/manufacturer was 0.2. At the 0.2 water cement ratio the mortar had poor workability. The effect of delaying the time between the casting of the mortar and the application of the overlay by approximately 20 minutes more than the PVA manufacturers' recommended pot life time, did not adversely affect strengths.

Many researchers have noted the vulnerability of homopolymer PVA to alkaline moisture such as, Shaw (1983) and Cherkinski (1967). Shaw (1983) suggested that copolymer PVA had been developed to combat this problem but Mattiotti (1967) noted that an early copolymer PVA was vulnerable to moisture although he did not perform bond tests. Frondistou-Yannas and Shah (1972) noted the detrimental effect of moisture on the strength of PVA in general. Both Frondistou-Yannas and Shah and Mattiotti suggest moisture damage is reversible after a sufficient period of drying.

Using no bonding agent at all appeared to yield relatively high bond strengths under the controlled laboratory conditions. The strength results were similar to the better portland cement mortar results although the explosive brittle failure mode was not desirable (both the base and overlay components of one specimen tested without the restraint packing described in Section 4.4.2. flew approximately 1.8 m (6 ft) after bond failure). High bond strengths have been noted before for composite specimens prepared under laboratory controlled conditions. (eg: Tabor (1979)).

7.2.2. Strain Results

Average compressive strain measured by LVDT's and the standard deviation is shown in Table 7.4. Each value is an average of the strains of each of the three specimens of each bond type. A statistical comparison between bond types using the same methods as with the analysis of different strengths is presented in Table 7.5. Stress/strain plots are presented in Figs. 7.1-7.3 for the most significant results. The plot shown for each bond type in an average of the plots of three specimens.

The results show that the PVA bonds and the portland cement mortar bonds had similar stiffness to the monolithic control prisms tested earlier. In general the strains did not vary much with different bond types. The exceptions are discussed next.

The portland cement mortar water cement ratio may affect stiffness to a small degree as there is a small significant increase in stiffness at some stress levels as the water cement ratio is increased (Fig. 7.1). This trend, however, is clouded by a few exceptions.

The effect of wetting concrete substrate before applying bonding mortar appears to increase flexibility at low stress levels and decrease them at high stress levels (Fig. 7.2). This difference is relatively small (32μ at 5 MPa and 250μ at 40 MPa) but is significant statistically at 40 MPa.

Table 7.4 Average LVDT Strains and Standard Deviations

BOND (DESIGNATION)	STRESS LEVEL (MPa)	AVERAGE STRAIN (μ)	STANDARD DEVIATION (μ)
B10	5	102	44
	8	183	51
	20	590	60
	30	960	60
	40	1400	48
B11	5	125	Only 2 results
	8	210	
	20	600	
	30	930	
	40	1420	
B12	5	127	10
	8	210	10
	20	610	16
	30	960	Only 2 results
	40	1430	Only 1 result
B13	5	132	18
	8	220	18
	20	620	25
	30	990	42
	40	1450	72
B14	5	100	5
	8	188	8
	20	610	6
	30	1020	8
	40	1590	50
B15	5	128	10
	8	230	10
	20	690	17
	30	-	-
	40	-	-

Table 7.4 (Continued)

BOND (DESIGNATION)	STRESS LEVEL (MPa)	AVERAGE STRAIN (μ)	STANDARD DEVIATION (μ)
B16	5	113	6
	8	210	6
	20	620	2 specimens only
	30	-	-
	40	-	-
B17	5	132	8
	8	250	5
	20	-	-
	30	-	-
	40	-	-
B18	5	145	9
	8	250	14.4
	20	700	54
	30	-	-
	40	-	-
B19	5	138	8
	8	240	9
	20	670	15.3
	30	1080	45
	40	-	-
B20	5	143	12.6
	8	240	21
	20	690	43
	30	-	-
	40	-	-
B21	5	118	20
	8	213	29
	20	670	29
	30	-	-
	40	-	-

Table 7.4 (Continued)

BOND (DESIGNATION)	STRESS LEVEL (MPa)	AVERAGE STRAIN (μ)	STANDARD DEVIATION (μ)
B22	5	130	0
	8	230	3
	20	680	16.1
	30	-	-
	40	-	-
B23	5	132	10.4
	8	220	6
	20	600	6
	30	940	8
	40	1340	6

Table 7.5 Comparisons of Strain Between Bond Types

BONDS COMPARED	PARAMETER VARIED	STRESS (MPa)	MEAN STRAIN OF FIRST BOND (μ)	MEAN STRAIN OF SECOND BOND (μ)	SIGNIFICANT DIFFERENCE (Y = YES, BLANK = NO)	HIGHLY SIGNIFICANT
B12 → B13	1/4":1/8"*	5	127	132		
		8	220	220		
		20	610	620		
		30	-	-		
		40	-	-		
B15 → B13	0.32:0.35+	5	128	132		
		8	230	220		
		20	690	620	Y	
		30	-	-		
		40	-	-		
B13 → B14	0.35:0.40+	5	132	100	Y	
		8	220	188	Y	
		20	618	610		
		30	990	1020		
		40	1450	1590		
B15 → B14	0.32:0.40+	5	128	100	Y	
		8	230	188	Y	Y
		20	690	610	Y	Y
		30	-	-		
		40	-	-		
B14 → B23	DRY:WET%	5	100	132	Y	Y
		8	188	220	Y	Y
		20	610	600		
		30	1020	940	Y	Y
		40	1590	1340	Y	Y
B16 → B17	Coats of PVA	5	113	132	Y	
		8	210	250	Y	Y
		20	-	-		
		30	-	-		
		40	-	-		
B18 → B19	NO DELAY:DELAY	5	145	138		
		8	250	240		
		20	700	670		
		30	-	-		
		40	-	-		

Table 7.5 (Continued)

BONDS COMPARED	PARAMETER VARIED	STRESS (MPa)	MEAN STRAIN OF FIRST BOND (μ)	MEAN STRAIN OF SECOND BOND (μ)	SIGNIFICANT DIFFERENCE (Y = YES, BLANK = NO)	HIGHLY SIGNIFICANT
B20 → B21	NO DELAY:DELAY	5	143	118		
		8	240	210		
		20	690	670		
		30	-	-		
		40	-	-		
B18 → B20	0.20:0.22+	5	145	143		
		8	250	240		
		20	700	690		
		30	-	-		
		40	-	-		
B19 → B21	0.20:0.22+	5	140	118		
		8	240	210		
		20	670	670		
		30	-	-		
		40	-	-		

* thickness
\+ water cement ratio
% surface moisture condition

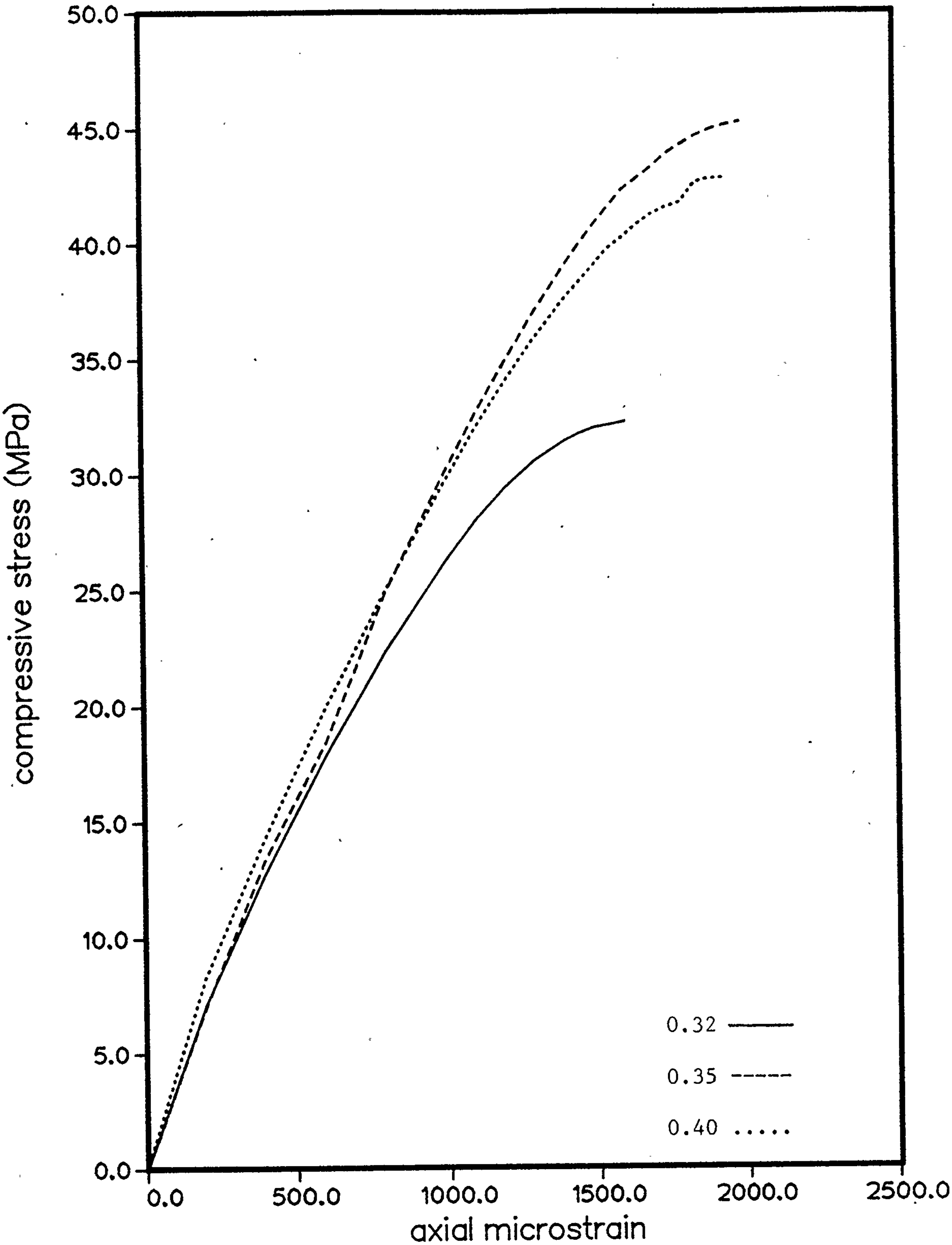


Figure 7.1 Effect of water cement ratio of the bond on the stress/strain curve of a slant shear prism

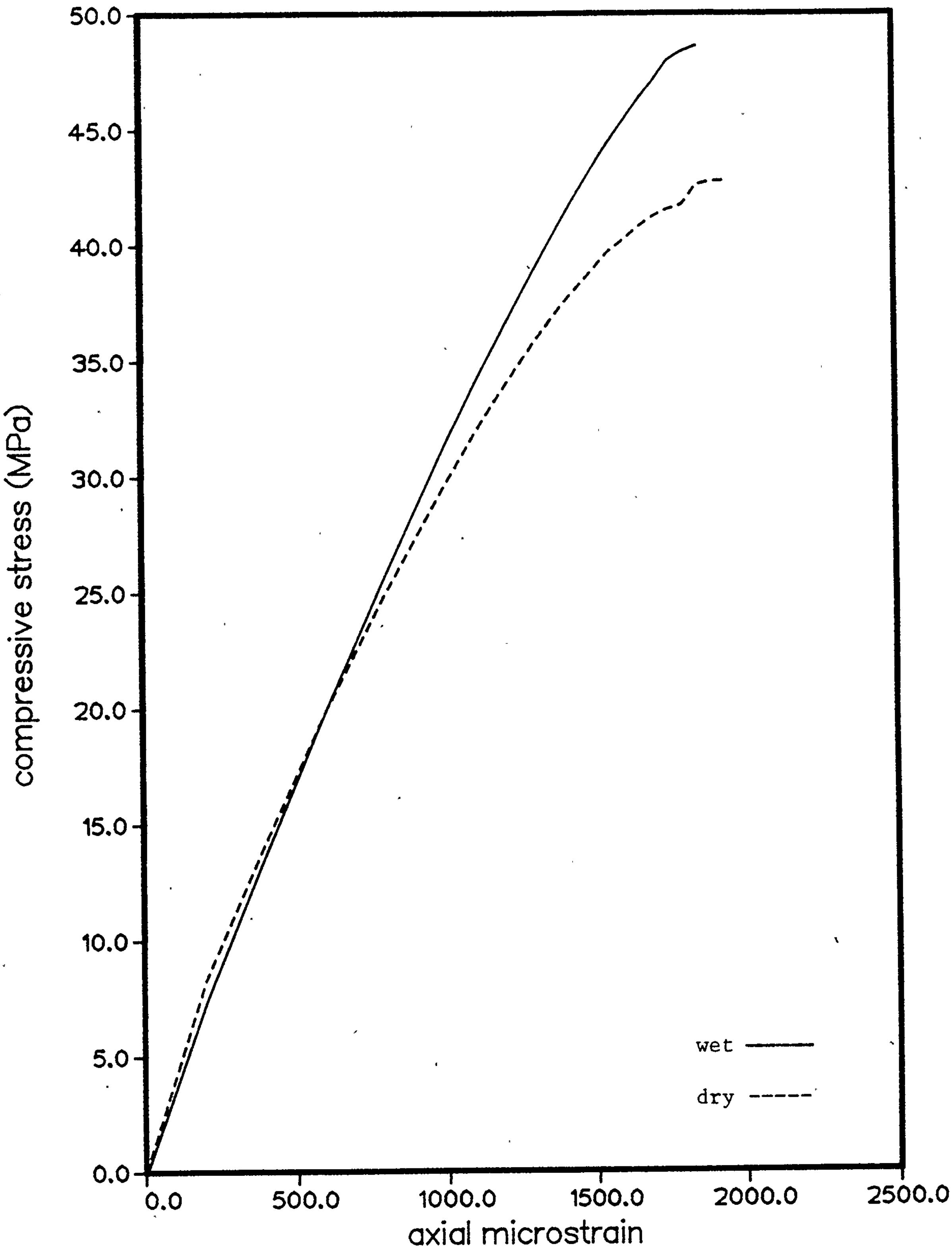


Figure 7.2 Effect of surface moisture condition on the stress strain curve of the slant shear prism

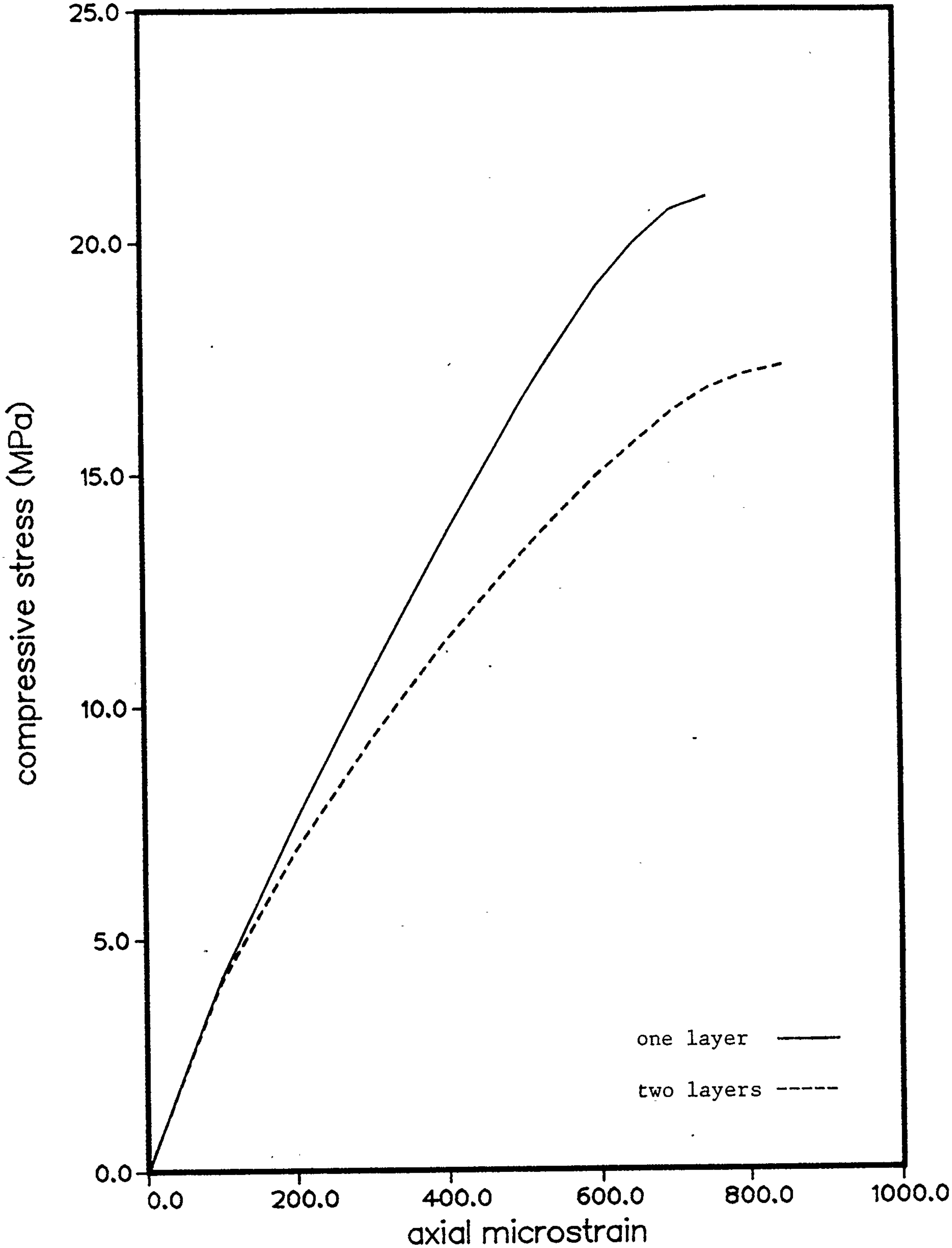


Figure 7.3 Effect of application technique of PVA paint on the stress/strain curve of the slant shear prism

The effect of a delay in application of a PVA paint also produced a small but highly statistically significant decrease in stiffness and is shown in Fig. 7.3.

As might be expected the strains of the prisms bonded together without the aid of a bonding agent were low but highly variable which made statistical comparison impossible. Results from this series of tests also suggest strains for the portland cement bond mortar used in the first series of tests may be higher than for most mortar bonds. The results indicating that the PVA paint was very flexible in the first series of tests are not contradicted, however, since no similar combination of bond and curing conditions was used in this test series.

7.2.3. Concrete and Mortar Controls

As mentioned in section 5.5 the concrete strength is not critically important unless it is less than the bond strength. Table 7.3 shows the average strengths of control cylinders for the base and overlay concrete batches. These strengths were assumed to be comparable to the prism strengths since it was found by experiment that the average strength of the unjointed slant shear specimens closely matches that of the cylinders.

The mortar strength results are shown in Table 7.6. The standard 0.35 water cement ratio portland cement mortar used in batches B11, B12, B13 and B23 had very consistent average strengths of between 70 and 74 MPa, far above that of the concrete even after accounting for the greater confinement present during the cube test. As expected, the strength was slightly lower for the 0.40 water cement ratio

Table 7.6 Mortar cube strengths

Bond (Designation)	Active Ingredient	Thickness (ins (mm))	Water Cement Ratio of Bond Mortar	Curing Period after 24 hrs (Days) 100% RH/ 50% RH	Avg. Compr. Strength (MPa)	Stand. Dev. (MPa)
B10	No Bonding Agent			27/0		
B11	PC	3/16 (4.8)	0.35	27/0	73.5	4.73
B12	PC	1/4 (6.4)	0.35	27/0	73.8	4.20
B13	PC	1/8 (3)	0.35	27/0	70.4	3.74
B14	PC	1/8 (3)	0.40	27/0	69.9	5.64
B15	PC	1/8 (3)	0.32	27/0	78.7	3.05
B16+	PVA	Paint	-	13/14	-	-
B17+	PVA	Paint*	-	13/14	-	-
B18+	PVA	1/8 (3)	0.20	13/14	20.1	1.86
B19+@	PVA	1/8 (3)	0.20	13/14	21.0	1.73
B20+	PVA	1/8 (3)	0.22	13/14	22.2	1.53
B21+@	PVA	1/8 (3)	0.22	13/14	25.5	1.18
B22+	PVA	1/8 (3)	0.22	27/0	13.4	3.68
B23+	PVA	1/8 (3)	0.40	27/0	70.8	3.68

PC portland cement
\+ substrate was wetted
* 2 coats
@ PVA pot life expired

mortar (approximately 70 MPa) and slightly higher (78.7 MPa) for the 0.32 water cement ratio mortar.

The PVA based mortars were much weaker. With a water cement ratio of 0.2 and cured under a tarpaulin for the first 24 hours, in 100% relative humidity for 13 days and then 14 days at 50% relative humidity (B20), the cubes developed average strengths of only 23.3 MPa and 21.0 MPa for the 2 identical batches. When exposed to 100% relative humidity for the last 27 days (B22 (1) and (2)) the average strengths were even lower, 13.3 and 13.5 MPa respectively.

The cubes cast after the pot life of approximately 40 minutes had expired (B19 and B21) had slightly higher strengths than their counterparts (B18 and B20) which were cast on time.

7.2.4. Other Factors Affecting Results

Several of these factors are the same as discussed in Sec. 5.2.2. and therefore will not be repeated here.

The prisms with a PVA based bond and cured in 50% relative humidity for the final 14 days before testing were tested immediately after removal from the 50% relative humidity environment. As a result, those prisms might yield a higher apparent strength than specimens cured at 100% relative humidity and containing 100% moisture content during the testing. However, the cement will not have hydrated as much in the 50% relative humidity environment as the 100% relative humidity environment. Neville (1981) shows data which indicate the moisture content of a specimen does not drastically affect the recorded strength for moisture contents above 50%. Some of the control specimens from batch B19 were cured under two different regimes. Three of the concrete specimens were cured for 13 days at 100% relative humidity and 14 days at 50% relative humidity, while the other three were cured for 27 days at 100% relative humidity. All the specimens were tested within 15 minutes of removal from their curing environments. The specimens cured at 100% relative humidity for the entire cure period had strengths less than 10% lower than the other specimens. This result confirmed the assumption that the curing difference affected the test strengths to only a small degree. Therefore, the conclusion that the PVA mortar bonds cured partially in 50% relative humidity are weaker than portland cement bonds is reinforced.

7.3. Conclusions

Several facts about the appropriate experimental procedure and the effect of various parameters on bond were found.

The ultimate loads provided the most useful information for evaluating bond performance. Stress/strain data provided information that was useful only in some instances, while stroke/load data were not useful or reliably accurate.

Conclusions about the effect on bond strength of the parameters investigated in this chapter are detailed in Chapter 8 (Conclusions).

CHAPTER 8

CONCLUSIONS

8.1. General

The conclusions are produced from the three main parts of the thesis:

1. selection of the most appropriate bond test;
2. finite element analysis of bonds using the test selected as most appropriate;
3. experimental analysis of bonds using the test selected as most appropriate.

In addition, recommendations for further research are also made.

8.2. Conclusions and Recommendations

The conclusions are first listed and then discussed in more detail. The conclusions are:

1. Of the four tests evaluated, the most sensitive and least variable method of testing for bond strength and flexibility is the *slant shear* test.
2. Bond materials with high moduli of elasticity cause higher compressive stresses at the bond line, and lower tensile stresses in the adjacent concrete, than bond materials with low moduli of elasticity.
3. Flexible areas of bond significantly increase stress in adjacent areas.

4. Casting procedures followed to produce the version of the slant shear test used for this thesis do not significantly contribute to errors in the results.

5. For portland cement mortar bonds, the thickness of the mortar layer has a highly significant effect on bond strength. An excessively thick bond will cause a considerable reduction in bond strength.

6. The treatment of the bond surface of the substrate concrete by pre-wetting appears to have a small beneficial effect on bond strength.

7. Copolymer PVA is a poor bonding agent over a wide range of curing conditions and mortar mix designs. Under the laboratory conditions employed, the use of PVA produced consistently weaker bonds than using no bonding agent at all.

The conclusion that the slant shear test is the most reliable and practical method for testing bond, is significant. Controversy over the best bond test method has existed for a long period of time.

A bond material which is stiffer than the adjacent concrete will have higher compressive stresses in the bond and lower tensile stresses in the concrete next to the bond, than a less stiff bond material. Therefore, a bond material with a modulus of elasticity that is similar to the adjacent concrete, is desirable. The high compressive stresses in a stiff bond may be acceptable, however, if the bond material is much stronger than the concrete. As expected, weak or flexible areas of bond create higher stresses in the bond and the adjacent concrete, compared to a bond of uniform stiffness, according to the finite element analysis.

The effect of thickness has not been studied as extensively in fresh concrete to hardened concrete, as compared to masonry. The finding that bond thickness, in a 3 mm (1/8'') to 6 mm (1/4'') range, has a strong effect on bond strength is of extreme importance. Therefore, maximum bond thickness limits of 3 mm (1/8'') specified by many highway departments are justified.

The effect of the substrate moisture condition on bond, when a portland cement bonding agent is used, has not been studied to any extent using the slant shear test. In addition, different opinions exist on whether the substrate should be kept dry or damp before bonding. Therefore, the result that a damp substrate provides a slightly better bond than a dry surface, when assessed using the slant shear test, is of interest. Thus, the practice of prewetting the bond surface is not critical.

Copolymer PVA based bonding agents used in both mortar and paint form are poor bonding agents. However, a delay between application of PVA based bonding agents and fresh concrete, did not affect bond strength adversely compared to the normal application procedure. The bond produced when the paint form of copolymer PVA is used is particularly weak. Use of copolymer PVA is not recommended.

8.3. Recommendations for Further Research

The following topics are worthy of further research:

1. The correlation between various microstructural properties of the concrete adjacent to the bond interface, and bond strength. This relationship should be studied for different water cement ratios of portland cement bonding mortar and different moisture conditions of the substrate.
2. The effect of salt contaminated substrate on bond strength.
3. The relationship between the sand cement ratio of portland cement bonding mortar on bond strengths.
4. The performance of portland cement mortar bonds subjected to sustained loads.
5. The finite element analysis of bonds using a non linear stress/strain relation.
6. The finite element analysis of bonds using different Poisson's ratios and elastic moduli for the concrete and the bond material.

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APPENDIX A

FINITE ELEMENT ANALYSIS OF INDIRECT TENSILE PRISM TEST

Finite element analysis was used to aid in the design of packing for application of the loads to the test prism. The finite element program used was FEMSKI, which uses a frontal solution technique. The mesh used to model the prism is shown in Fig. A.1. If the concrete on both sides of the bond has the same properties, then each quadrant of the cross-section of the test shown in Fig. A.2 will be symmetrical. Both top quadrants were included in the model in order to have available a check for symmetry. The mesh was designed to minimize elements with an excessively large aspect ratio, where practicable.

Hybrid quadrilateral elements were used to maximize accuracy in modelling stresses. All stresses were compared to the gross tensile stress found using the Brazilian test.

A proposal to load the 100 mm × 100 mm × 350 mm prism with 10 mm wide, 5 mm high steel strips was tested. Section A (Figs. A.3-A.4) is located perpendicular to the bond line and slightly below the top surface of the prism. Horizontal and vertical tensile stresses in section A are large a few millimeters away from the bond line. Horizontal stresses in section B (Fig. A.5) gradually increase as the bond is approached, providing a near constant tensile stress field adjacent to the bond. Large horizontal tensile stresses along the bond line are shown in section C (Fig. A.6). Although, an almost constant horizontal tensile stress near the bond will likely provide a good test of bond, the high tensile stresses next to the steel loading strip could adversely affect the performance of the test.

To reduce the tensile stresses near the point of load application, a 20 mm wide strip of plywood was placed between the steel loading strip and the concrete prism. The tensile stresses in section A (Figs. A.7-A.8) near the point of loading are reduced significantly compared to the tensile stresses generated without the plywood packing. Horizontal stresses in section B (Fig. A.9) gradually increase toward the bond, the same favorable pattern that was achieved without the plywood packing. Large horizontal tensile stresses are still present along the bond line (Fig. A.10).

As a result of the finite element analysis, the combination of a 5 mm high by 10 mm wide steel strip resting on a 20 mm wide plywood strip was chosen as the load application system.

A plot of the horizontal stresses at the vertical center line of the Brazilian test was determined by Wright (1955) and is shown in Fig. A.11. The stress distribution is very similar to those in the indirect tensile prism when steel and plywood packing is used.

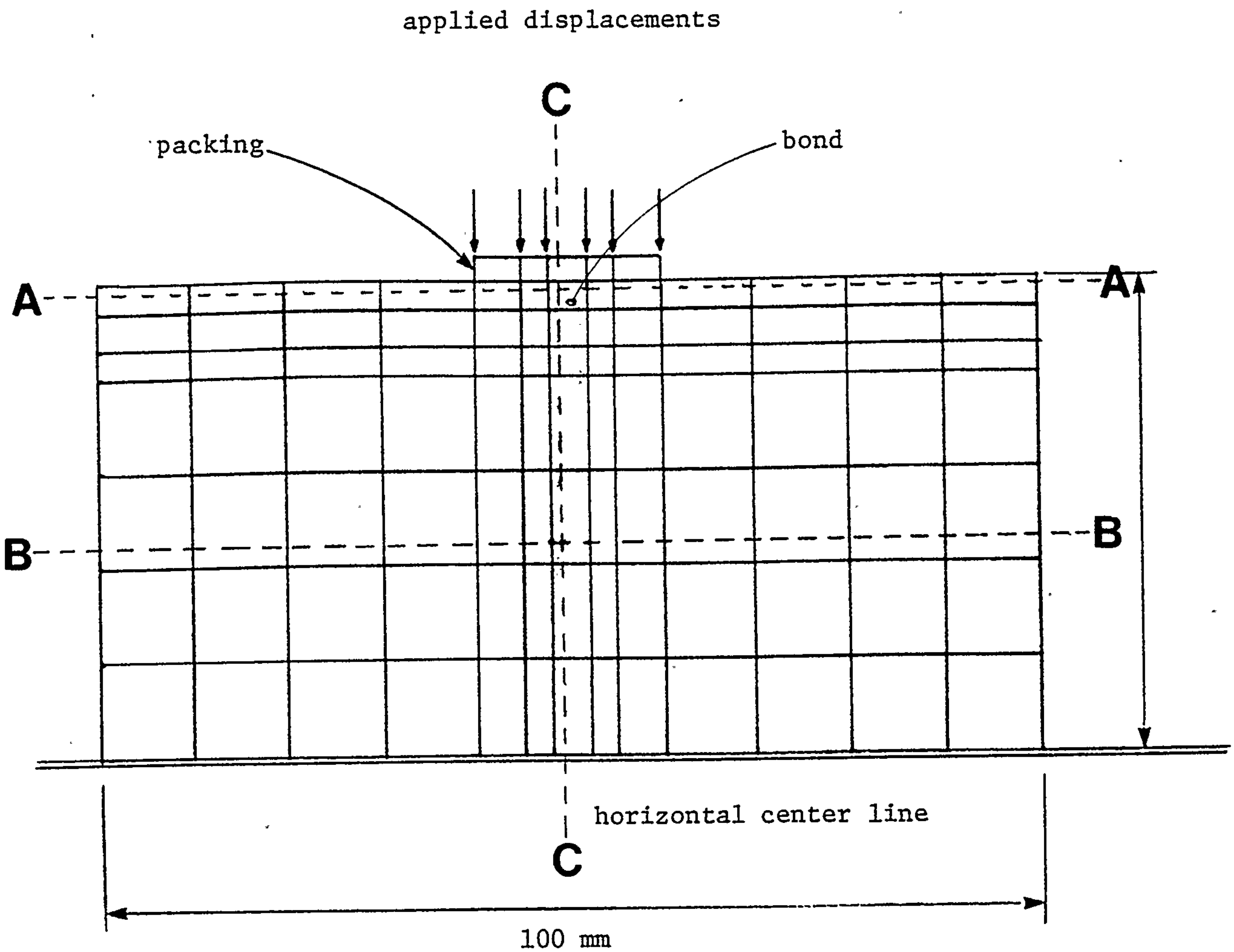

Figure A.1 Finite element mesh of indirect tensile prism

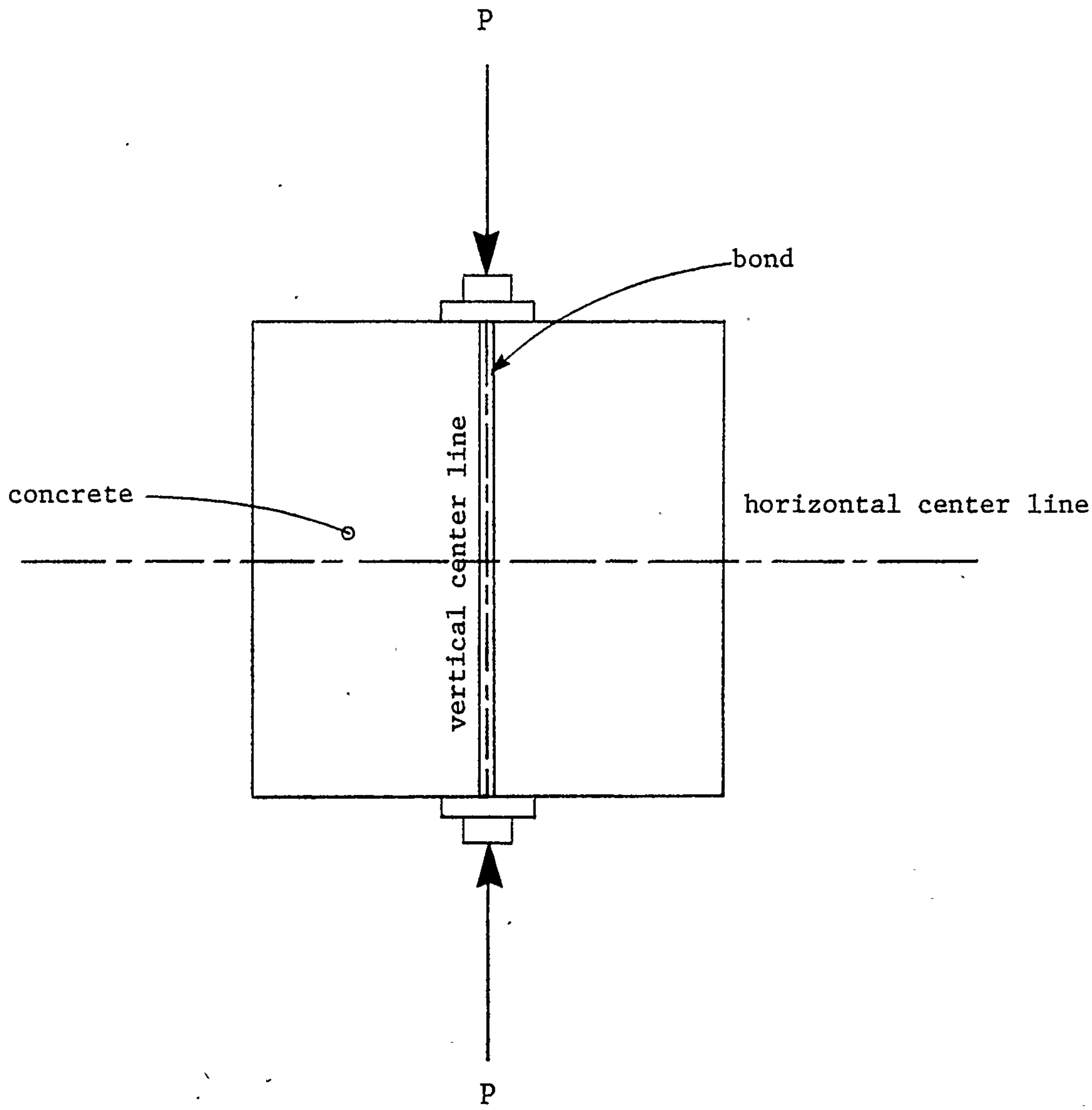

Figure A.2 Cross section of indirect tensile prism

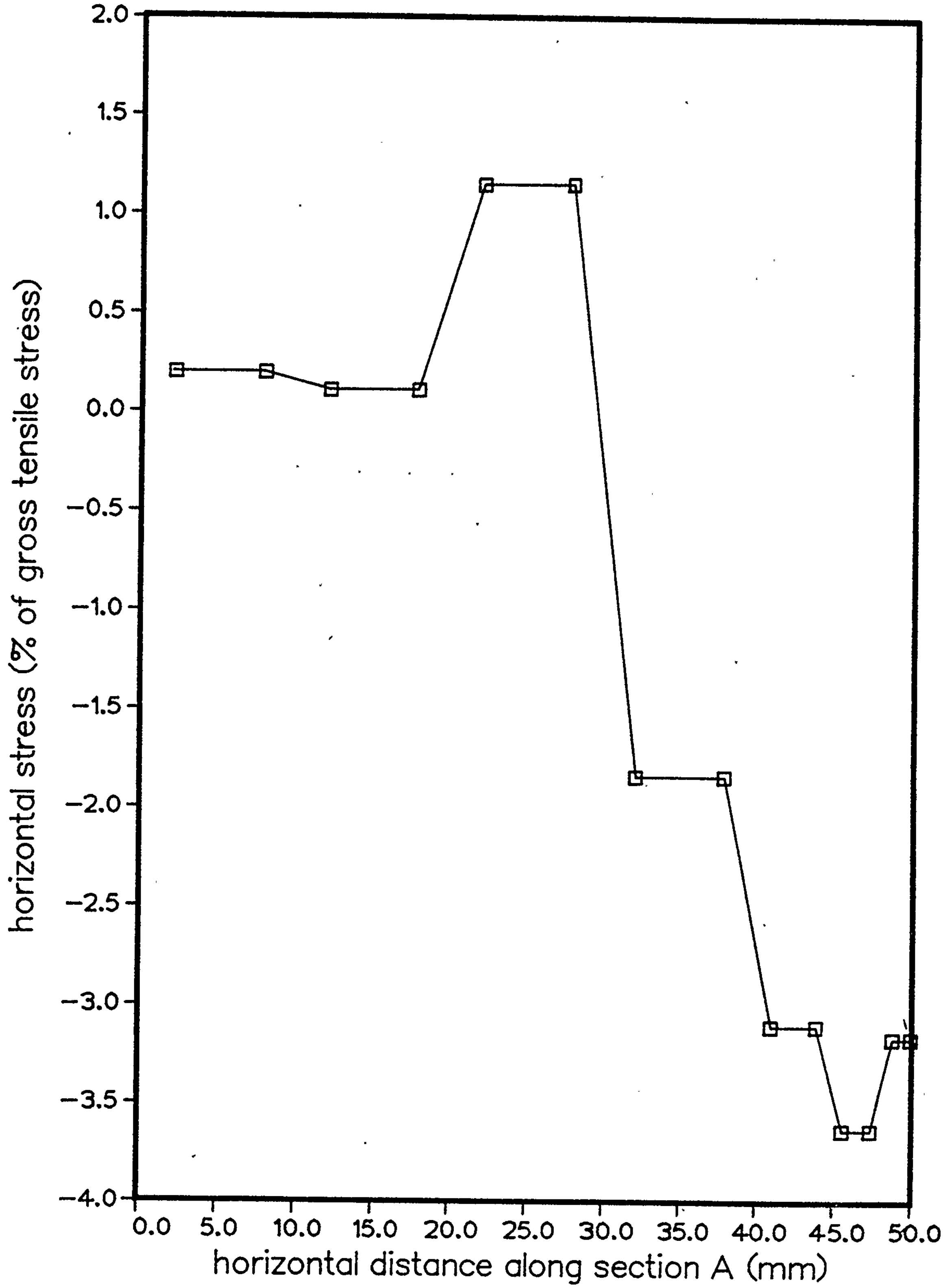

Figure A.3 Horizontal stresses along section A

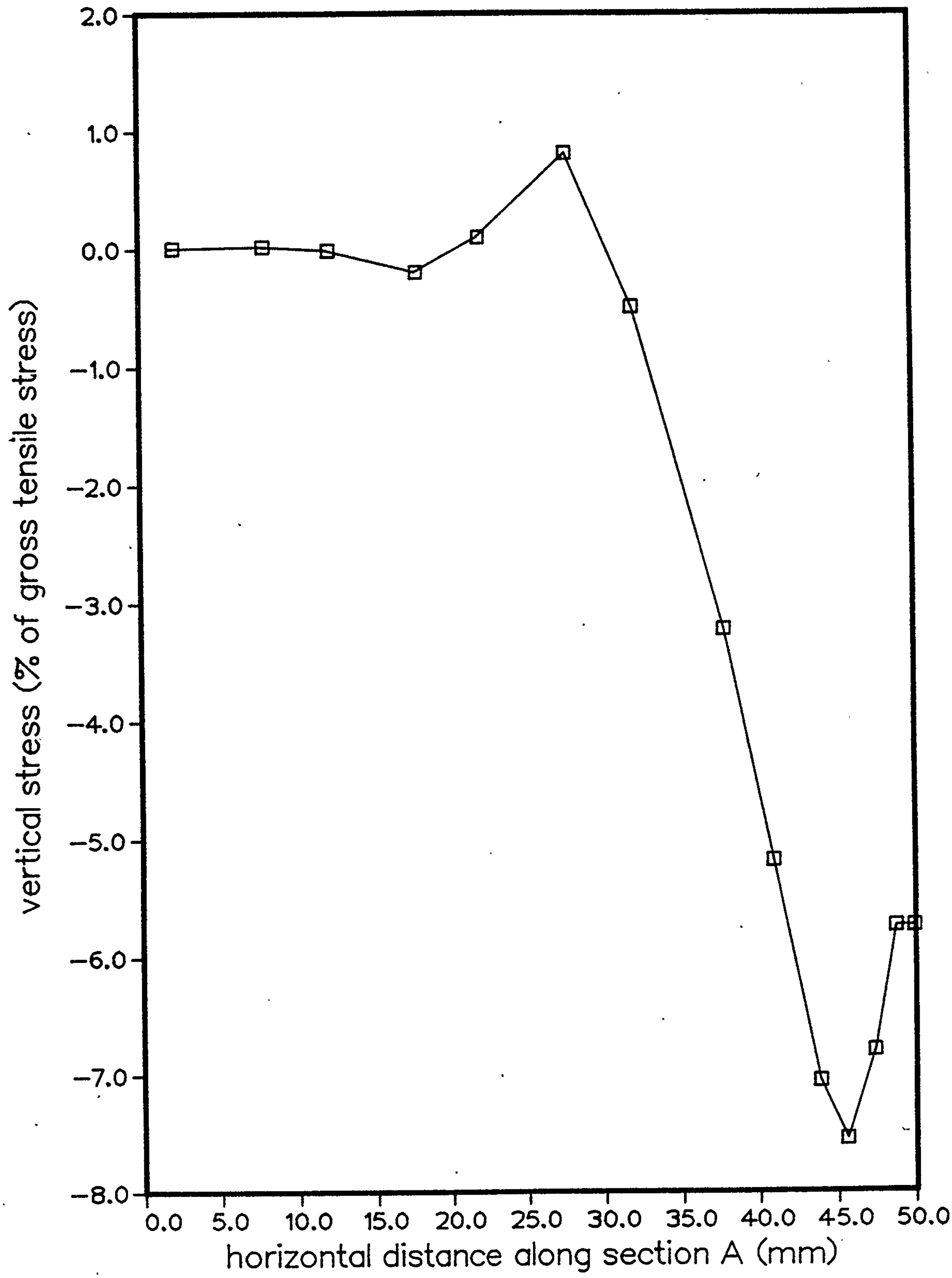

Figure A.4 Vertical stresses along section A

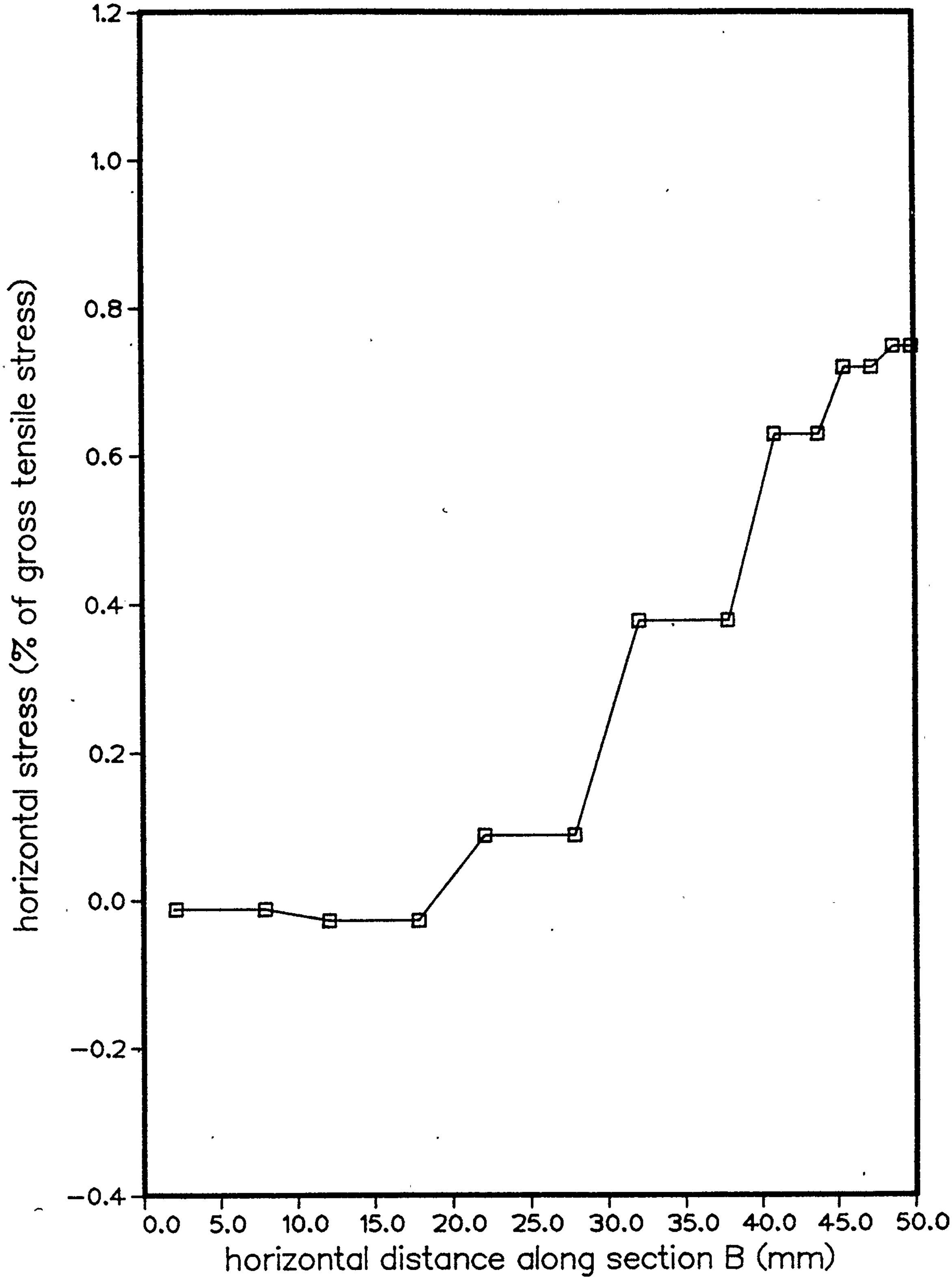

Figure A.5 Horizontal stresses along section B

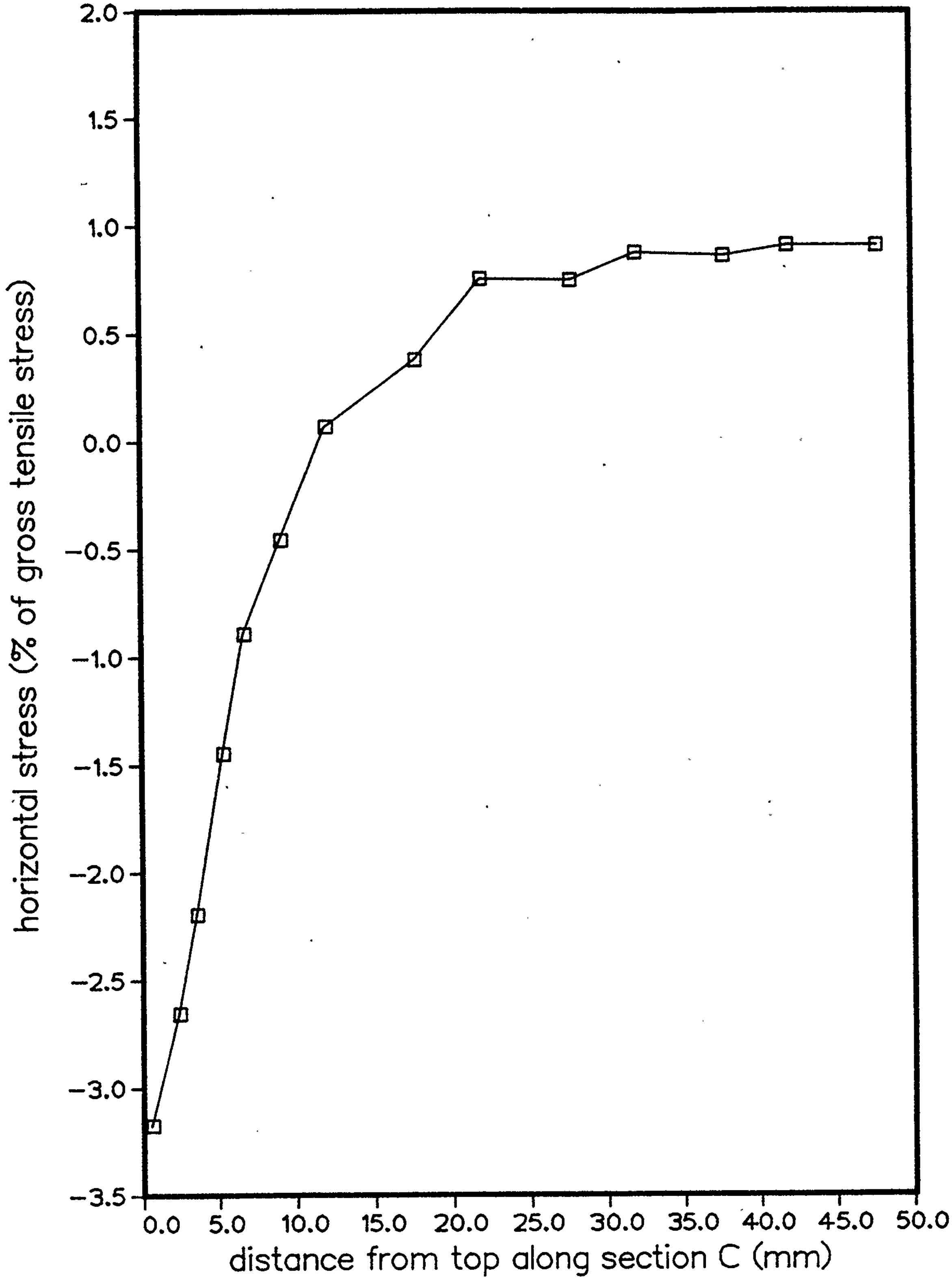

Figure A.6 Horizontal stresses along section C

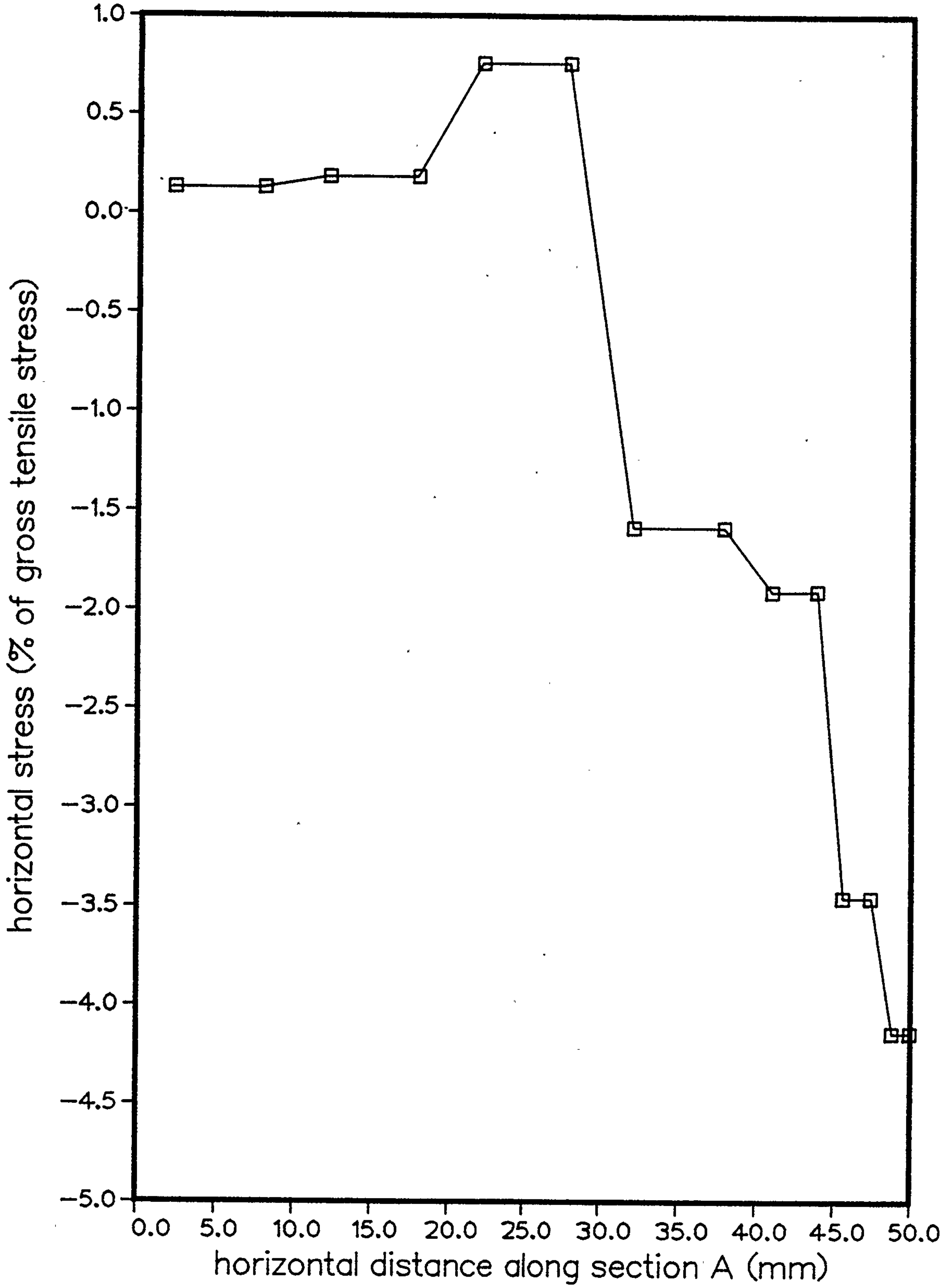

Figure A.7 Horizontal stresses along section A when plywood packing is used

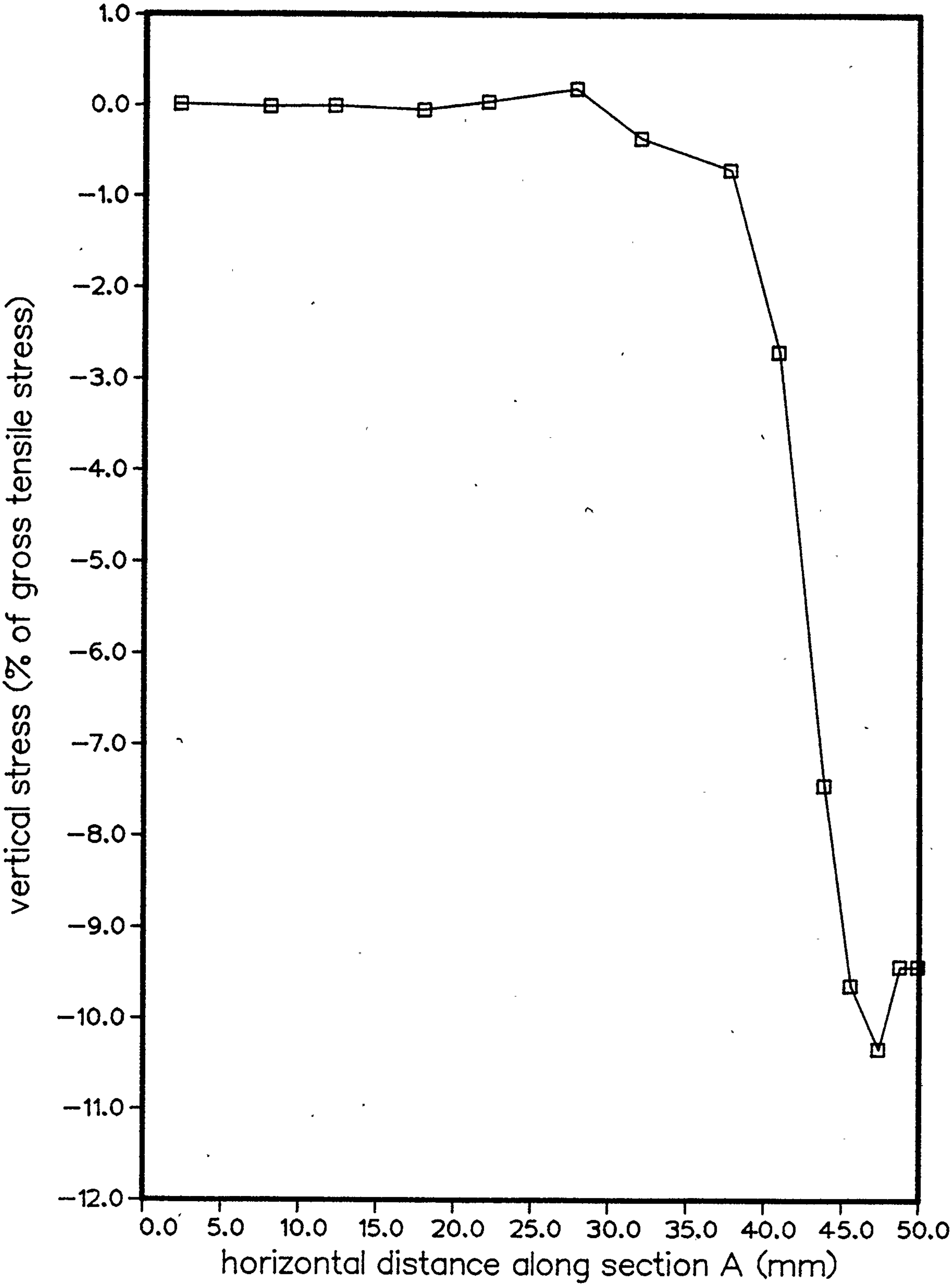

Figure A.8 Vertical stresses along section A when plywood packing is used

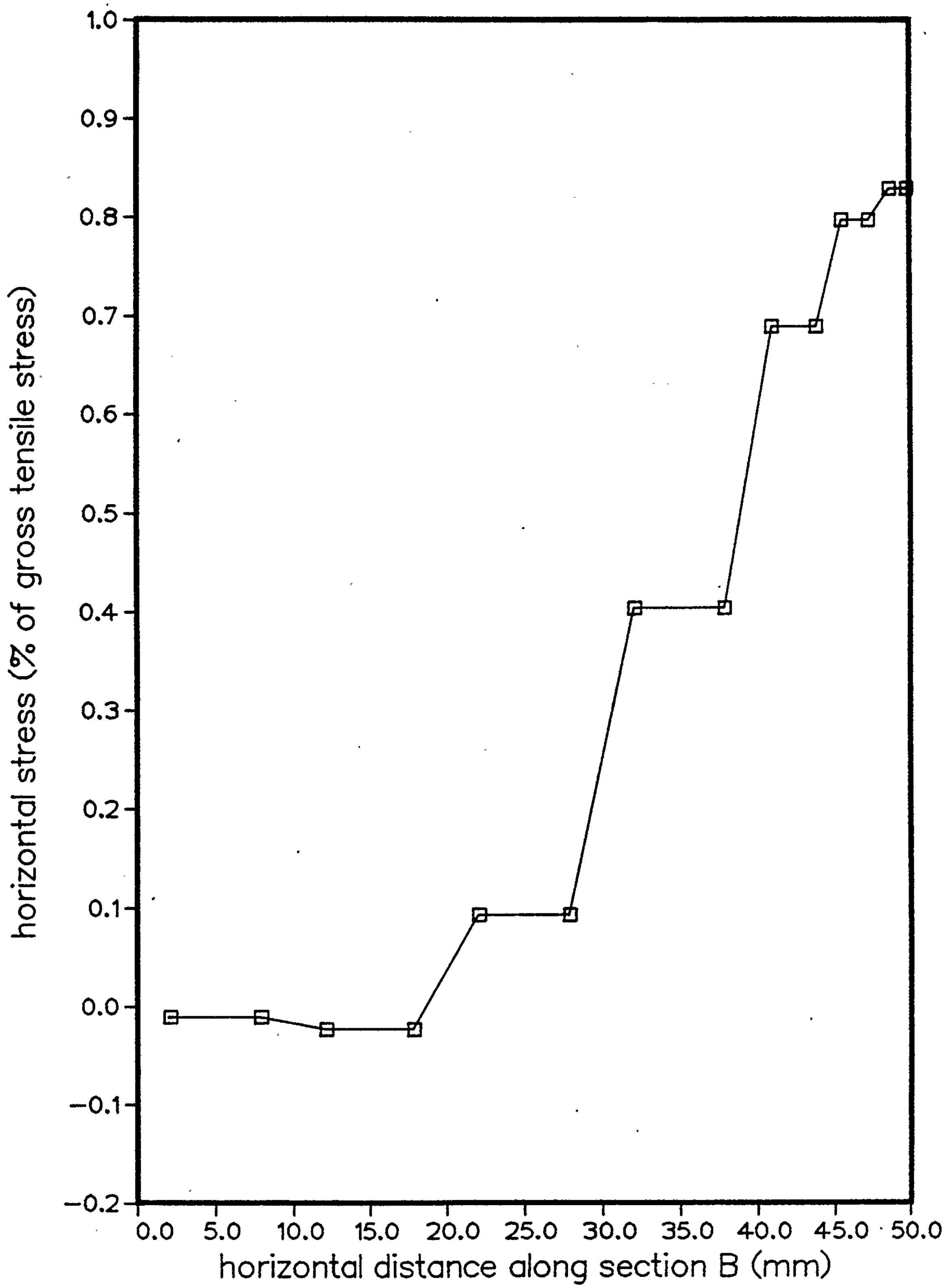

Figure A.9 Horizontal stresses along section C when plywood packing is used.

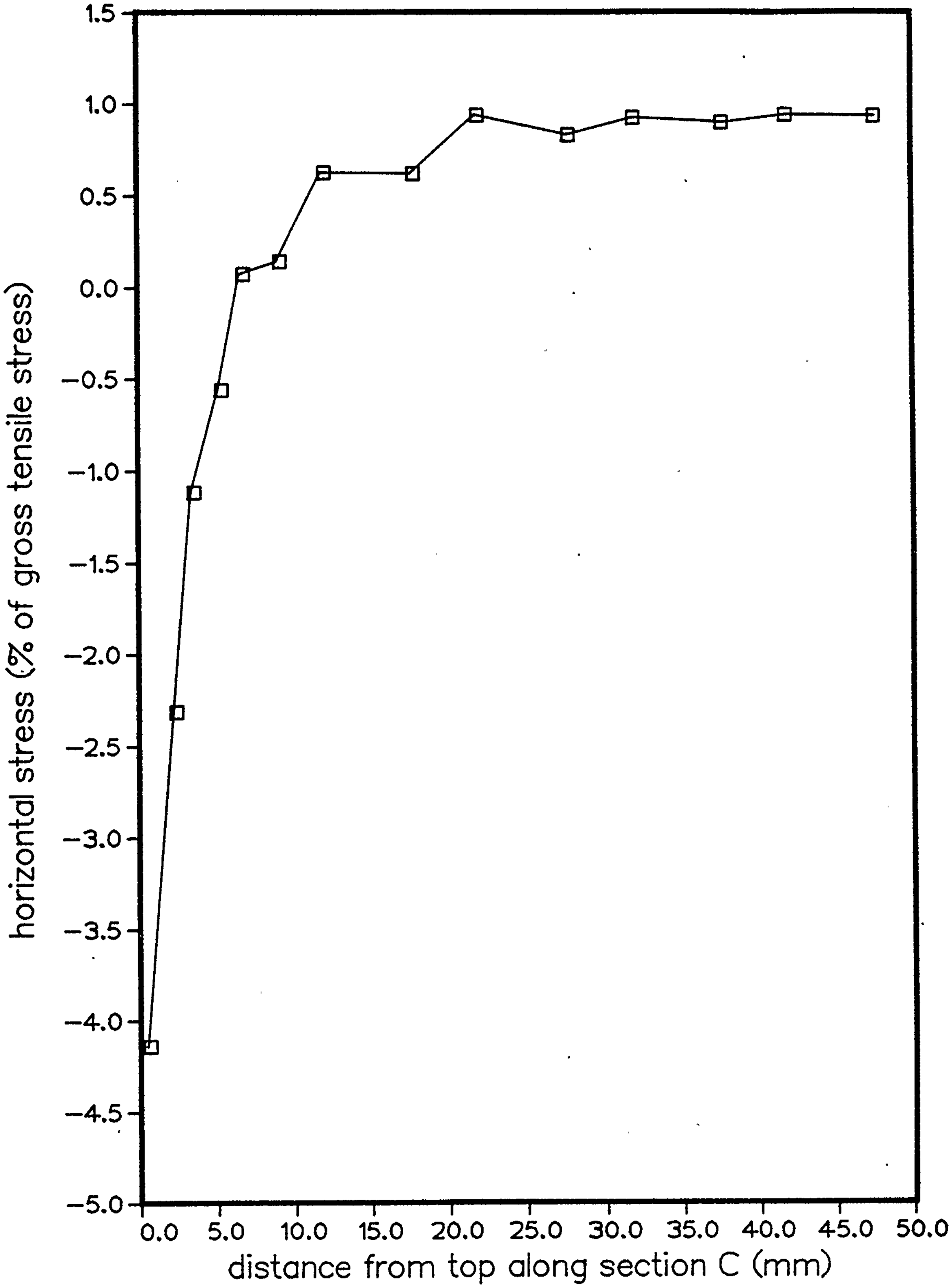

Figure A.10 Horizontal stresses along section C when plywood packing is used

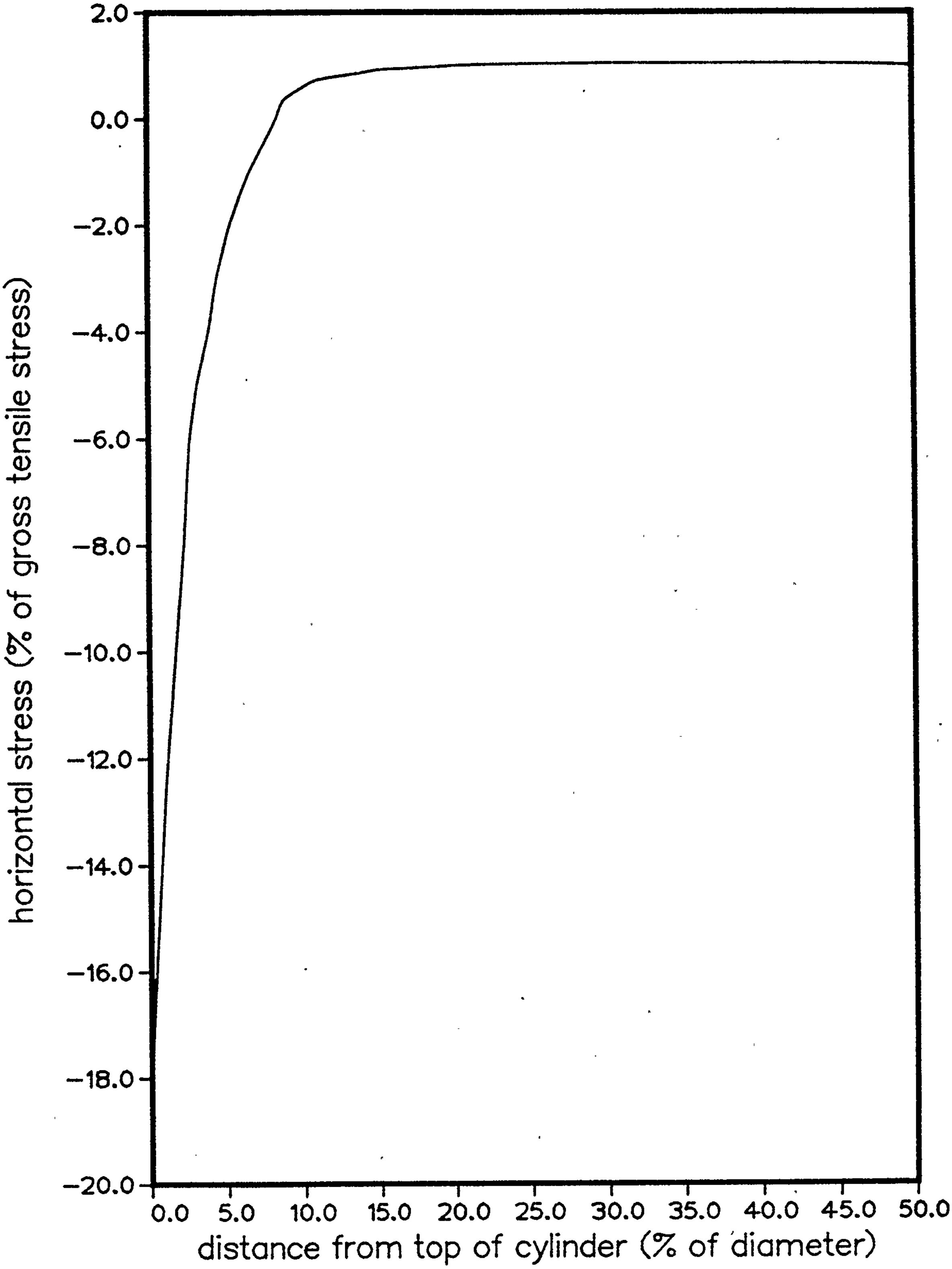

Figure A.11 Horizontal stresses at vertical center line of the Brazilian test cylinder; taken from Wright (1955)

APPENDIX B

INDIVIDUAL SLANT SHEAR STRENGTH RESULTS

Bond (Designation)	Active Ingredient	Thickness (ins (mm))	Water Cement Ratio of Bond Mortar	Curing Period after 24 Hrs (Days) 100% RH/ 50% RH	Specimen Strengths (MPa)
B10	NO BONDING AGENT			27/0	41.64
					38.75
					47.93
					46.88
					43.88
					42.36
					43.54
					42.9
B11	PC	3/16(4.8)	0.35	27/0	44.52
					46.38
					44.45
					45.15
					46.05
					44.37
					44.86
					44.85
B12	PC	1/4(6.4)	0.35	27/0	26.95
					44.15
					30.56
					38.58
					34.35
					39.45
					33.79
					31.22

Bond (Designation)	Active Ingredient	Thickness (ins (mm))	Water Cement Ratio of Bond Mortar	Curing Period after 24 Hrs (Days) 100% RH/ 50% RH	Specimen Strengths (MPa)
B13	PC	1/8(3)	0.35	27/0	43.78
					43.06
					44.89
					46.37
					44.10
					46.07
					45.71
					41.00
B14	PC	1/8(3)	0.40	27/0	42.55
					42.34
					42.34
					42.96
					42.66
					40.41
					39.85
					40.48
B15	PC	1/8(3)	0.32	27/0	32.30
					30.56
					30.73
					30.76
					32.91
					32.77
					30.29
					31.71

Bond (Designation)	Active Ingredient	Thickness (ins (mm))	Water Cement Ratio of Bond Mortar	Curing Period after 24 Hrs (Days) 100% RH/ 50% RH	Specimen Strengths (MPa)
B16	PVA	Paint	-	13/14	22.13
					19.81
					18.18
					21.97
					21.99
					21.08
					18.91
					17.40
B17	PVA	Paint	-	13/14	17.62
					18.21
					16.30
					18.23
					19.66
					15.43
					16.79
					17.20
B18	PVA	1/8(3)	0.20	13/14	34.74
					29.28
					35.01
					22.04
					30.53*
					31.71*
					37.36*
					34.33*

Bond (Designation)	Active Ingredient	Thickness (ins (mm))	Water Cement Ratio of Bond Mortar	Curing Period after 24 Hrs (Days) 100% RH/ 50% RH	Specimen Strengths (MPa)
B19	PVA (Pot life Expired)	1/8(3)	0.20	13/14	36.45+ 32.71+ 33.95+ 31.17+ 24.53 26.71 30.77 24.99
B20	PVA	1/8(3)	0.22	13/14	28.10 26.04 24.20 22.06 27.29% 26.34% 27.51% 27.27%
B21	PVA (Pot life Expired)	1/8(3)	0.22	13/14	25.51@ 27.78@ 30.19@ 28.32@ 23.31 27.07 24.40 24.31

Bond (Desig-nation)	Active Ingredient	Thickness (ins (mm))	Water Cement Ratio of Bond Mortar	Curing Period after 24 Hrs (Days) 100% RH/ 50% RH	Specimen Strengths (MPa)
B22	PVA	1/8(3)	0.22	27/0	17.73
					22.03
					21.76
					23.41
					21.75
					19.74
					19.30
					21.73
B23	PC	1/8(3)	0.40	27/0	48.64
					44.52
					41.00
					48.13
					28.90
					42.45
					49.53
					48.01

PC Portland Cement

* cast with concrete from B19

\+ cast with concrete from B18

% cast with concrete from B21

@ cast with concrete from B20

APPENDIX C

TECHNIQUE FOR STATISTICAL COMPARISON

The difference between 2 sets of results was analysed statistically using a modified version of the *t* statistic (from Walpole and Myers (1978)). The equation used was:

$$T = \frac{\bar{X}_1 - \bar{X}_2 - (\mu_1 - \mu_2)}{S_p\sqrt{(\frac{1}{n_1}) + (\frac{1}{n_2})}} \quad , \quad lower\ \ limit < T < upper\ \ limit \tag{C.1}$$

where

$$S_p^2 = \frac{(n_1 - 1)\, S_1^2 + (n_2 - 1)\, S_2^2}{n_1 + n_2 - 2} \tag{C.2}$$

where

$\bar{X}_1$ = experimentally measured mean of the first set of results
$\bar{X}_2$ = experimentally measured mean of the second set of results
μ_1 = actual mean of the first set of results
μ_2 = actual mean of the second set of results
n_1 = number of results in first set
n_2 = number of results in second set
S_1 = sample standard deviation for the first set of results
S_2 = sample standard deviation for the second set of results

If the value of T falls outside the two limits when μ_1 and μ_2 are set to equal each other a statistically significant difference exists.

The value of the lower limit and the upper limit are determined from the area under the tail sides of the *t* distribution. The value of the *t* distribution was determined from Table 5 in Walpole and Myers. In order to determine the value of t using the table, 2 parameters must be calculated. The first parameter, the number of degrees of freedom (ν) is determined by the equation $\nu = n_1 + n_2 - 2$. The second parameter (α) is a function of the degree of statistical significance desired. For a statistical significance of 95% $\alpha = 0.025$, and for a statistical significance of 99% $\alpha = 0.005$.

There are two assumptions necessary to use the modified t statistic:

1. the two populations being compared are normally distributed;
2. the two populations being compared have equal variances.

The second assumption does not need to be satisfied if the sample size taken from each group is the same. Since concrete and mortar properties are thought to be normally distributed a reasonable assumption is that they would have normally distributed properties when acting in composite.

In one case two sets of results were compared which had different sample sizes. As a result, another equation was used which is also based on the t statistic. The equation is:

$$T = \frac{\overline{X}_1 - \overline{X}_2 - (\mu_1 - \mu_2)}{\sqrt{(S_1^2/n_1) + (S_2^2/n_2)}} \quad , \quad lower\ \ limit < T < upper\ \ limit \qquad \text{(C.3)}$$

where all variables are defined as in equation C.1. The procedure remains the same as that used for equation C.1 with one exception. The equation for the number of degrees of freedom (ν) becomes

$$\nu = \frac{(S_1^2/n_1 + S_2^2/n_2)^2}{[(S_1^2/n_1)^2/(n_1 - 1)] + [(S_2^2/n_2)^2/(n_2 - 1)]} \tag{C.4}$$