RESEARCH REPORT

Tests of Full Scale Brick Veneer Steel Stud Walls to Determine Strength and Rain Penetration Characteristics

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Mr. Wilson's M.Eng. thesis, "Structural Behaviour and Rain Screen Performance Wall Systems", McMaster University, 1990 was used as the basis for this report.

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ABSTRACT

The design, construction and physical testing of five full scale (2.75 m × 5.2 m) brick veneer rain screen wall specimens are reported. Also, the documentation of the design and fabrication of a new test apparatus and of the development of test procedures are major components of the report. The test program included sequences of air pressure loading stages both with and without simulated rain to establish both the structural and rain penetration performances of the test walls. The test walls included four brick veneer/steel stud specimens and one brick veneer/concrete block specimen. Additional tests were performed on bricks, mortar and masonry assemblages to define relevant characteristics.

The design and construction of the wall specimens were consistent with current practices in order to assess the appropriateness of these practices. The major points addressed in the report relate to the vulnerabilities of the wall system to excessive rain penetration and resulting moisture damage. In line with these concerns, the likelihood of veneer cracking, the impact of cracking on structural behaviour and on rain penetration and the importance of cavity compartmentalization were addressed.

The conclusions indicated that brick veneer rain screen walls are vulnerable to rain penetration if adequate air tightness in the backup and clean comparted cavities are not provided. Also, it was concluded that veneer cracking is likely under full design loads. It is recommended that the design should address the properties of the brick veneer/backup wall system and that the veneer deflections should be limited to control the size of cracks.

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INTRODUCTION

1.1 GENERAL INTRODUCTION

Brick veneer with concrete block or steel stud backup systems forms a major portion of the cladding systems constructed today, whether the application is residential, industrial, commercial, one storey or highrise building. Over the past two decades, the market share brick veneer/steel stud (BV/SS) wall systems has increased significantly. The reasons for this trend are complex and involve the availability of material and labour, short term economic considerations, regional factors or merely the designers' personal preferences. However, from documented performances and evaluations[31,43,46,47,48] of early BV/SS wall construction, it is clear that implementation preceded due consideration of the systems' limitations or vulnerabilities to moisture damage.

Wind driven rain and the corresponding lateral loading are often identified as sources of problems in existing wall construction. Damage to the backup and veneer have often resulted in legal action against contractors and designers. In cases of irreparable damage, veneer has had to be replaced at a costs significantly greater than the original construction costs.

Concern over the performance and long term integrity of BV wall systems is not only an economic issue, but one borne out of concern for the safety of the general public. Brick veneer is normally not designed to resist structural loads. However provisions are necessary to ensure adequate anchorage and integrity during exposure to wind or seismic forces. The greatest safety hazard occurs when spalled, crumbled, cracked or loose masonry falls from the building endangering those below. The actual number of accidents is not documented, however evidence of deteriorating masonry and the occasional missing unit or portion thereof is not uncommon. Since the deterioration of brick masonry is often related to moisture problems, serviceability performance requirements and corresponding construction details are needed.

In recognition of the general lack of knowledge of the wall system's behaviour and the lack of adequate design requirements, many studies have been carried out to examine the BV/SS issue. As Part of a major Canada Mortgage and Housing Corporation/McMaster University (CMHC/McMaster) research program, the research documented in this report was focussed mainly on examining the performance of five full scale BV wall panels tested under the influence of wind driven rain and air pressure loading. Four BV/SS and one BV/CB wall panels were designed and constructed to represent present day practices and details.

In order to examine the rain penetration and structural behaviour of the wall systems, a test apparatus and test procedures were required. Currently, standard methods for testing BV wall systems do not exist. Therefore, the development of a test apparatus and of test procedures were significant parts of this research.

The test program was preceded by two earlier experimental investigations[33,36], at McMaster University, aimed at establishing the behaviour of individual wall components such as: wall ties, steel studs, steel stud connections and steel stud/gypsum board panels. Thus the behaviours of these components as part of the overall behaviour of the wall system can be compared to their behaviour in isolated test conditions. Such comparisons can help determine whether isolated tests of components adequately represent their behaviours as part of the complete wall system.

1.2 BACKGROUND INFORMATION

As background to the topics addressed in this report, sources of moisture and design issues related to the performance of exterior masonry walls are discussed. In addition, a brief synopsis of research literature relevant to this study is provided.

1.2.1 Moisture Sources in Masonry Construction

There are many ways for moisture to accumulate in exterior walls. Moisture in walls resulting from vapour diffusion has been studied extensively[52, 7,58,70,77,78]. In the presence of a vapour pressure gradient across a wall resulting from different interior and exterior humidity or temperature levels, vapour passing through the wall will condense on the warmest plane below the dew point temperature. To prevent vapour diffusion, provision of a vapour barrier has proven to be an effective practice. However, in past practice, vapour barriers have not normally been designed to share in load resistance and have often been unsupported. Consequently, tears or punctured holes in it have allowed considerable air leakage.

Although vapour diffusion was identified as a significant source of moisture condensation, it is now understood that in the Canadian winter climate, the exfiltration of warm humid air is much more critical. Simple analyses, assuming isothermal conditions and continuity of vapour flow, show that only a minor accumulation of moisture resulting from vapour diffusion is possible compared to the condensation from leakage of humid air[34]. This observation is confirmed a number of times in the literature[52,58,71,77].

Prevention of the flow of humid air through a wall system or a building envelope is accomplished with a continuous plane of air tightness, or an air barrier. Moisture in exterior walls resulting from condensation and diffusion are not within the scope of this study. However, the possibly more damaging effects of rain penetration are studied. As will be discussed, there is a relationship between the air tightness of the building envelope and the potential for rain penetration.

1.2.1.1 Rain Penetration

Rain penetration of exterior walls and the mechanisms by which it occur are outlined in the literature[40,70,74,76]. There are two forms of rain penetration, through-wall and partial rain penetration. However, for veneer wall systems employing the open rain screen concept, partial rain penetration of the wall is the topic of interest. This rain penetration can occur as a result of any one or combination of direct flow, gravity flow, capillary action or a pressure differential.

1) Direct Flow

Wind can blow rain against a building with a certain velocity. This gives the rain drops momentum that can force the droplets of water through openings in the exterior wall. These openings could be wall vents, weep holes or large cracks. Reduction in the size of the openings or installation of a mechanical device, such as a baffle, to shatter the water droplets or merely to obstruct the straight passage are popular methods used to reduce direct flow of water into the wall.

2) Gravity Flow

As a mechanism of rain penetration, gravity flow alone usually is not a problem. Water flows under the influence of gravity and proceeds by the path of least resistance. Simple flashing details can be used to direct downward flowing water away from vulnerable material. This mechanism is used to drain water from the cavity through weep holes preventing damage to the interior construction of the building. It is important to locate vent holes and other openings away from paths of high surface water flow such as at the edges of window ledges.

3) Capillary Action

Capillary action is complex and is difficult to envision in a material such as masonry possessing small unconnected pores of limited length. Nonetheless, the contribution to partial rain penetration by capillary action does exists. However, this mechanism requires external forces to release the capillary water. Small fire cracks and fine fissures found in masonry are usually not a major contributor to movement of water by capillary action. It is reported that these low volume reservoirs hold the water with capillary forces much greater than those held by poorly bonded interfaces[41,74].

4) Pressure Differential

Probably the dominant driving force leading to the majority of rain penetration problems is air pressure differential. An air pressure differential can supply the necessary force to discharge capillary water, force water along a wall opening or accelerate or redirect gravity flow. The main cause of air pressure differentials is wind pressure although stack effect and mechanical ventilation have some influence[85,86,87].

Positive pressures on the windward side of a building are most critical for rain penetration considerations. The actions taken to minimize the effect of this driving force are to provide an open cavity and sufficient wall openings to allow the cavity pressure to equalize with external conditions. The wind pressure is then transferred to a plane of air tightness (an air barrier) in the backup wall, while the rain is intercepted by the veneer. This type of construction is known as the open rain screen.

1.2.1.2 Open Rain Screen Principle

The open rain screen principle is used to protect building materials from wind driven rain through pressure equalization of an open cavity, between the cladding and the air barrier.

Equalizing the cavity pressure with the exterior air pressure removes the pressure differential across the cladding[37,38,59,70], which is the main driving force causing rain penetration. The driving force, the pressure differential, is moved to the dry plane of air tightness in the backup wall. Successful application of this principle is jointly dependent on achieving pressure equalization in the cavity and adequate air tightness of the air barrier. If the cavity pressure is to be rapidly equalized with changing exterior pressures, two conditions must be satisfied:

1. An adequate plane of air tightness in the backup wall is required.
2. Vent openings in the veneer must be large enough to allow sufficient air flow to achieve pressurization.

Application of the open rain screen principle is a protective measure against rain penetration occurring under the action of an air pressure differential. However rain may still, and probably will, penetrate the veneer. It is required that this water be directed back out of the cavity by providing suitable flashing details and clear weep holes at the bottom of the wall. If the wall, designed using open rain screen, is properly designed and constructed, the incidental leakage occurring through the veneer openings should not cause deterioration.

If an open rain screen wall does not have an adequately air tight backup wall, a very severe condition for rain penetration exists. In this instance, even for a very small air pressure differential across the veneer, air flowing through the wall will carry water into the cavity. Once inside the cavity, the air pressure differential across the backup wall can carry water into and through the backup wall.

Practically speaking, neither full pressure equalization of the cavity nor perfect air tightness in the air barrier can be assured. However, what must be provided in order to achieve near instantaneous cavity pressurization, is an open comparted cavity and a plane of air tightness that is much less air permeable than the cladding.

Analytical studies[56] indicate that instantaneous cavity pressurization is possible where the air barrier has accidental openings of only one tenth the area of the openings in the exterior cladding. Although this result is useful in assessing cavity pressurization provisions, it should not be used to judge air tightness. As previously discussed, an air barrier also controls the exfiltration of warm humid air. Limits on the allowable air permeability of the material and the freedom from flaws in the construction must address both functions.

The cavity in an open rain screen design must also be comparted in order to attain pressure equalization with the external air. Even if perfect air tightness is achieved in the backup wall, a lack of compartmentalization will reduce the benefits of a open rain screen design. Compartmentalization can be accomplished by partitioning the cavity horizontally at every storey and vertically at corners and other locations within each storey level. The importance of this detail cannot be overstated. It is most critical at building corners where negative side wall pressure will permit air flow from the windward wall area thereby drawing water into the cavity.

1.2.2 Review of Research Related to Permeance of Masonry

The literature review pertaining to masonry permeance included previous tests to determine the permeability of brick masonry assemblages, documentation of the rain screen principle as it applies to exterior masonry walls, and previous investigations on the permeance of masonry walls.

1.2.2.1 Permeability of Brick Assemblages

As early as 1934, the permeability of masonry construction was questioned. Voss[82] presented the hypothesis that "leakless" masonry was possible provided a bond layer, dependent upon brick and mortar characteristics, of unknown substance or chemical composition develops. The optimistic nature of Voss' work was offset by the experimental work of Palmer and Parsons[68] during the same year.

Palmer and Parsons tested 8-inch (200 mm) brick wallet specimens under a constant head of 1 inch (25 mm) of water. It was observed that joint filling was critical and the paper reported that 73 per cent of the leaks occurred at the intersection of vertical and horizontal mortar joints. Discussion by Connor[68] criticized the authors for not constructing the specimens in a standard manner.

It was suggested that by building the wallets one brick at a time, as opposed to spreading enough mortar to set several units at once, the influence of the water retentivity of the mortar had been limited. The results indicated that the best results were achieved with bricks having low initial rates of absorption without regard for the mortar's water retentivity. Conner claimed that the combination of low absorption units and mortar possessing high water retentivity could not be conducive to satisfactory performance.

Connor, at the same time, examined 38 existing buildings[30] constructed with 7 different mortar mixes and 36 different makes of brick. It was reported that separation cracking was the major cause of water penetration through masonry. Separation cracking was described in the paper as a condition of lack of adhesion between the brick and the mortar, at the exposed surface of the brickwork, without regard for the cause.

Later work in 1946, by McBurney et al[61] addressed the influence of initial rate of absorption of the brick on the permeability of masonry. Three mortar mixes were used, with low, medium and high lime contents, along with ten different types of bricks. The permeability tests conducted were similarly to Palmer and Parsons' work and demonstrated superior results for high cement-low lime mortars. Again, Connor criticised the research and proclaimed the results "valueless" and acknowledged them as "little more than laboratory curiosities". Connor's main objection stemmed from the "excellent results" reported for high cement-low lime mortar used in conjunction with low absorptive units, a performance that was in complete contradiction to the observations from his field investigations.

In 1948, Conner[29] published the results of another field survey, this time covering 91 buildings. New information presented included 31 cavity walls of which 30 where found to be moisture proof. In his paper, Conner failed to note the significance of cavity walls and in reply to written discussion cited other favourable factors such as mortar and brick type as accountable for the moisture proof performance. There was no indication of whether the cavity walls were designed using the open rain screen principle.

Grimm[45] prepared an extensive review of the literature on the water permeance of masonry walls in 1980.

1.2.2.2 Literature on the Rain Screen Principle

Although the rain screen concept existed earlier, in the 1960's it gained attention in Canada. In 1963 Garden[41] described the rationale for the rain screen principle as it applied to exterior walls. In 1973 Latta[59] presented the details from five existing buildings with rain screen walls from Eastern Canada, where wind-driven rain is common. The deteriorating effects of wind driven rain were reported by Robinson and Baker[75] in 1975. The report emphasized water penetration, dirt marking and deterioration of building elements. In the same year, the Alderly Manor apartment building in Nova Scotia drew considerable attention to rain leakage problems as reports of excessive deterioration and building failure were produced by Cowie[31,32], Haseltine[48], and Grimm[43]. It was recognized that further study into the performance and behaviour of the elements that comprise the rain screen design were required.

1.2.2.3 Experimental Investigations

The amount of experimental work on either full scale laboratory specimens or existing walls is very limited. However reports from three countries were reviewed and are discussed below.

1) United States

In 1980, two test programs provided data on water permeance of masonry. Ribar[73] tested sixty-six walls composed of 8 inch (200 mm) concrete block and 4 inch (100 mm) clay brick built solid with a 3/4 inch (19 mm) collar joint. Tests, conducted in accordance with ASTM E 514 (Standard Test Method for Water Penetration and Leakage Through Masonry[8]), indicated that all mortar types performed satisfactorily. It was also reported that, contrary to earlier hypothesis on masonry permeance, there was no correlation between the bond strength of the masonry and water permeance. The paper recommended that ASTM E 514: require specific mortar composition and flow, require a record of the wall design, establish a criteria for workmanship and materials, change its rating system, change the curing conditions and change the rain exposure conditions.

Brown[17] tested twelve masonry walls, constructed of both clay brick and concrete block. Tests conducted in accordance with ASTM E 514 were carried out both before and after coating with a proprietary clear water repellant. Of the six single wythe brick walls, three were constructed using masonry cement and three with Portland cement-lime mixes. The maximum leakage rate reported for the uncoated masonry cement specimens was 0.007 L/min/m^2 compared to approximately 0.002 L.min/m^2 established for the Portland cement-lime specimens. Brown also examined the possible water proofing benefits of post-tensioning the masonry.

It was observed that, as the pressure of 479 Pa was applied to the first brick specimen it cracked in flexure. The addition of support along the sides of the specimens prevented this from occurring over the remainder of the program. The cracked wall was experimentally post-tensioned and retested. It was reported that where profuse leakage occurred at the crack location prior to post-tensioning, none existed in the post-tensioned condition.

In 1982, a research project on BV/SS wall systems, jointly sponsored by the Metal Lath/Steel Framing Association and the Brick Institute of America, was reported by Arumala and Brown[11]. The program included limited permeance testing of the wall system which, according to the authors, were not completely reliable owing to difficulty with the tests. The tests were conducted in a manner similar to the procedures outlined in ASTM E 514 but on a limited portion of the masonry wall. Conclusions on the influence of cracking on the permeance of the masonry were not possible since the structural and water permeance test were conducted in separate programs.

2) United Kingdom

In 1982 Newman et al[65,66] reported on field testing of nine retrofitted (insulation injected some time after complete construction) and three cavity fill walls with built-in insulation (insulation placed at time of construction). The study involved placing rigid board insulation as opposed to different blown-in or injected thermal insulation material into a wall cavity. The tests were conducted by wetting the gable area of houses at rates often reached during periods of driving rain in the British Isles.

The nine retrofit buildings were initially tested with an open cavity. These tests revealed numerous faults in construction and visible dampness on the interior plaster was observed. Inspection with a "borescope optical system" indicated that 55% of the wall ties supported complete mortar bridges, responsible for directing free flowing water across the cavity to the interior leaf. Of the nine walls retested with insulation fill, all but one demonstrated an increase in water penetration. This was attributed to the new bridging paths provided by the fill.

For the three cavity walls with 25 mm polystyrene boards as the built-in fills tested, the results are most interesting. It was observed that water leaked through the exterior brickwork at vertical mortar joints, crossed the 50 mm open cavity on wall ties, flowed down the insulation and entered the concrete block interior wall at joints between the insulation boards. It was concluded that partial fills should not be used unless close attention to installation is provided. The cited problems associated with partial fills included: adhering insulation to the backup wall, mortar fins bridging cavities of 25 mm, and wall ties providing paths for free flowing water.

3) <u>Canada</u>

In 1989, Keller[55] reported on a CMHC sponsored field investigation on BV/SS wall systems. Eight buildings, two from each of four cities in Canada, were investigated and evidence of areas of deterioration due to moisture was reported. Photographs and descriptions within the report indicate poor performance and in one case an overall inability of the system to withstand severe climatic conditions. Corrosion of metal components including studs, tracks, drywall screws and wall ties along with deteriorated gypsum board, unclean or bridged cavities and plugged weep holes were among the noted building deficiencies.

In light of these observations the report recommended the practice of rigorous inspection, use of 50 mm open cavities, better moisture control and the use of corrosion resistant materials to promote long term performance. The report did not identify conditions or practices that produced areas of satisfactory performance. It is suggested that future studies should include this other side of the issue to provide a balanced view of requirements for

BV/SS construction. The results are valuable indicators of existing problems but point to the need for a more extensive coverage to get a better statistical description of the extent of deterioration in existing BV/SS construction. This would provide a more quantitative evaluation of the real vulnerabilities related to certain existing practices.

1.2.3 Present Design Practices for BV Wall Systems

The design of BV wall systems in Canada is not covered by one specific Code nor are construction details standardized. Documents such as CAN3-S304-M84[25] (Masonry Design for Buildings), CAN3-A370-M84[22] (Connectors for Masonry) and CAN3-A371-M84[24] (Masonry Construction for Buildings) do provide information on the design and construction of both BV/SS and BV/CB wall systems. However, from a 1986 survey conducted by Suter Keller Inc.[54], it is apparent that most designers rely on product literature for design guidance.

Advisory documents provided by Canada Mortgage and Housing Corporation and prepared by Plewes[69] and Drysdale and Suter[35] are available and provide information on the design and construction of BV wall systems. The later advisory document in particular provides considerable information on the BV/SS wall system and was commissioned to respond to the present lack of design and construction guidance. Presently most BV/SS walls are designed by limiting the deflection of the steel studs. The concept is that limiting the deflection of the flexible backup will either prevent or control flexural cracking in the rigid veneer. Designers have chosen deflection limits ranging from L/360 to L/2000.

1.2.4 Laboratory Test of Full Scale BV/SS Walls

1.2.4.1 Clemson University Research

In 1982, Arumala and Brown[11] reported on an experimental study co-sponsored by the Brick Institute of America and the Metal Lath/Steel Stud Framing Association. The test program comprised of six full scale BV/SS wall panels loaded under both positive and negative pressures, using a wooden pressure chamber. The SS panels were constructed with 92 mm deep, 20 gauge cold formed steel channel sections, spaced at 600 mm centres. Other panel details included one line of 16 gauge through-the-web bridging attached with clip angles and screws, exterior and interior 12.5 mm gypsum board sheathing fastened with 6-DG screws at 200 mm spacing and DW10X wall ties placed in accordance with BIA recommendations[15]. There were no provisions for vertical movement joints in the SS panels. The BV panels measured 2.85 m high and the SS panels were 2.4 m high.

Arumala and Brown reported that flexural cracking was not observed until twice the design load had been applied. The design was based on an L/360 deflection criteria for the steel studs. The conclusions also mentioned that the tie forces were not uniform and that composite action between the gypsum boards and steel stud panel was not significant.

1.2.4.2 University of Alberta Research

In 1985, an experimental study on the lateral load behaviour of BV/SS wall systems was conducted by Hatzinikolas et al[50] at the University of Alberta. It was co-sponsored by Dow Chemical Canada Inc. and The Prairie Masonry Research Institute. The thirty-two BV/SS wall specimens were 1.2 m wide with 3.2 m veneer heights and 3.0 m steel stud heights. Test variables in the program included wall ties, wall tie arrangement, stud size and gauge and cavity width.

It was concluded that brick veneer will crack at pressures less than the design loads if the backup is designed using the L/360 steel stud deflection criteria. It was also reported that composite action between the gypsum board and SS panel was insignificant and that the gypsum board provided more lateral bracing than did polystyrene sheathing.

1.2.4.3 Closure

The conclusions related to composite action between the gypsum boards and the SS wall panels are in agreement with the work by Murden[64]. Murden observed that some composite action could be achieved by taking great care in installation. However, this stiffening was rapidly lost with cyclic loading.

The considerable difference in SS and BV wall heights in the Clemson tests and the high walls tested by Hatzinikolas may not be representative of residential BV/SS applications. Also, a majority of the walls tested by Hatzinikolas employed strip or crimp wall ties which are generally considered inadequate for BV/SS wall construction today. In both research programs, the walls were built without the required movement joint in the SS wall panel.

A movement joint is typically located at the top of the wall and this results in a flexible support condition permitting translational movement. The effective translational stiffness of this joint has been documented in previous experimental work[13,33] in the CMHC/McMaster research program. Further independent numerical analysis[34] confirmed the influence of this on structural behaviour and wall cracking strength.

It should be noted that tests to study the influence of cavity pressurization on BV/SS structural behaviour of the wall systems have not been previously carried out.

1.3 SCOPE AND ORGANIZATION OF THE CMHC RESEARCH PROJECT

Although useful information on BV/SS construction has been recently published, limitations on scope and/or some controversy regarding interpretation of the results meant that the need for reasonably comprehensive research effort remained. In early 1986, Canada Mortgage and Housing Corporation sponsored a project to provide an independent investigation of the BV/SS wall system. The project was divided into the following three activities:

A. Production of an Advisory Document on design and construction aspects.

B. Organization of a Canada wide survey of BV/SS design and construction practices.

C. Laboratory testing of the BV/SS system and components.

Dr. R.G. Drysdale of McMaster University and Suter Keller Inc. were asked to undertake this research. The Advisory Document[35] written by R.G. Drysdale and G.T. Suter has been prepared and H. Keller reported the findings of the Canada wide survey[54].

The Laboratory Testing Program was conducted at McMaster University under the direction of R.G. Drysdale. It was composed of the following five parts identified by working titles:

Part 1: Fabrication and Testing of Components of Steel Stud Backup Walls.

Part 2: Fabrication and Testing of Brick Masonry Assemblages for Leakage.

Part 3: Fabrication of a Small Wall Test Facility and Tests of Small Walls for Air, Water Vapour and Heat Flow.

Part 4: Tests of Ties and Interactions of Ties with Other Wall Components.

Part 5: Fabrication and Tests of Full Scale Walls.

In addition to a CMHC Advisory Committee which reviewed the original proposal and attended a mid term meeting at McMaster University to monitor progress, an open door policy was adopted which resulted in significant interaction with interested parties who arranged intermittent visits to the laboratory.

This report contains the results of the full scale tests of BV/SS walls in terms of structural performance and rain penetration. This report is identified as Part 5 of the CMHC McMaster BV/SS Laboratory Test Program.

1.4 SCOPE AND OBJECTIVES OF INVESTIGATION

It is considered to be within the scope of this research to identify inadequacies in design and construction practices and to recommend alternative details and methods where these have been examined in the laboratory or established within other Parts of the CMHC/McMaster Laboratory Program.

Although a BV/CB wall was tested, the limited experimental results preclude extensive recommendations or conclusions pertaining to this wall system. Thus the majority of the report is focussed on the BV/SS wall system including design and construction.

The overall objectives of the report are summarized below:

- Development of a new test apparatus and test procedures to provide assessments of BV wall systems with respect to rain penetration and structural performance.
- Design, construction and tests of five wall specimens representative of current construction practices and design methods.
- Test of a BV/CB wall system to provide data for comparisons.
- Assessment of the vulnerabilities of the wall system to rain penetration to document the effectiveness of the rain screen design.
- Documentation of the structural behaviour with primary consideration being given to development of cracks in the veneer and to the effects of support details.
- Documentation of the structural performance and rain permeance performance with respect to cavity pressurization before and after cracking of the veneer.

CHAPTER 2

DESCRIPTION OF THE TEST APPARATUS AND TEST PROCEDURES

2.1 INTRODUCTION

To conduct this test program on full scale walls, a significant amount of the research effort was devoted to the design and construction of the test apparatus and for the development of test procedures. Currently no compatible standard test procedures are available to permit both the structural and building envelope performance of wall systems to be evaluated using the same specimens. Also there have been few experimental studies of either the structural behaviour or the building envelope performance of complete wall systems. The procedures described in this chapter were developed to establish a coherent means of examining both aspects of wall performance within the same test protocol.

2.2 DESCRIPTION OF THE WALL TEST RIG, "WALTER"

2.2.1 General

The test facility described in this chapter was designed to test full scale wall systems for both structural behaviour and building envelope performance. The Wall Test Rig, referred to as WALTER, was constructed in 1987. It was dimensioned to accommodate test specimens with an interior wythe of approximately 5.2×2.6 m and an exterior wythe of 5.2×2.8 m, the apparatus has a working load capacity estimated at an internal pressure of 12.5 kPa.

Walter is shown in the closed position in Figure 2.1. The apparatus consists primarily of two sections; the specimen frame supporting the test specimen and the pressure chamber housing the instrumentation and controls for application of load. It is equipped to provide a wide range of test conditions for both structural and building envelope evaluation. Simulation of wind driven rain is one of the features leading to the apparatus having been identified as

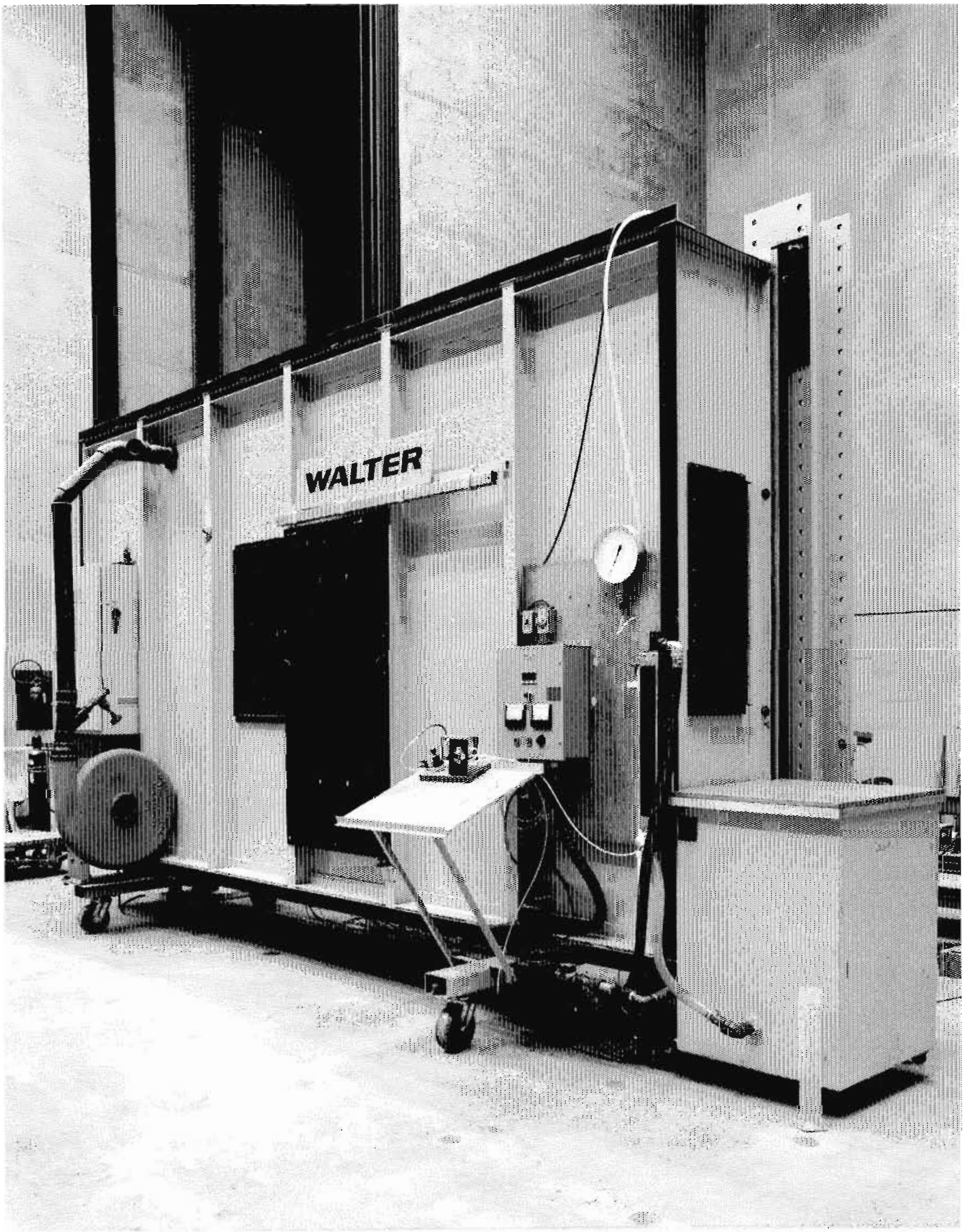


FIGURE 2.1 WALL TEST RIG: WALTER

unique to North America by many visitors to the laboratory. A description of the features and components of the test apparatus follows.

2.2.2 Specimen Frame

A drawing of the Specimen Frame which houses the test specimen is shown in Figure 2.2. For double wythe walls, the interior panel is intended to be positioned inside the rectangular 200×200×12 mm HSS frame and the exterior panel is to be placed between the supporting 75×75×10 mm steel angles also shown. The design criteria for the frame was to provide a rigid non-deflecting support for the wall specimens. A deeper 200×300×12 mm HSS bottom section was used to provide clearance between the pressure chamber and the wall specimen when the pressure chamber is attached to the specimen frame.

The specimen frame was bolted to two columns using the 12.5 mm thick steel plates welded to its corners. The columns were fixed to the structural floor of the Applied Dynamics Laboratory as shown in Figure 2.3. Fixing the specimen frame to the floor was adopted to provide stable support during construction of the wall specimens. However, the frame was also designed to be supported by the pressure chamber alone and tests could be run in that position.

The steel stud backup walls constructed within the frame were attached top and bottom with 9.5 mm bolts threaded into tapped holes in the HSS sections at a maximum spacing of 900 mm. Where side support of the backup wall was required, similar tapped holes at a maximum spacing of 600 mm were provided. For construction of the veneer panels, structural steel angles were used for support to represent actual construction practise. However, contrary to the normal practice of placing the bottom shelf angle with the leg up, it was positioned leg down to accommodate a drainage system for the collection of water that leaks through the veneer. The shelf angle was connected to the specimen frame by six 16 mm diameter bolts positioned with a maximum spacing of 850 mm. An adjustable top shelf angle

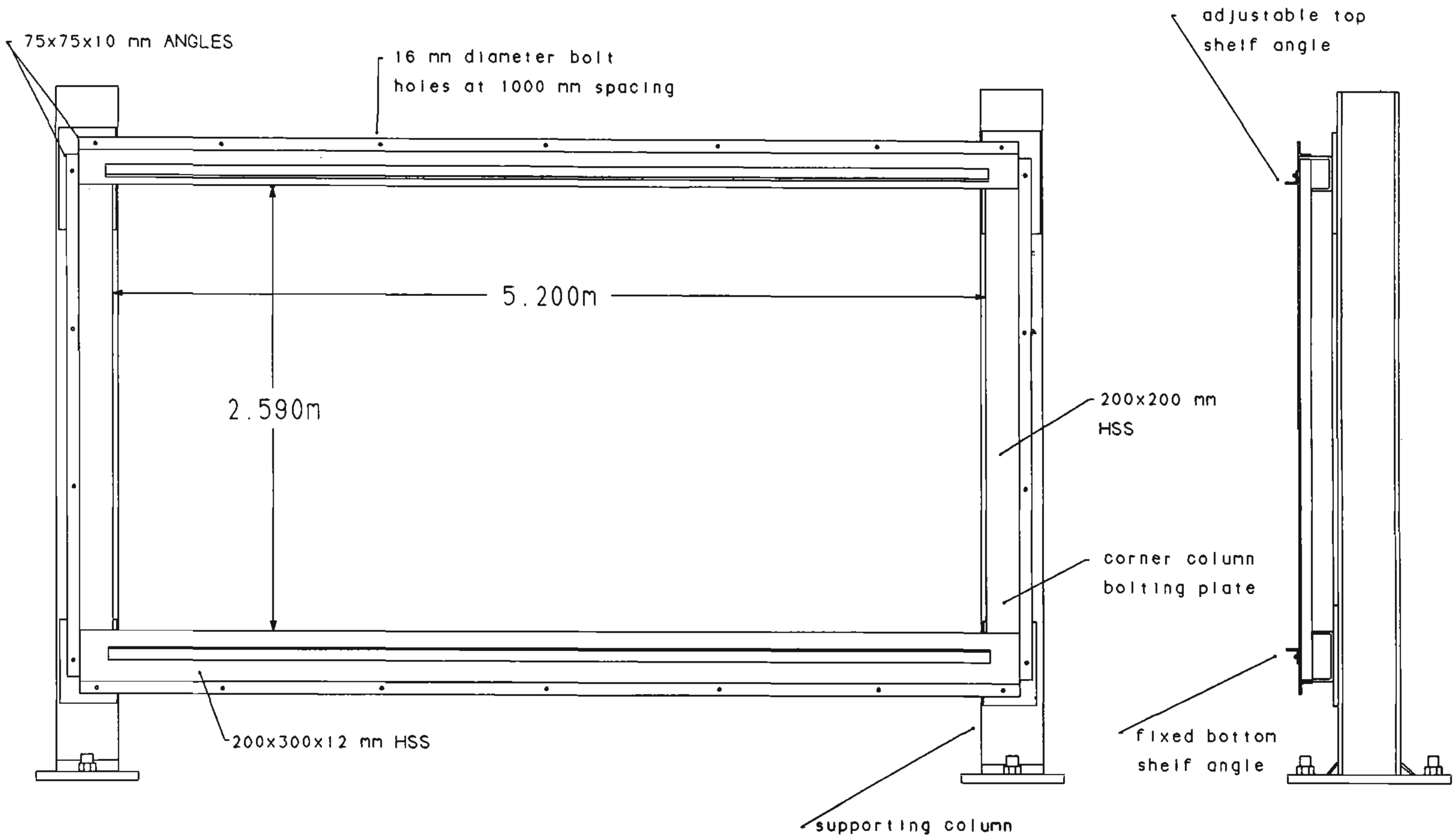


FIGURE 2.2 SPECIMEN FRAME

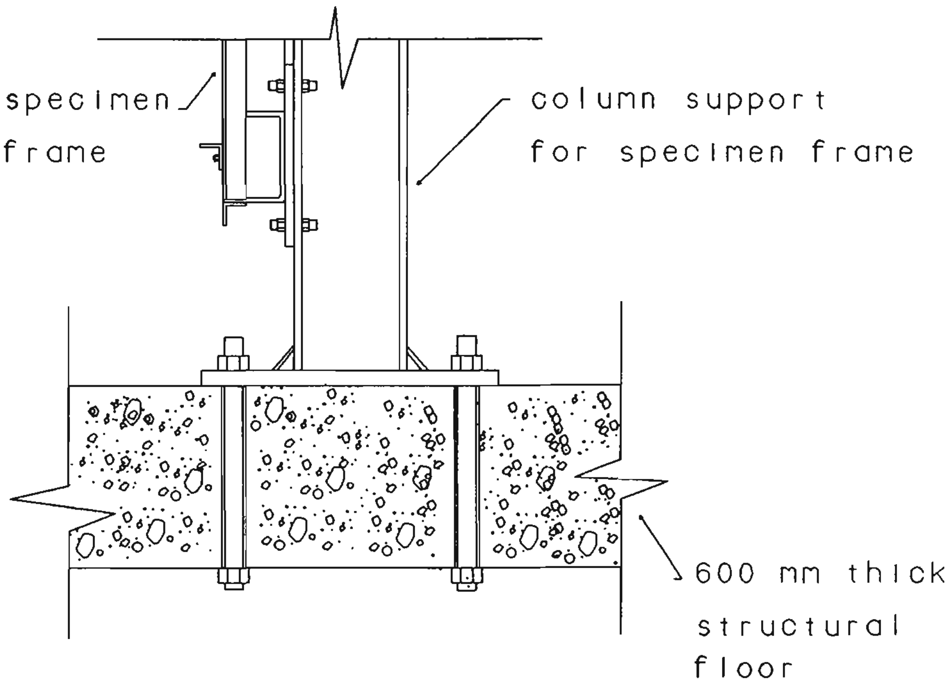


FIGURE 2.3 BASE CONNECTION

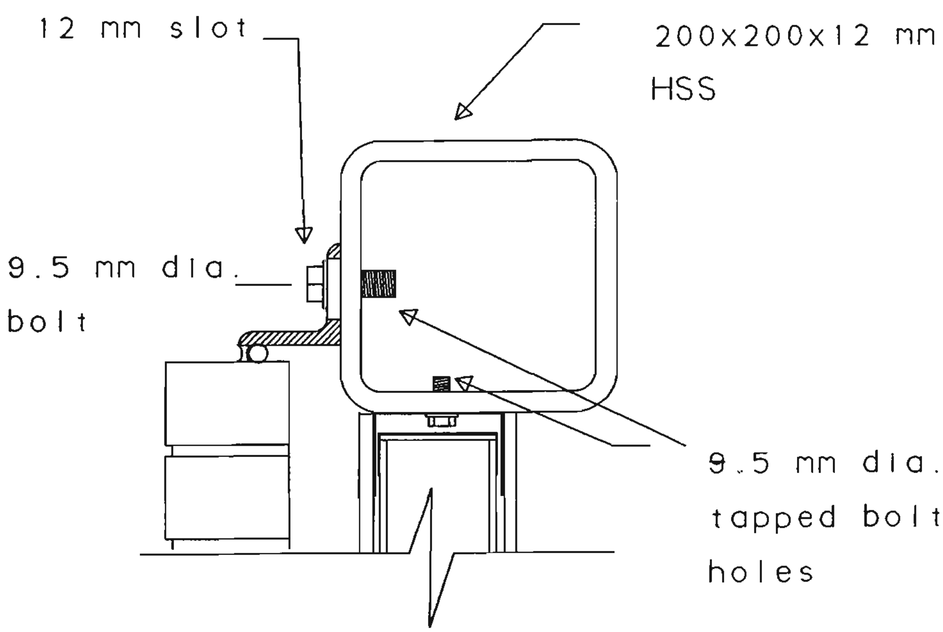


FIGURE 2.4 ADJUSTABLE TOP SHELF ANGLE DETAIL

was similarly fastened to the specimen frame as shown in Figure 2.4. It was fitted with slotted bolt holes to accommodate vertical tolerance in the order of 10 mm for construction of the brick veneer wythe.

2.2.3 Pressure Chamber

The five sided pressure chamber housed the air pressure supply system, a closed loop water supply system, water spray equipment, interior lighting and electronic controls. In addition, as shown in Figure 2.5, large windows permitted visual observations during the experiments and physical access to the specimen was provided through a man door. The structural design was based on a working load pressure of 12.5 kPa with minimal deformation in the chamber.

The pressure chamber was constructed with inside dimensions of 5.6 m wide by 3.6 m high which allowed adequate clearance of specimens to facilitate attachment to the specimen frame. Four extra heavy duty forged steel swivel castors, rated at 1400 kg each, were used to support the approximately 3400 kg mass of the pressure chamber. These wheels also allowed the pressure chamber to be rolled into place and fastened to the specimen frame. Twenty 16 mm diameter bolts positioned evenly around the chamber's perimeter ,with a maximum spacing of 1 mm, were used to fasten the two parts together. Although the wheels allowed the pressure chamber to be moved by one individual, shackle bolts were also built onto the top of the pressure chamber to accommodate manoeuvring with the aid of an overhead crane.

Structurally, the pressure chamber was framed vertically with 130×15 I sections spaced at 940 mm centres and it was framed horizontally top and bottom with 125×75×10 mm angles. A skin of 7 mm thick steel plate covered this frame with full penetration fillet welds at all seam joints ensuring both strength and air tightness. The partial horizontal cross section in Figure 2.6 shows these structural details.

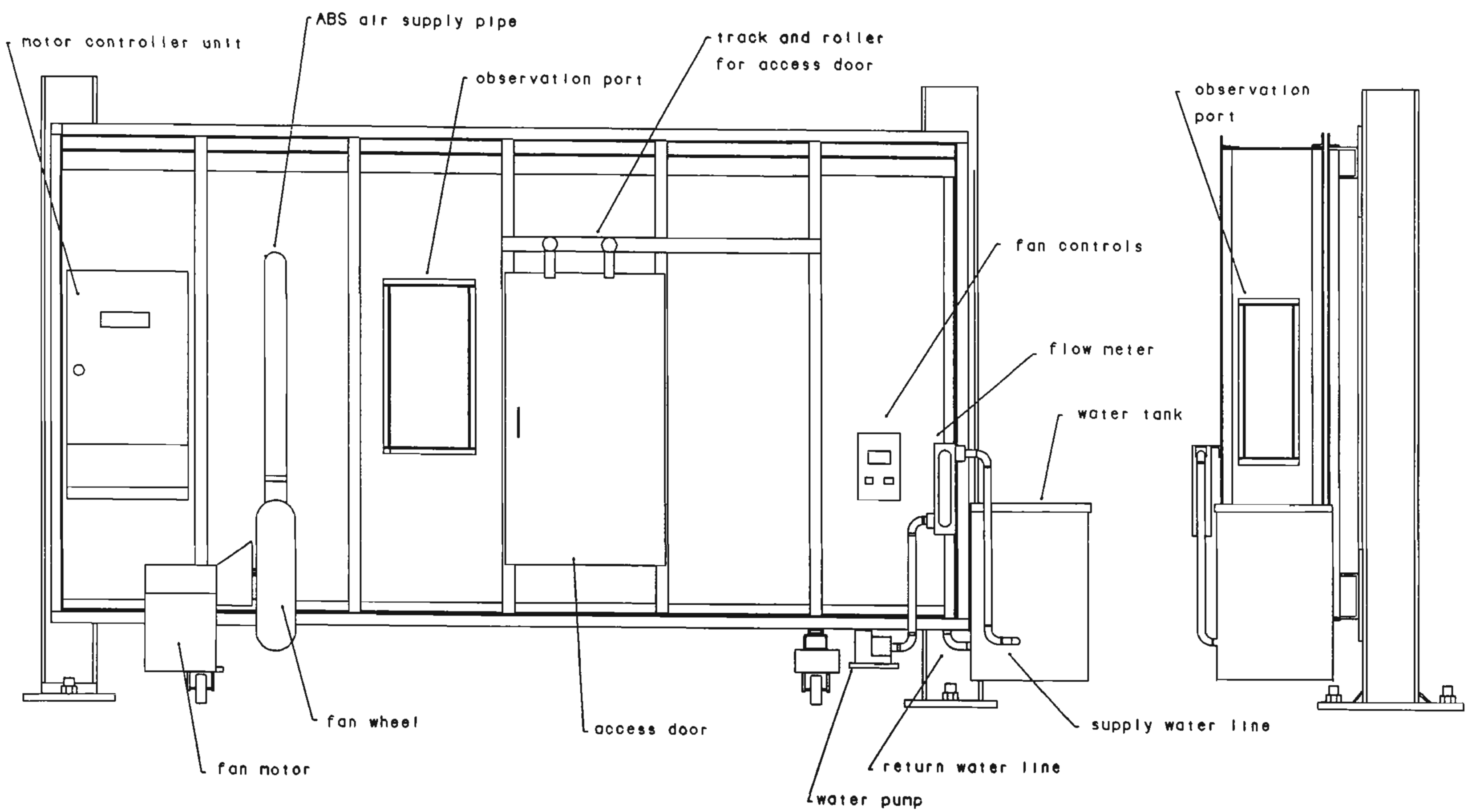


FIGURE 2.5 PRESSURE CHAMBER

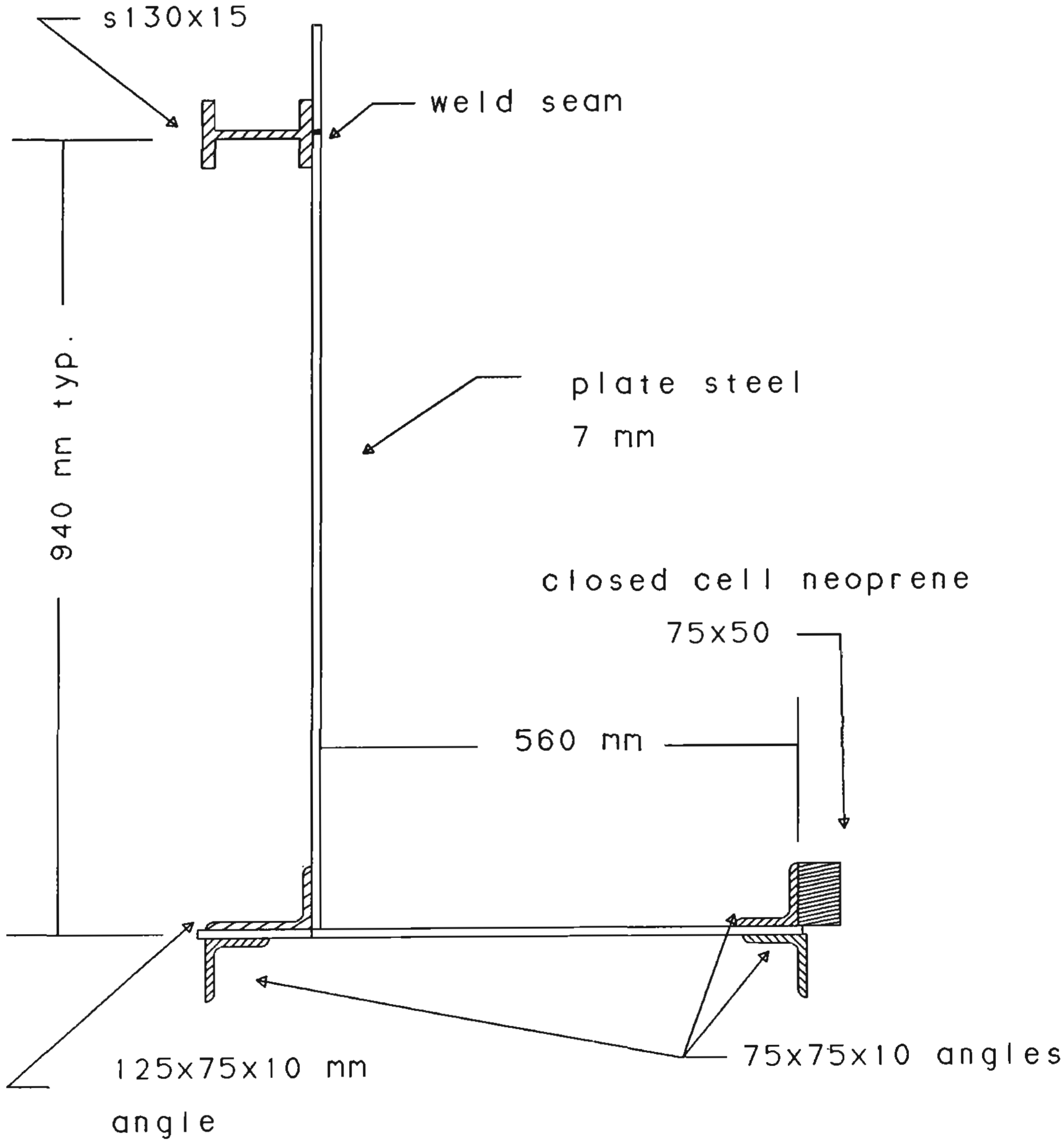


FIGURE 2.6 HORIZONTAL SECTION THROUGH PRESSURE CHAMBER WALL

For air tightness of the pressure chamber, special attention was paid to the access door and the four windows. The $1000 \times 1900 \times 7$ mm steel plate door was supported by an overhead arrangement of track and rollers. During tests, the door was fixed to the pressure chamber with ten 6 mm diameter bolts at a maximum spacing of 600 mm around the perimeter of the door. These bolts were tightened to compress a continuous closed cell neoprene gasket to provide an air tight seal. Figure 2.7 is a drawing of these details and Figure 2.8 is a picture of the door in the open position.

The windows were constructed of 12.5 mm thick acrylic sheets. A steel frame constructed of $45 \times 45 \times 10$ mm angles was used to clamp a 16 mm diameter continuous closed cell neoprene cord between the acrylic window and the steel box. The clamping force was provided with 6 mm diameter bolts spaced at 150 mm intervals around the perimeter of the window frame. The sketch of this detail in Figure 2.9 also shows the additional measure of welding the bolt heads to the inside skin of the pressure chamber to achieve better air tightness.

The final consideration for air tightness involved the connection of the pressure chamber to the specimen frame. As shown in Figures 2.6 and 2.10, air tightness was accomplished by providing a continuous closed cell neoprene gasket compressed by the 16 mm diameter bolts used to attach the pressure chamber to the specimen frame. The steel angles used to connect the two parts are also shown in Figure 2.10.

2.2.4 Air Pressure Supply

Air pressure was supplied by a 3550 RPM cast iron Buffalo Pressure Blower (Model 4RE) manufactured by Canadian Blower/Canada Pumps Ltd. The blower has a 650 mm diameter wheel and is rated for a maximum pressure of 11.5 kPa. The blower is directly driven by a three phase 480 volt DC 2500 RPM motor manufactured by General Electric. The motor was designated as a Frame Size CD 218 AT and rated at 15 HP[18]. Motor speed was controlled

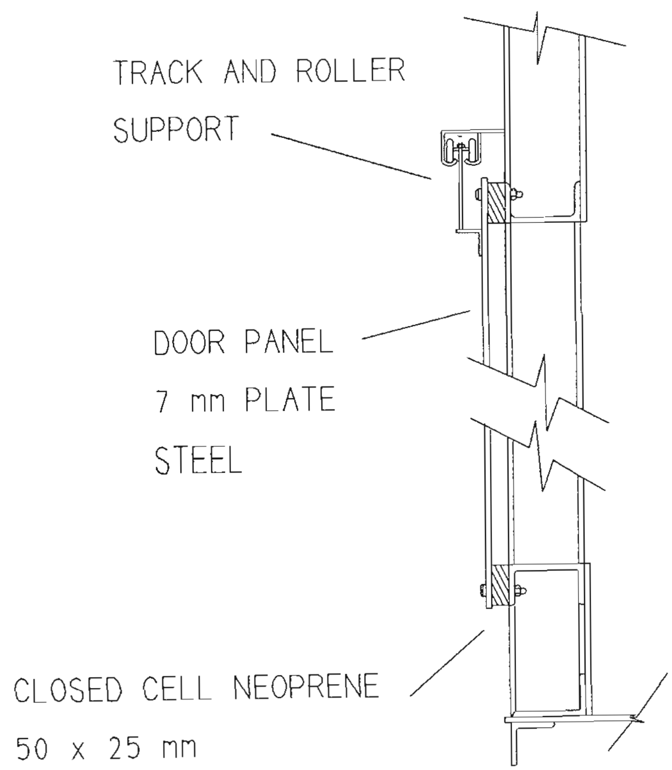


FIGURE 2.7 ACCESS DOOR DETAILS

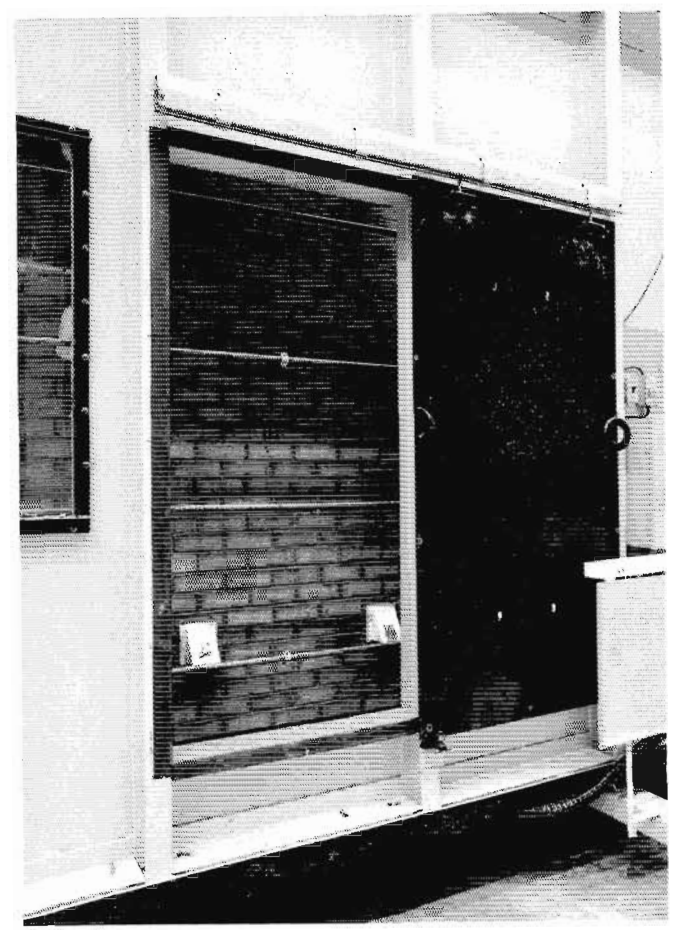


FIGURE 2.8 ACCESS DOOR IN OPEN POSITION

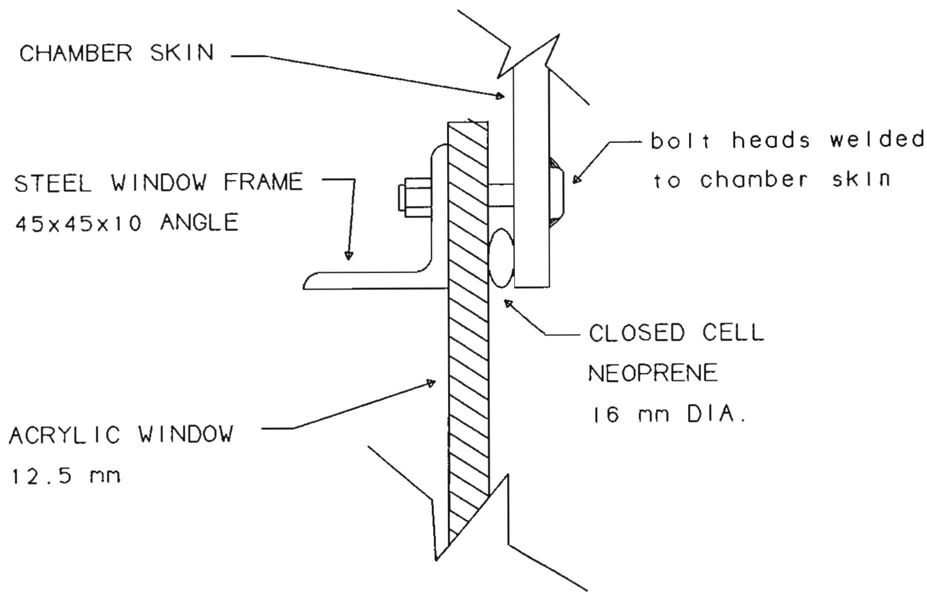


FIGURE 2.9 PRESSURE CHAMBER WINDOW DETAIL

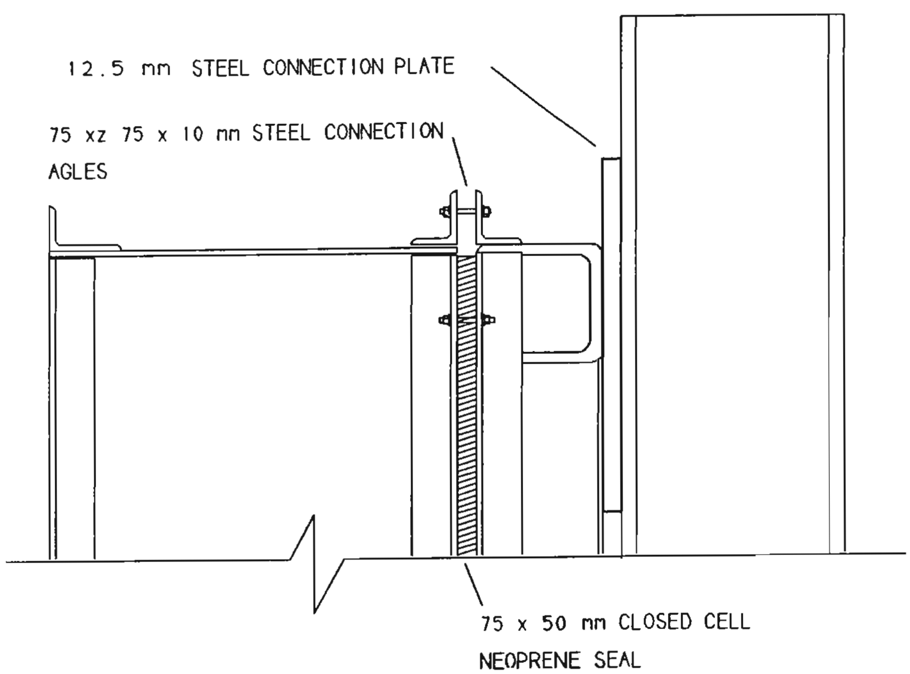


FIGURE 2.10 SEAL AND PRESSURE CHAMBER TO SPECIMEN FRAME CONNECTION DETAILS

by a custom manufactured controller unit designed and built by Serv-e- tronic Ltd. A photograph of the blower, motor and the open cabinet of the controller is reproduced in Figure 2.11.

The controller unit was built to be either computer controlled or to be used as a stand alone unit. It is currently operated as a stand-alone system with motor speed controlled through signal digitization as opposed to using reference signals. This allows the motor speed to be precisely controlled in both the run mode, and for safety reasons, in a disabled mode. The drive unit component was specified by the manufacture as capable of handling up to 1000 horsepower.

2.2.5 Water Spray Equipment

To simulate wind driven rain, water was sprayed on the surface of the wall uniformly by a system of nozzles. These brass nozzles, manufactured by Spraying Systems Co., were identified as cone shaped wide angle spray nozzles[79]. The layout shown in Figure 2.12 was arranged so that the 28 nozzles operating at 69 kPa, supplied water at the rate of 3.03 L/min to the surface area of the wall. Owing to the overlapping wetted areas over the tributary area of 0.54 m^2 per nozzle a maximum coverage rate of 5.6 L/min/m^2 was provided. This rate satisfies the requirements of the ASTM test standard[10] for rain penetration of exterior walls.

Copper pipe was used to connect all the nozzles to the water supply in the system shown in Figure 2.12. The system was designed to be recirculating with the water collected in the pressure chamber fed back to a reservoir and then reused by pumping it through a filter and back into the spray system. Pressure gauges and a flow meter were added to the water supply side of the system to indicate line pressures and flow rates. These latter features are illustrated in Figure 2.5.

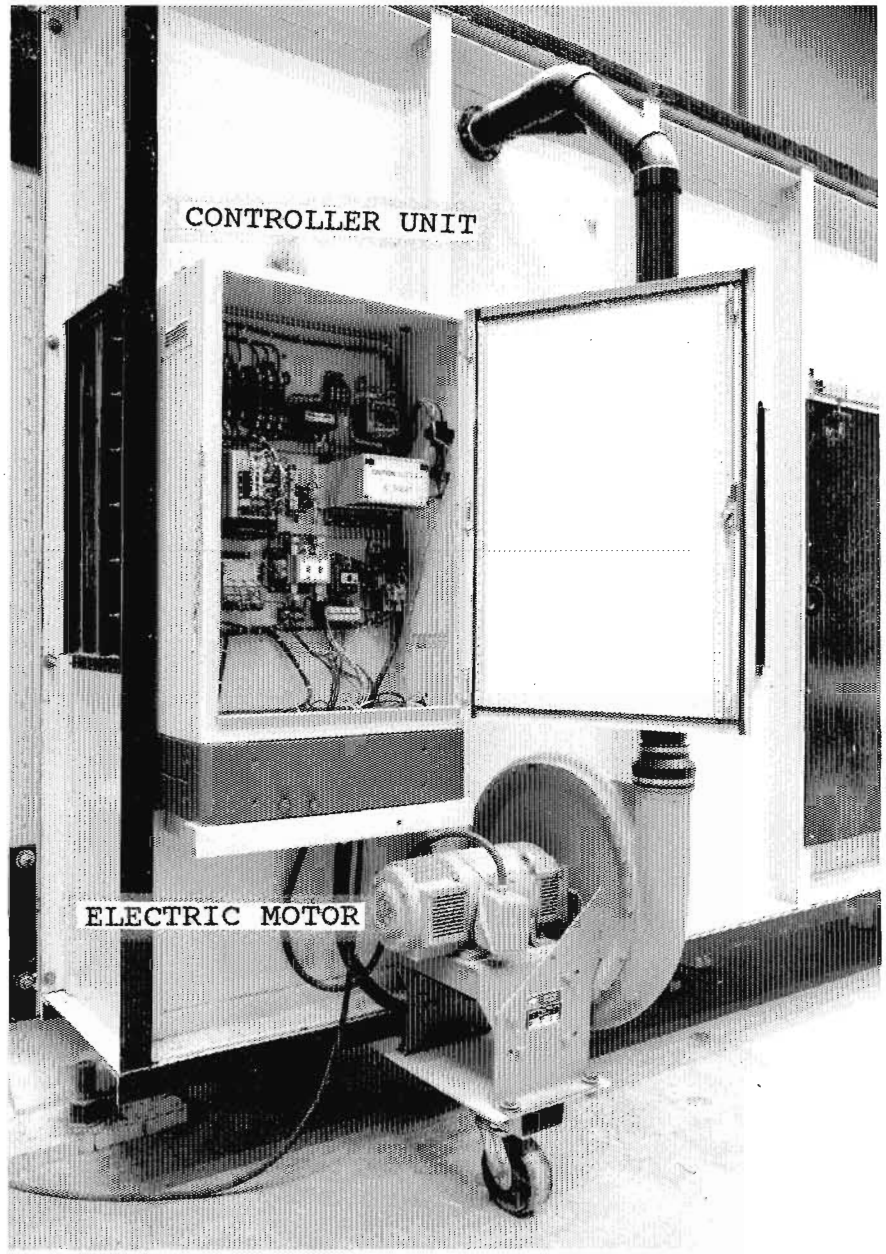


FIGURE 2.11 BLOWER, MOTOR AND CONTROLLER UNIT

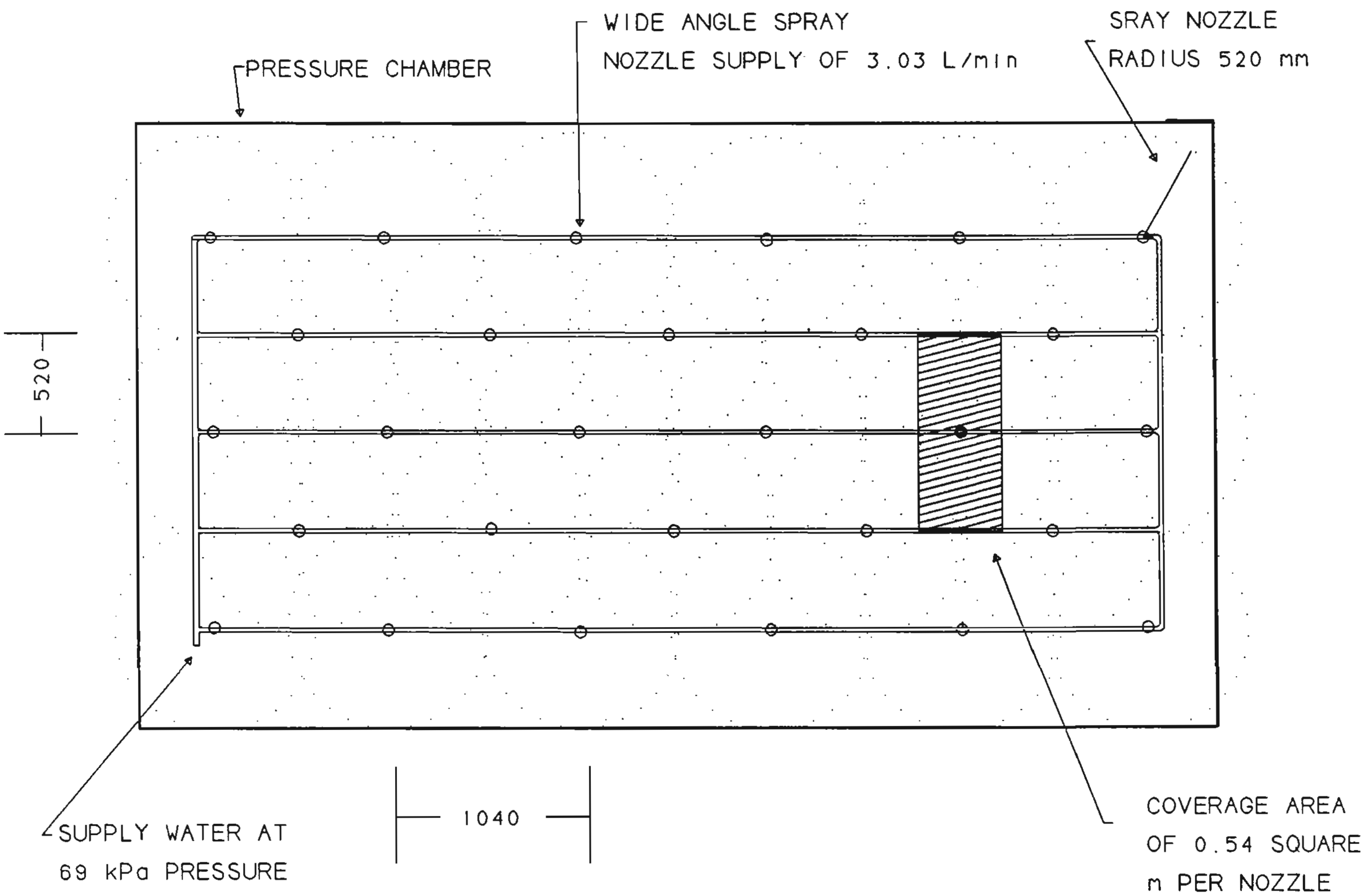


FIGURE 2.12 LAYOUT OF SPRAY NOZZLE SYSTEM

2.2.6 Water Collection System

A major feature of the test procedures was the development of the means for collecting the cavity water that leaks through the veneer. In buildings, this water would be drained to the bottom of the cavity and then flashing on the shelf angles would direct it back out of the wall through weep holes. However, to measure the quantity of water reaching the cavity, it was necessary to keep it separated from the water on the exterior of the wall.

Water was collected by elevating the weep holes from their normal position at the shelf angle and by eliminating the standard flashing details. Then a plastic trough secured between the shelf angle and the specimen frame and fitted with drain pipes at approximately every metre allowed the cavity water to be drained directly out of the cavity as shown in Figure 2.13. The elevated weep holes were provided because, although they were not required for cavity drainage, they were required for cavity pressurization studies.

2.2.7 Instrumentation

For the structural test program, the quantities to be monitored included displacement, strain and air pressure. Pressure was monitored continuously by means of standard inclined and U-Tube manometers and preset pressure levels were maintained by adjusting the fan speed. Solid state piezoresistor pressures transducers were used to accurately record the pressure at various locations within the wall specimens and the pressure chamber.

Displacements at various wall locations were recorded at preset pressure levels. These measurements were made with a combination of mechanical dial gauges and LPDT's (Linear Potentiometric Displacement Transducers) located on both the interior side of the steel stud wall and the exterior face of the brick veneer. Figure 2.14 is a photograph of the grid system used to support the transducers used to measure the displacements of the steel stud backup wall. The gauges for monitoring displacement of the brick veneer were protected from the

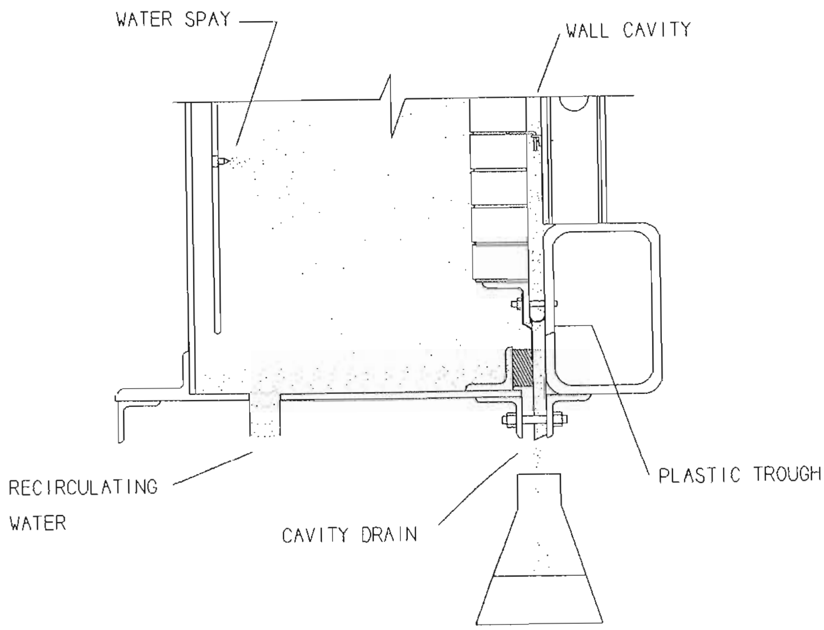


FIGURE 2.13 WALL CAVITY DRAINAGE DETAIL

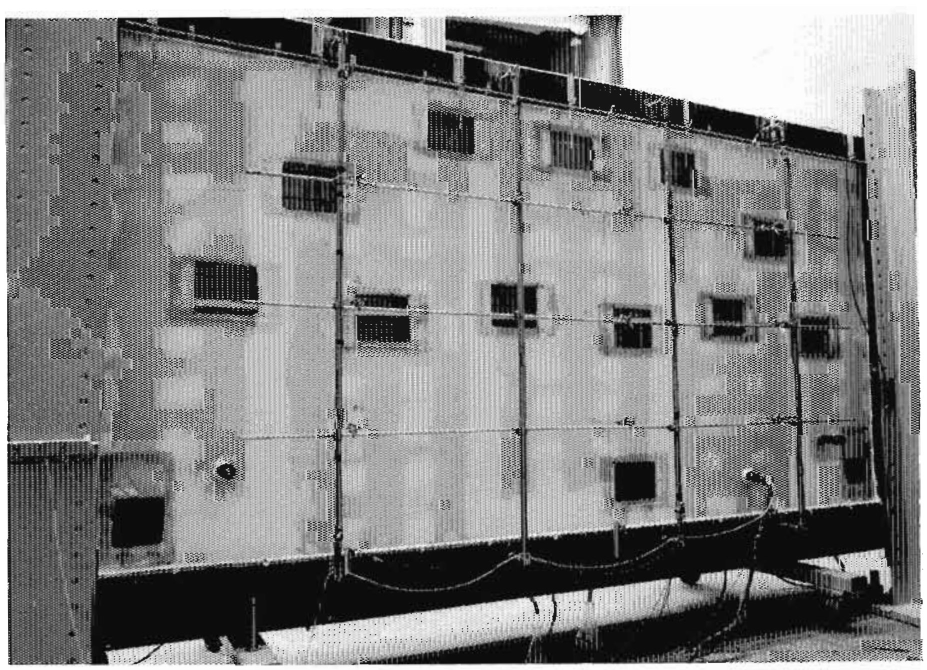


FIGURE 2.14 INSTRUMENTATION GRID

water spay with plastic covers. All of the displacement gauges were mounted on a grid system directly attached to the specimen frame. This arrangement limited any accidental movement and provided displacements readings independent of any possible movement of the apparatus.

Strains were determined by attaching the LPDT's over a gauge length and monitoring the relative displacement between the ends of the instrument. The use of electronic data collection allowed one individual to rapidly collect the data without affecting the structural behaviour of the wall system by prolonging the duration of each load increment.

2.2.8 Data Acquisition

The electronic instruments previously mentioned were monitored by a data acquisition system identified as an OPTILOG data logger controlled by a Texas Instrument micro computer. The data acquisition system allowed numerous data recordings to be monitored and recorded on diskettes. The computer operated the OPTILOG in the MS-BASIC environment with a program housing a library of instrument calibration and installation parameters allowing real time displacements and pressures to be visually returned on the computer screen during the tests. In addition to recording the data on diskette, it was displayed graphically during the test to provide an immediate means of monitoring the results.

2.2.9 Concluding Remarks on Apparatus Design

The apparatus described above was designed and constructed specifically for physical testing of BV/SS wall systems. However its versatility will lend itself well to future experimental investigation of other wall systems. In fact the final specimen of this program, which had a concrete block backup wall, is an example of this versability.

Aside from accommodating different wall systems, the test data provided by the apparatus can also be further developed. Although measurement of air flow and quantitative air barrier leakage rates were not objectives for this research program, the apparatus and instrumentation can be augmented to include these aspects. Accurate measurement of air flow would require determination of accidental air leakage through the pressure chamber and the addition of flow measuring devices.

Also, it should be stated that although the pressures reported in this program are all positive, reverse loading or negative pressures could be provided by reversing the exhaust and supply lines connecting the fan to the pressure chamber.

2.3 GENERAL LABORATORY PROCEDURES

It has been documented[6,11,17,35,41,45,46,58,63,73,74] that water will leak through masonry when a pressure difference exists across the wall. Thus the object of the rain penetration part of this research was to evaluate the design philosophies and the principles utilized to minimize and control water penetration. Use of the rain screen is the approach most commonly employed by designers. However the current ASTM standard methods for evaluating water penetration and leakage through masonry cannot be used to assess the performance of this design approach as it applies to the BV/SS wall system.

Examination of previous rain penetration evaluations of brick masonry[11,17,63,65,66,73] revealed a wide variety of test methods and a large range of results. To aid in the acceptance of results from this program, the apparatus and the test procedures were made to correspond as much as possible to related ASTM standards. Therefore ASTM E330, E331, E514, E547 and E1233 were closely examined[6,7,8,9,10].

Although the above standards all involve evaluation of the rain penetration performance of masonry walls, none are directly suitable for testing BV/SS wall systems. The reason for this relates to the intended significance of the test results. In the ASTM water penetration tests, the masonry is evaluated for water tightness, something which many believe cannot be achieved without additional measures[35,45,69]. Such measures could include clear coatings and torch applied or cold adhesive bituminous membranes which provide the required barrier to water penetration. For BV/SS wall systems, the additional measure is a design technique – the rain screen principle. For rain penetration tests of BV/SS wall systems, it is necessary to subject not only the veneer but also the design features of the rain screen to sustained wind driven rain conditions.

Test procedures were also included for the investigation of the structural behaviour of the wall system. Previous structural tests of BV/SS walls have relied on air bags to load the specimens[49,50]. Although the results from these studies provide valuable information, more insight into the influence of cavity pressurization, edge restraint, and support condition on wall panels of representative size is required.

The following sections address the major points of concern dealt with in developing the procedures for both the rain penetration and structural tests.

2.4 RAIN PENETRATION TESTS

Flexibility in the types of tests to be included and thoroughness in the range of variables to be examined were achieved using a staged sequence of loading and external control over the independent performance of certain features. Within test variations for the purpose of examining the performance of the rain screen included the quality of movement joints, the degree of cavity ventilation, the crack condition of the veneer, the degree of compartmentalization and the condition of the air barrier. Along with these features, the other parameter of interest for rain penetration was identified as the influence of cavity pressurization and an assessment of the suggested benefit of pressurizing the cavity to equal the external pressure levels[37,41,71,72].

2.4.1 Cavity Pressurization

The significant effect of a pressure gradient on the leakage rate of water through masonry has been previously identified[41]. However, quantification of this effect is important. To examine this factor, the chosen two extreme conditions of cavity pressure were full pressurization (equal to external pressure) and depressurization (equal to internal air pressure). The cavity depressurized condition, (entire pressure differential is across the veneer) is shown in Figure 2.15 (a) and the condition of cavity pressurized, (no pressure differential across the veneer) is illustrated in Figure 2.15 (b). It was decided that rain penetration tests under these two conditions would provide the necessary information to quantify the influence of cavity pressurization. Additional tests for partially pressurized cavities at varying pressure levels would serve to establish the direct influence of pressure gradient on water penetration.

In practice, the cavity pressure will usually be between the internal and external air pressures as shown in Figure 2.15c). Depending on the effectiveness of the air barrier, size of vents in the veneer, and adequacy of cavity compartmentalization, the pressure differential will be shared between the veneer and the steel stud backup wall in different ratios. For this reason, pressure gauges were used to measure both the external and cavity air pressures.

To produce a pressurized or a depressurized cavity, external control over the volume of air supplied to the cavity and exhausted from it was required. The natural ventilation of the veneer is provided by weep holes and vents. These weep holes and vents, consisting of empty head joints, were used to ensure an air supply under positive air pressures. To protect the cavity from direct water penetration and to provide a means of sealing these openings, plastic ventilation hoods were attached to the brick veneer. The photograph in Figure 2.16 shows a plastic vent hood along with the bituminous membrane used to seal the side of the veneer to the specimen frame.

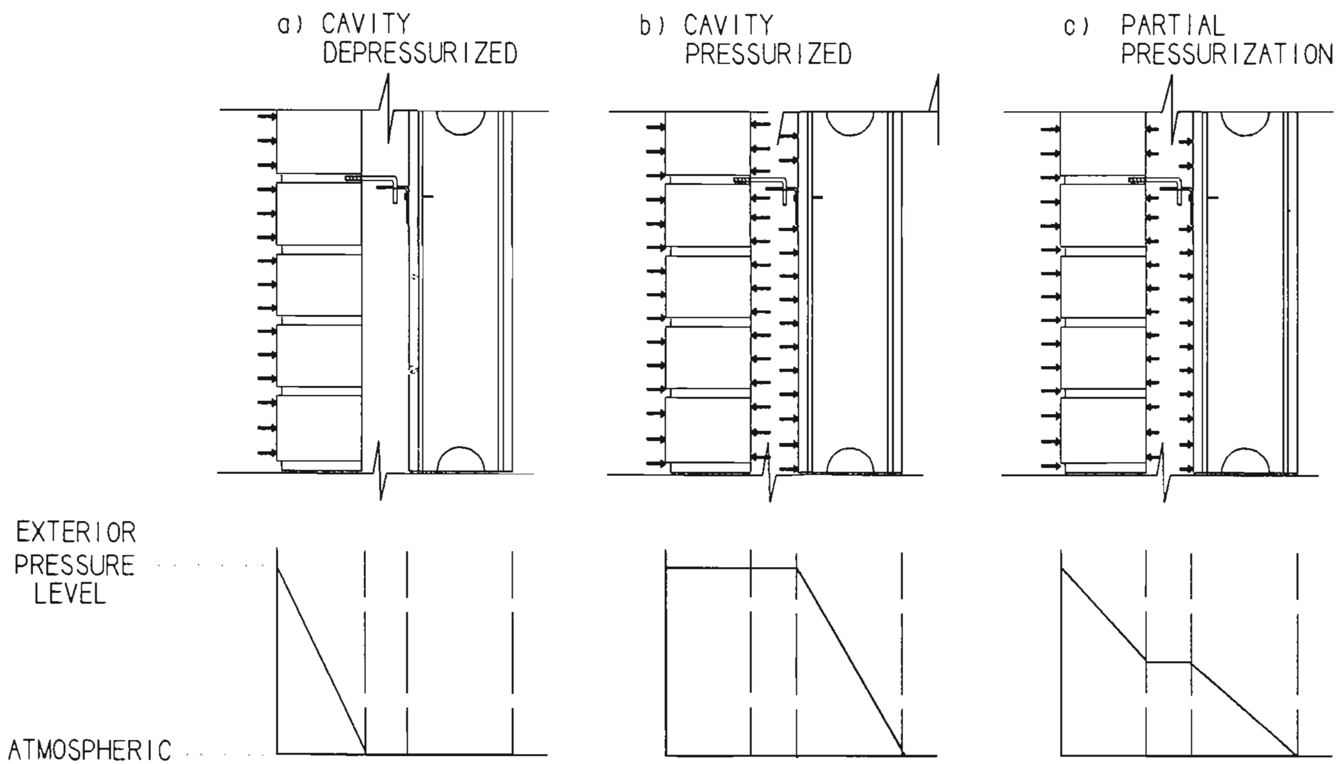


FIGURE 2.15 LOCATION OF PRESSURE GRADIENT IN BRICK VENEER STEEL STUD WALL SYSTEM

FIGURE 2.16 PLASTIC VENTILATION HOOD

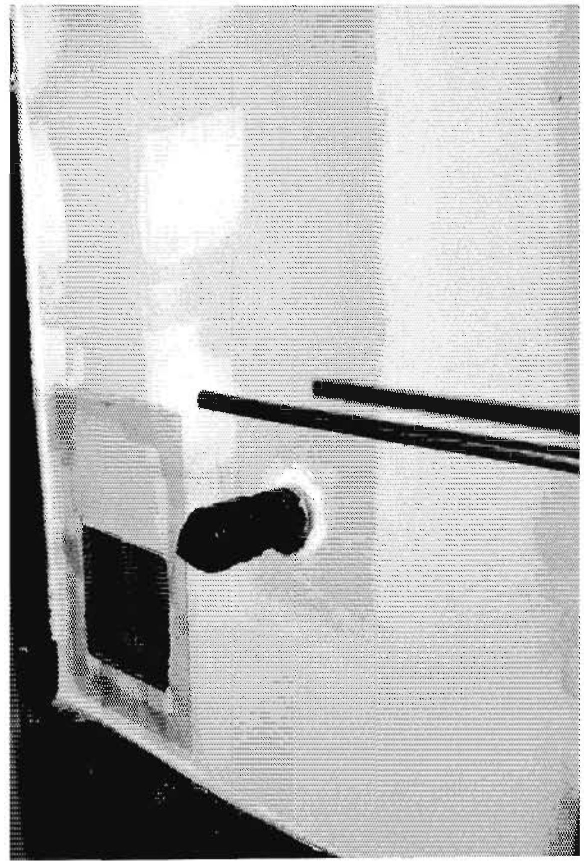


FIGURE 2.17 CAVITY VENT THROUGH BACKUP WALL

The backup wall was also fitted with two large control vents to exhaust air from the cavity to produce the depressurized test condition. As long as these vents provide openings of approximately ten times the possible leakage area through the veneer, effectively instantaneous depressurization of the cavity should be possible[37]. Air leakage through the veneer was reduced by utilizing the plastic vent hoods to seal the weep holes and vents. The photograph in Figure 2.17 shows one of the capped plastic pipes used as a control vent to exhaust air from the cavity. An observation port used to identify water leakage paths is also shown in the lower left corner.

2.4.2 Standard Pressure Level

Rather than attempt to represent either typical or worse sustained conditions, the use of a standard set of test conditions has been accepted practice[44,45,63]. ASTM rain penetration test procedures specify an air pressure of 500 Pa. This pressure corresponds to a wind speed of 100 km/hr. In the continental United States, this wind speed is reported to have a recurrence time of less than 25 years for durations considerable less than one hour[63]. This puts in perspective the level of severity of the 0.5 kPa wind pressure.

2.4.3 System Permeance Performance

ASTM E514 is only intended to provide data on the permeance of masonry and ASTM E331, while applicable to external curtain wall construction, does not use procedural specifications consistent with those deemed appropriate for masonry in ASTM E514. Thus a question exists as to which pressures, flow rates, and duration periods should be adopted for masonry walls utilizing the rain screen principle. In this research, a method of testing is proposed which allows evaluation of the performance of the entire BV/SS wall system in an as-built condition.

This is a very important point considering the interaction of the many components relied upon in BV/SS walls to resist lateral load and to control and prevent water penetration.

Since separate tests of veneer in accordance with ASTM E514 would place the entire pressure differential across the veneer, it might be considered a more critical test. However, it is suggested that use of the ASTM E514 test conditions as a worst case scenario for the BV/SS wall system could be too severe and thus misleading. This is because water penetration in the context of the rain screen principle should be judged not only on the leakage through the exterior cladding but also on the effectiveness of the materials and backup system designed to handle the water beyond the veneer.

The effectiveness of a rain screen is dependent upon the existence of a pressurized air space suitably confined between an external boundary and a plane of air tightness. In this regard, the longevity and performance of a rain screen will ultimately depend on the performance of its components. Often the failure of one component compromises the intended function of others.

As an example, if the weep holes and vents provided in the BV/SS wall system for ventilation and cavity drainage are plugged with mortar droppings, neither a pressurized air space nor a cavity drainage system can exist. The may result in large pressure gradients across the veneer and excess water in the cavity to accelerate corrosion of metal components and deterioration of other building materials. Thus, in evaluating permeance performance, the test conditions should examine the possible behaviour of the wall system and the interactions of components. Consideration of this approach led to many of the features of WALTER. Most importantly, the apparatus can be used to house and test entire full scale wall specimens. Moreover the instrumentation and controls built into the apparatus allow full investigation into the factors influencing the performance of the rain screen.

2.4.4 Within-Test Verification of Leakage Rates

A concern regarding the rain penetration tests involved the identification of major leakage sources. It has been suggested that, in the presence of local unfilled or partially filled mortar joints, other sources of leakage are insignificant[44,45,47]. To try to identify non-uniformity of water leakage due to single major leakage sources, partial-wall rain tests were planned to allow a degree of within test comparison and verification. In order to achieve this within-test comparison, half of the veneer was protected from the water spray by a plastic sheet. Comparison of the two half wall leakage rates provided an indication of the uniformity of the filling of the mortar joints within each specimen. The photograph in Figure 2.18 shows the right half of the wall covered and, on the left side, the plastic bags used to protect the electronic displacement transducers from the water spray.

2.4.5 Intensity of Water Spray

Of much less importance to the degree of water penetration is the volume of water supplied to the wall[63]. The rate of water spray applied to the wall was observed to establish a thin sheet of water over the entire veneer surface. Additional water volume beyond this would not greatly, if at all, affect the permeance of the wall at a given wind pressure[63].

2.4.6 Compatibility With Standard Test Procedures

To facilitate future comparison with tests completed in accordance with ASTM specifications, an attempt was made to stay within the general framework of these standard test techniques. Since the main adaptations involved variations in cavity pressurization, structural condition of the brick veneer and condition of the air barrier, this was not found to be difficult. In fact many important aspects of the test procedures such as duration, water

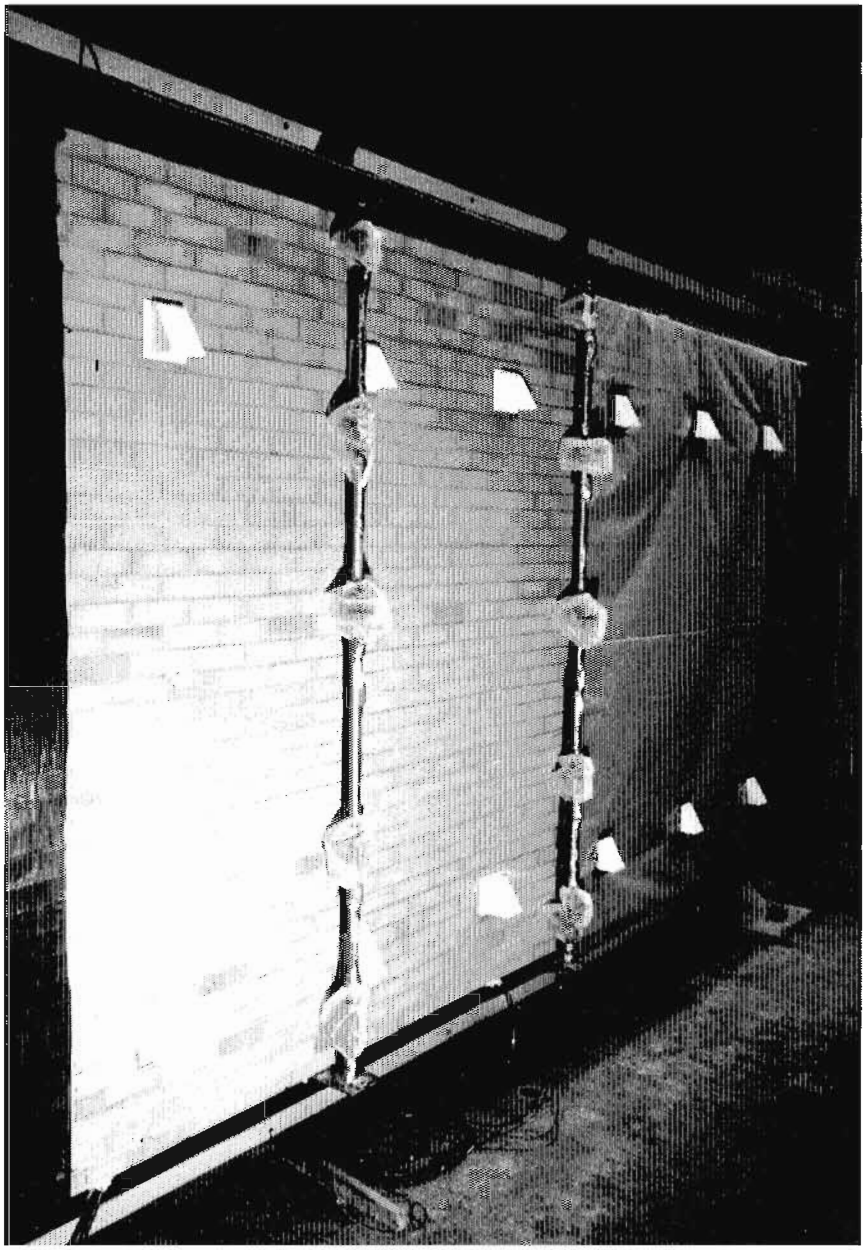


FIGURE 2.18 WALL SPECIMEN READY FOR HALF-WALL RAIN PENETRATION TESTING

volume and applied air pressure are compatible with ASTM standards for measuring permeance of masonry.

2.4.7 Required Observations and Data

One of the most important aspects of the test procedure involves the recording of observations and data. The data collected included measured volumes of leakage water, cavity pressure, pressure levels and displacement readings. Observations and data were recorded at intervals not exceeding 30 minutes. Other observations such as the time of first sign of dampness, wetness and water flow were noted.

2.5 STRUCTURAL TESTS

Application of the rain screen principle might at first only appear to have an impact on the performance of the building envelope. However, it can have an important effect on the structural behaviour of the wall system. The reason is that the rain screen principle dictates the position and magnitude of the air pressure gradient across the various components of the wall system.

In a properly designed rain screen, the entire wind induced pressure differential between the interior and exterior conditions will be resisted by the air barrier which in turn, defines the location of the primary load resisting elements[37,39,40,41,56,71,72]. All elements suitably connected to the air barrier or supporting it will share in resisting load depending on their stiffness and the means of load transfer. Detailing must ensure that proper performance is not jeopardized by an unintential weak link.

In previous research, possible weak links have been investigated by separately testing components of the wall system such as: studs, bracing, wall ties, sheathing material and connection details without the need for full scale testing[11,13,32,51]. To investigate the influence of the rain screen design on overall structural behaviour, three major areas of interest were identified for special consideration. These areas included the influence of: cavity pressurization, degree of cracking in the veneer and edge support of the veneer wall.

Paralleling the rain screen test conditions, the influence of cavity pressurization was identified as a primary structural test parameter. Under cavity pressurized or depressurized conditions, the structural significance of the location of the pressure gradient was examined.

Secondly the influence of veneer cracking on the structural behaviour of the wall systems was identified as an important parameter. In the rain screen design, the air pressure will be transferred from the primary resisting element, the air barrier, to more rigid elements. Although the steel stud backup wall is designed as the structural load resisting element to support the air barrier, the veneer is significantly stiffer than the steel stud wall. Thus it is of interest to examine the actual structural role played by the veneer in the wall system. This can be accomplished by testing the wall system with an uncracked veneer and then again after cracking has occurred for both cavity pressurized and depressurized conditions.

Finally, the third area of interest identified included the influence of support conditions on the initial cracking levels, ultimate strength and failure patterns of the wall systems. Typical conditions were one way support – providing top and bottom support of the backup wall, and two way support - introducing edge restraint in the backup wall. For the required loading sequence, loads were kept within the elastic range prior to cracking and at a standard pressure level in the post-cracked state.

2.5.1 Displacement History

Since the loading sequence allowed for numerous load repetitions in the elastic range spaced over an extended period of time, records of all displacements were required. Although the initial load levels were well within the design load, residual displacements were expected to occur with each load sequence. The residuals may not represent plastic deformation but rather settling or shifting of the specimen where the structural response of interconnections of components may be non-uniform or may include some initial take up due to lack of fit.

Residual displacements could occur where the two major components, the brick veneer and the steel stud backup wall, were linked together by numerous wall ties which initially may or may not have been structurally engaged. That is, mechanical play could allow some unrestrained movement[36,88]. Also the support details, representing actual construction, provided neither pinned nor fixed conditions. Residual displacements do not detract from the significance of the test results and in fact are likely to represent field conditions. However, their existence does require additional care in the presentation of data. Both incremental and cumulative displacement values were required to fully describe the behaviour and to allow comparative studies for each test specimen. In order to obtain incremental displacements during the course of a single load sequence along with cumulative displacements over the course of the entire loading sequence, gauge readings at intermediate stages were required. Also, readings taken before and after every single load sequence ensured that any disturbance of the gauges between test sequences would not affect the results.

2.5.2 Identification of Cracking of the Veneer

From the displacements collected during the test sequence, the flexural displacement of the veneer was obtained. This displacement is schematically illustrated in Figure 2.19. It is found by subtracting the effects of any translational movement occurring at either the top or bottom shelf angle and represents the deflection of the veneer due to out of plane bending. Related to this out of plane bending action, a crack will be expected to form when the ultimate flexural tensile bond capacity of the brick-mortar interface is exceeded.

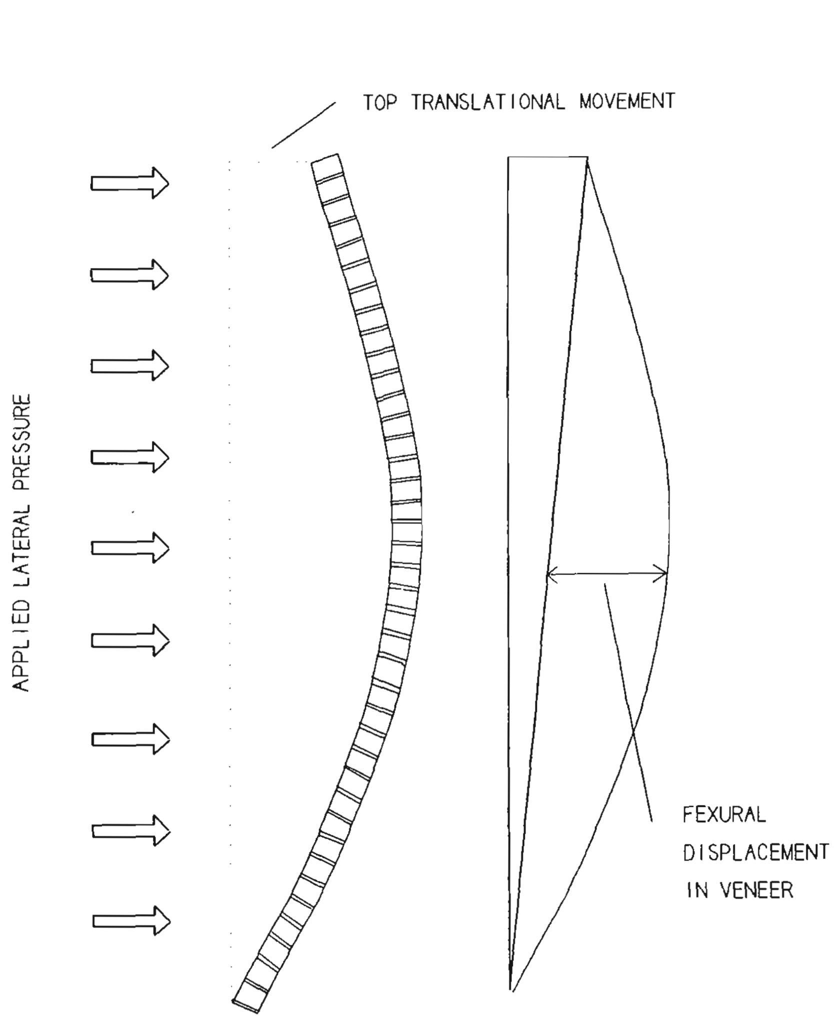


FIGURE 2.19 FLEXURAL DISPLACEMENT IN VENEER

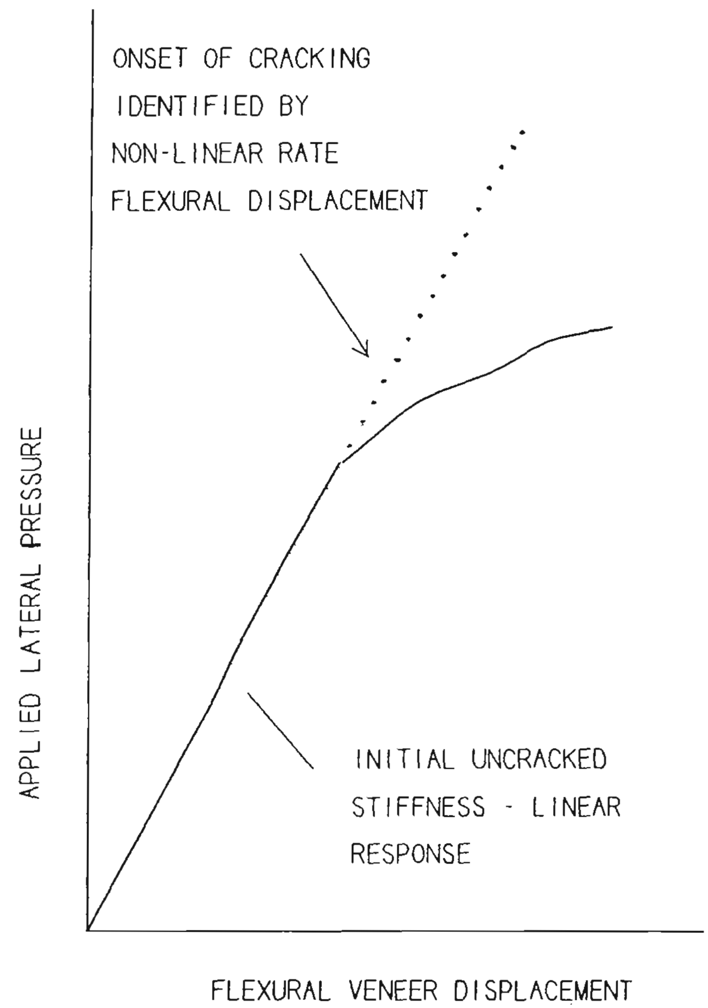


FIGURE 2.20 GRAPHICAL IDENTIFICATION OF ONSET OF VENEER CRACKING

Graphically the onset of cracking can be estimated from a plot of the flexural displacement vs. lateral pressure. Initially the slope will represent linear elastic flexural stiffness and will remain constant as the load increases. However, at the onset of cracking, the flexural displacement will increase disproportionately with the increased lateral pressure and the tangential slope will decrease indicating a loss of stiffness. This behaviour is schematically represented in Figure 2.20. Once the veneer was identified as being cracked, additional lateral pressure was applied to confirm the reduced flexural stiffness and to provide a well developed crack.

2.5.3 Ultimate Strength

Following completion of the structural tests and the rain penetration tests, the final load sequence was to determine the ultimate strength of the wall system. Since the intended use of the wall system results in air pressure on the air barrier, its capacity was quantified prior to failure of the wall system. The wall system was loaded in the cavity pressurized configuration to a level which initiated failure in the gypsum board air barrier, but did not structurally damage the steel stud backup wall or significantly harm the veneer. This was useful information since the importance of the air barrier being able to resist the structural load should not be overlooked. Otherwise the benefits of a structural wall system with enormous reserve strength may be compromised by the premature failure of a poorly designed air barrier.

To load the wall system to failure, the cavity depressurized condition was employed to avoid any influence from the previously damaged air barrier. When necessary, a plastic sheet was draped over the veneer to achieve reasonable air tightness over the specimen. Because the failure could be sudden and without warning safety precautions included termination of the manual collection of displacement data after large displacements or high pressure levels were reached.

2.5.4 Required Observations and Data

The structural test observations and data were intended to be used for comparative studies between test specimens and to verify the application of an analytical model. In addition to the displacement and pressure data, visual observations helped provide a better understanding of the overall behaviour of the wall system.

Before failure of an air barrier, its performance was evaluated so that a qualitative comparison between the test specimens was possible. Particular attention was paid to leakage paths through the air barrier and possible weaknesses in the construction details. Also the load levels at initial failure and the modes of failure and signs of distress in the air barrier were recorded.

2.6 TEST PROTOCOL

To ensure that the previously discussed structural behaviour and rain screen performance were properly covered in the overall test program, a test protocol was developed. This protocol presented schematically in Figure 2.21, was organized to ensure that all test objectives were met. Although the final sequence of loading for each test specimen varied somewhat from this outline the general framework of the protocol was common to all specimens.

2.7 SUMMARY

The laboratory procedures and test protocol developed for the rain penetration and structural tests conducted in this research project were reported. In developing these proced-

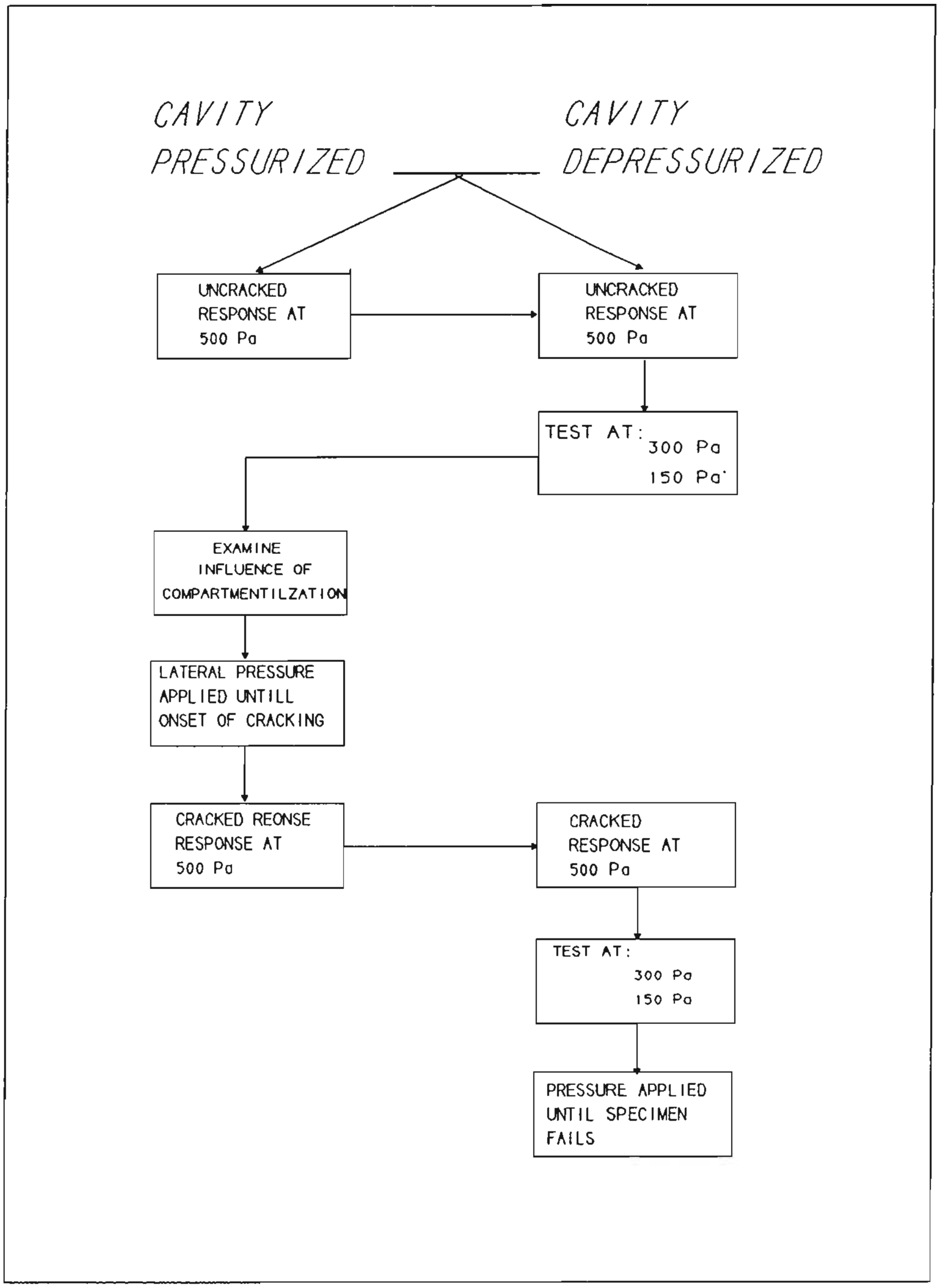


FIGURE 2.21 TEST PROTOCOL

ures and the protocol, various rationale for the test conditions and procedures have been discussed. Although the procedures and apparatus used in the program are original and unique they were developed with due consideration for relevant ASTM standards. Thus comparisons can be made between results obtained from standard tests and those from this research. The major features discussed in this chapter have been summarized below for easy reference and to provide a more concise presentation of the test procedure.

1: Objectives: A description of test objectives along with a sequence of loading within the testing protocol was designed for each specimen.

2: Control of Cavity Pressurization: A method of providing open and closed weep holes and vents in the veneer was adopted. This together with controlled exhaust of air from the cavity allowed various levels of cavity pressurization to be achieved.

3: Collection of Water in the Cavity: A water collection system was installed within the cavity. This system provided several drains and prevented any accidental spillage.

4: Air Pressure: A standard air pressure of 500 Pa was maintained throughout the test sequence unless otherwise varied in the test protocol.

5: Water Supply: A line pressure of 69 Pa and a global flow of approximately 5.6 $L/min/m^2$ was supplied and produced a thin sheet of water over the entire wall surface.

6: Duration: Each rain penetration sequence within the test continued for 4 hours.

7: Record of Observations: Leakage measurements were recorded every 30 minutes and observations were reported in intervals not exceeding 30 minutes. Displacement and pressure data was collected at 50 Pa increments for all load sequences. Observations included the time of first sighting dampness, wetness and water flow from the cavity.

CHAPTER 3

MATERIAL PROPERTIES AND FABRICATION OF TEST SPECIMENS

3.1 INTRODUCTION

To properly document the wall tests and provide a basis for comparison between component and full scale testing, it is necessary to quantify the basic properties of the components that comprise the wall systems. Because it is not practical to investigate the significance of every parameter through full-scale wall tests, knowledge of material and physical properties provides the information required for numerical analyses which can be used to supplement the test results.

In this chapter, the results from standard tests conducted to define various strength and stiffness properties of the wall components are presented. In addition, the quality control measures adopted in the laboratory, with respect to the masonry materials, are discussed along with their significance to the study. Also included is a description of the design considerations and construction details for each wall specimen.

3.2 MASONRY MATERIALS

3.2.1 General

An extensive series of tests on blocks, bricks, and mortar were carried out as part of this project. These results were used both to quantify material properties and to judge quality control.

3.2.2 Clay Brick Characteristics

The characteristics of the brick units identified as significant to the test program included physical appearance, flexural strength, compressive strength and absorptive properties.

1) Physical Appearance

The yellow clay bricks had a high quality appearance with very little evidence of fire cracking and were identified as SW grade type FBX [21]. Canada Brick supplied all the bricks in one shipment to ensure uniformity. The dimensions and wet and dry weights for ten bricks measuring approximately 57x90x190 mm with three 36 mm diameter cores are listed Table 3.1. A sketch of the brick is shown in Figure 3.1.

2) Initial Rate of Absorption (IRA)

A strong bond between bricks and freshly laid mortar requires intimate contact and sufficient water for the hydration process. If a brick's IRA is low, then the unit may float on the mortar and draw very little moisture into its pore structure. Alternatively if a brick has a very high IRA, the mortar may loses too much water and stiffen to an unworkable state. Both cases can result in poor bond and water permeable joints.

Previous researchers have indicated the importance of the IRA with respect to water permeance and have suggested limits [29,61,68]. However, it has also been documented that, because of other factors such as roughness, pore structure and fineness modulus of the mortar mix, the brick's IRA alone cannot be used to predict bond strength [42,90]. Consideration should also be given to the relationship between the IRA of the brick and the water retentivity of the mortar. Although the precise significance of the brick's IRA is not known, the current Canadian standard [21] contains a recommended limit of 30 g/min/194 cm^2 but this is not man-

TABLE 3.1 BRICK CHARACTERISTICS

Anet = Agross − 3×(pi×18²)

No.	L mm	D mm	T mm	Wdry g	Agross mm²	Anet mm²	Density g/mm²	Wwet g	IRA g/min/200 cm²	IRA g/min/194 cm²	Wsat g	C %	Wb g	B %	C/B
1	188	90	57	1460.0	16920	13866.4	0.0018	1475.5	22.36	21.69	1622.0	11.1%	1703.0	16.6%	0.67
2	190	88	57	1458.2	16720	13666.4	0.0019	1474.1	23.27	22.57	1621.5	11.2%	1707.0	17.1%	0.66
3	190	89	58	1463.2	16910	13856.4	0.0018	1479.3	23.24	22.54	1631.6	11.5%	1711.0	16.9%	0.68
4	190	90	57	1455.0	17100	14046.4	0.0018	1470.5	22.07	21.41	1617.0	11.1%	1701.0	16.9%	0.66
5	189	90	57	1456.0	17010	13956.4	0.0018	1473.0	24.36	23.63	1624.0	11.5%	1704.5	17.1%	0.68
6	189	89	57	1460.1	16821	13767.4	0.0019	1475.0	21.65	21.00	1620.5	11.0%	1705.0	16.8%	0.65
7	190	91	58	1458.3	17290	14236.4	0.0018	1472.7	20.23	19.62	1618.5	11.0%	1700.5	16.6%	0.66
8	189	89	58	1460.4	16821	13767.4	0.0018	1475.2	21.50	20.86	1624.5	11.2%	1708.0	17.0%	0.66
9	190	89	56	1439.8	16910	13856.4	0.0019	1455.8	23.09	22.40	1605.0	11.5%	1689.0	17.3%	0.66
10	190	90	58	1468.4	17100	14046.4	0.0018	1482.2	19.65	19.06	1626.5	10.8%	1712.0	16.6%	0.65
MEAN	189.5	89.5	57.3	1457.9	16960.2	13906.6	0.0018	1473.3	22.14	21.48	1621.1	11.2%	1704.1	16.9%	0.66
COV.	0.4	0.9	1.2	0.5	1.0	1.2	1.7	0.5	6.5	6.5	0.4	2.3	0.4	1.4	1.4

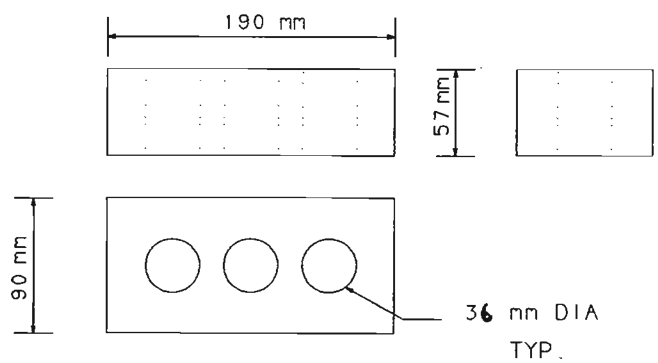


FIGURE 3.1 BURNED CLAY BRICK UNIT

datory. The results of the IRA tests done in accordance with CSA A82.2 [27] are shown in Table 3.1.

Calculation of the IRA, as indicated in the test standard [27], normalizes the unit's net area to 200 cm^2 for cored samples. However, the limit recommended by the current brick standard [21] expresses the IRA normalized to 194 cm^2 and is consistent with the dimensional units provided in American test standards [5] (ie. g/min 30 in^2). To facilitate use, the average results have been expressed for both 200 cm^2 and 194 cm^2. The average IRA for the yellow clay bricks was 21.5 g/min/194 cm^2.

3) Absorption

Also listed in Table 3.1 are the results, expressed in percent increase in mass, from the standard 24 hour cold submersion, "C", and 5 hour boiling absorption tests, "B". The ratio of these two absorption values is called the C/B ratio or the saturation coefficient. The significance of this test lies in its indication of brick pore size distribution and durability to freeze thaw action. The average 5 hour boiling absorption (B=16.9%) and saturation coefficient (C/B=0.66), shown in Table 3.1, indicate that the unit's absorptive properties satisfy the corresponding limits [21] of 17% and 0.78 for grade SW brick.

4) Strength Properties

The compression and the modulus of rupture tests were conducted in accordance with standard test procedures [27] with the exception that whole brick units as opposed to half units were used for the compression tests. The test configurations and typical failure modes are shown in Figure 3.2. The failure loads and calculated ultimate strength based on average net and on gross areas are listed in Table 3.2. The failure mode consisted of vertical splitting of

TABLE 3.2 CLAY BRICK STRENGTH TEST RESULTS

BRICK No.	COMPRESSION			MODULUS OF STRENGTH	
	Load N	Strength Net Area MPa	Strength Gross Area MPa	Load N	Strength MPa
1	914064	65.73	53.89	12454	10.54
2	909616	65.41	53.63	5427	4.59
3	1094208	78.68	64.52	4448	3.76
4	1118672	80.44	65.96	9341	7.91
5	1223200	87.96	72.12	12899	10.92
6	1127568	81.08	66.48	13344	11.29
7	1256560	90.36	74.09	8451	7.15
8	1243216	89.40	73.30	7117	6.02
9	1035384	74.52	61.11	6672	5.65
10	1123120	80.76	66.22	9341	7.91
MEAN	1104660.80	79.43	65.13	8949.38	7.57
COV.	11.1	11.1	11.1	35.1	35.1

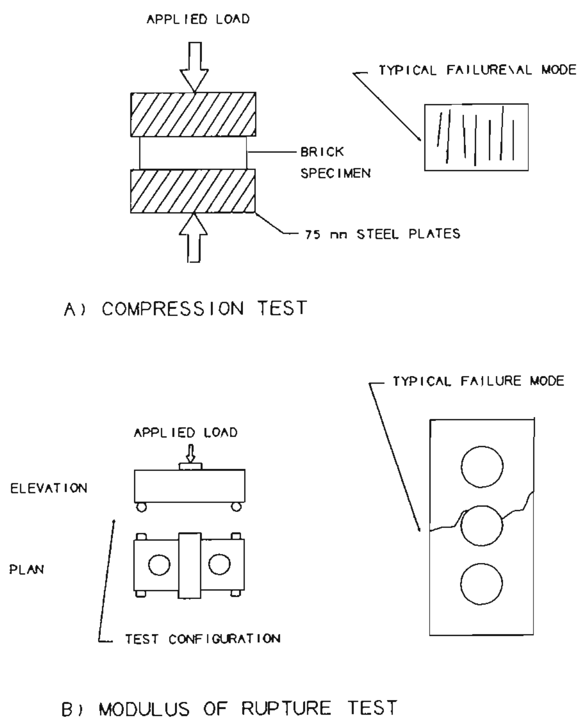


FIGURE 3.2 BRICK UNIT STRENGTH TEST CONFIGURATIONS

the unit into a number of columns which eventually crushed. The flexural failure loads and modulus of rupture calculated using the net cross-section are listed in Table 3.2.

3.2.3 Concrete Block Characteristics

1) Physical Appearance

The concrete blocks used in the program were delivered in one shipment. The blocks nominally measured 390x190x190 mm and contained two pear shaped cores with flared tops. The dimensions are shown in Figure 3.3. Only stretcher units were used in the wall specimens in order to avoid non-uniformity due to splitter units.

2) Compressive Strength

The compressive strengths of 10 blocks, determined in accordance to standard test procedures [4,26], are shown in Table 3.3 in terms of both net and gross areas. Also a typical failure pattern is shown in Figure 3.4.

The net area of 41500 mm^2, corresponding to 56% of the gross area, was adopted from OCBA literature [67]. The basis for this value lies in the net volume to gross volume ratio (percent solid) of the unit, which was 56%. It is recognized that by not discounting the flared sections, this is an overestimate of the actual effective net area of the unit.

3.2.4 Mortar Characteristics

The type S mortar chosen for the test program had proportions by volume of either Portland Cement:Masonry Cement:Sand of 1:2:8 or Portland Cement:Hydrated Lime:Sand of 1:0.5:4. Mortar batches were actually proportioned by weight to improve quality control and were limited to approximately 70 kg batches to avoid excessive retempering. A sieve analysis was performed on the sand to ensure adequate gradation. Physical tests of the fresh mortar

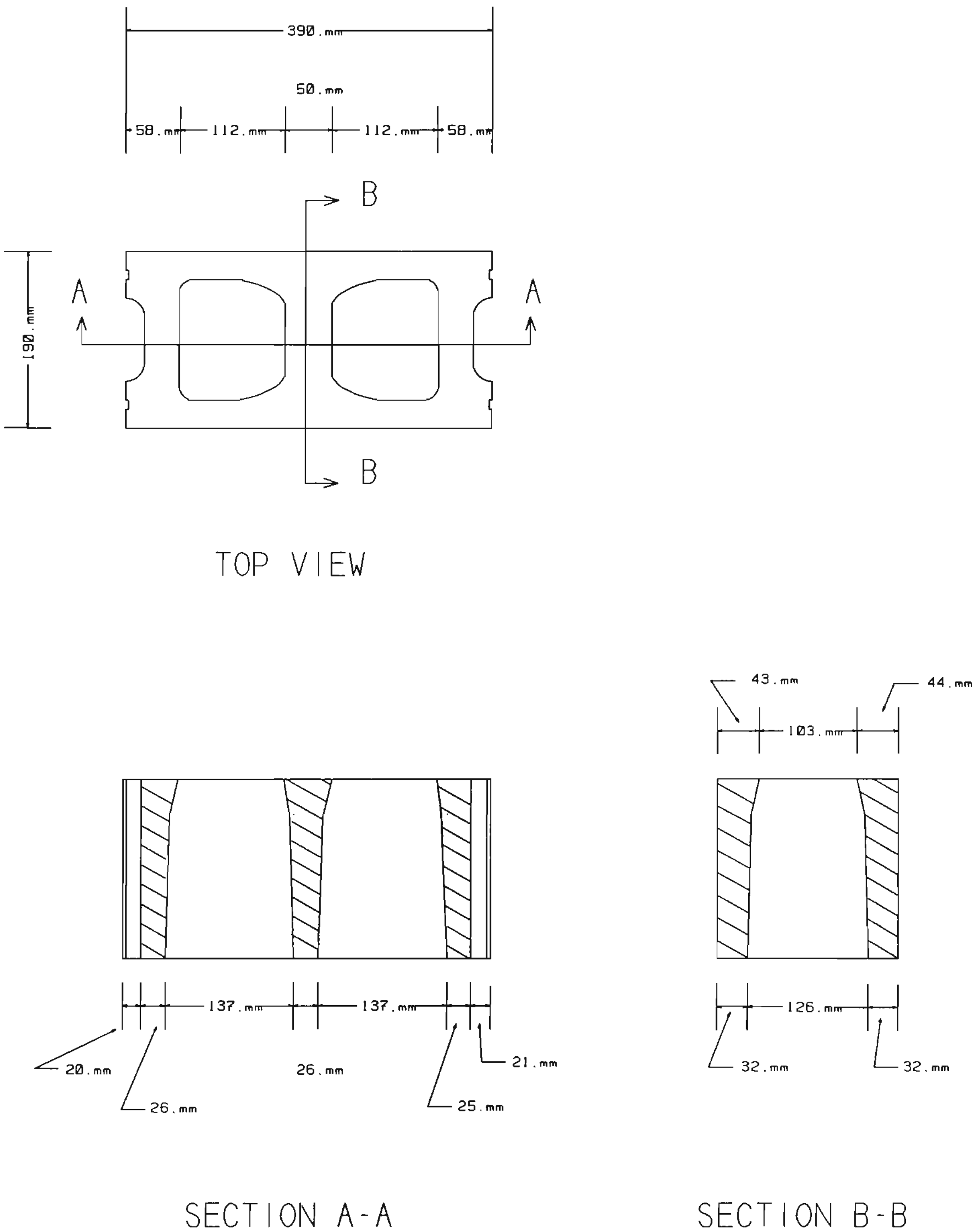


FIGURE 3.3 CONCRETE BLOCK DIMENSIONS

TABLE 3.3 CONCRETE BLOCK STRENGTH TEST RESULTS

BRICK No.	COMPRESSION		
	Load N	Strength Net Area MPa	Strength Gross Area MPa
1	944088	22.75	12.74
2	993016	23.93	13.40
3	896272	21.60	12.10
4	925184	22.29	12.49
5	942976	22.72	12.73
6	1070856	25.80	14.45
7	900720	21.74	12.16
8	985232	23.74	13.30
9	937416	22.59	12.65
10	1008584	24.30	13.61
MEAN	960434.40	23.14	12.96
COV.	5.6	5.6	5.6

Area Gross – 74100 mm^2
Area Net – 41500 mm^2

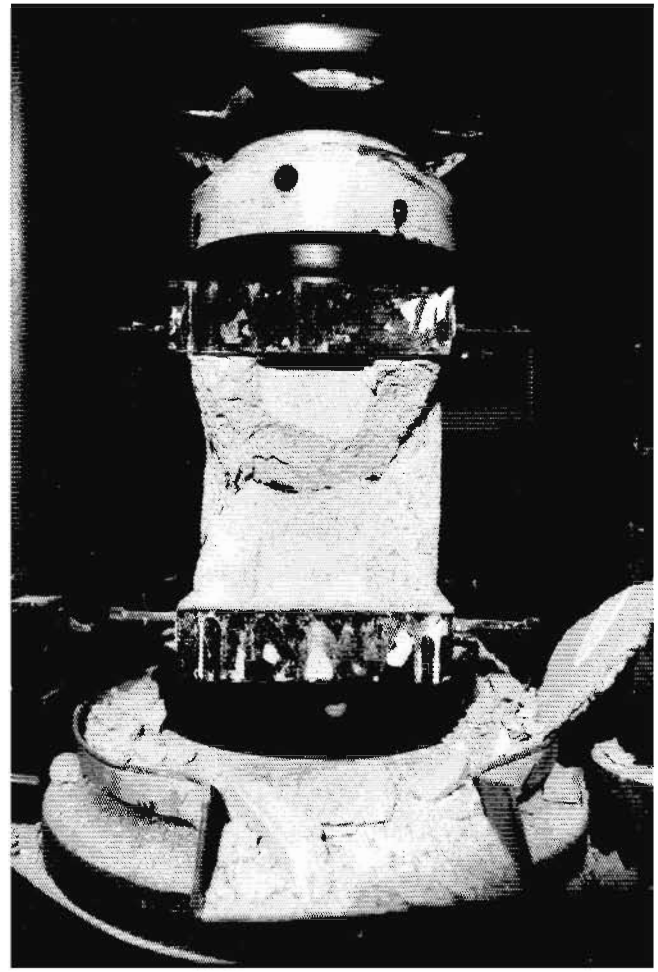


FIGURE 3.4 TYPICAL COMPRESSION FAILURE PATTERN FOR CONCRETE BLOCK

included: flow measurements, air content and water retentivity. Mortar cubes were tested after 28 days. Average values are listed in Table 3.4 and the individual test results for all mortar batches are reproduced in Appendix 1. These resultsare discussed below:

1) Sieve Analysis of Masonry Sand

The sand was dried before use to improve moisture consistency. Three gradation curves for the sand are shown in Figure 3.5 along with the gradation limits from CSA A82.56 [20]. The fineness modulus was determined to be 3.4 for the three very similar gradation curves.

2) Flow Measurements

Mortar flow measurements were performed after mixing each batch and used as an indication of the mortar's consistency. The average results for each wall are shown in Table 3.4. Batching in small quantities and limiting the use to less than 2 hours allowed construction in the laboratory to proceed without retempering the mortar.

3) Water Retentivity

The water retentivity tests were conducted on the same mortar samples used in the above flow measurements in accordance with the standard procedures [23]. From current standards [21], the minimum flow after testing is 70% of the initial flow. The data shown in Table 3.4 indicates that the water retentivity values for the mortars used in this test program were adequate.

4) Air Content

Current North American masonry standards are not consistent regarding the importance of air content. Canadian standards provide no guidance on the acceptable air

TABLE 3.4 MORTAR CHARACTERISTICS

DESCRIPTION		TEST SPECIMEN				
		Wall 1	Wall 2	Wall 3	Wall 4	Wall 5
Mix Proportions:	PC	1	1	1	1	1
(by weight)	MC	1.44			1.44	1.44
	L		0.33	0.33		
	S	9.52	4.81	4.81	9.52	9.52
Flow Measurement:						
	Initial - %	120	125	120	125	126
	COV(%)	(1.4)	(1.0)	(3.40)	(3.2)	(1.5)
	Retention - %	99	109	98	92	101
	COV(%)	(1.5)	N/A	(2.4)	(3.0)	(4.4)
Air Content:						
	%	12.1	6.5	8.3	14.9	17.2
	COV(%)	(6.2)	N/A	(6.8)	(2.8)	(4.4)
Cube Strength:						
	Air Cured - (MPa)	9.4	22.2	14.6	15.73	10.9
	COV(%)	(13.6)	(8.0)	(9.1)	(10.2)	(12.8)
	Water Cured - (MPa)			15.2	12.1	
	COV(%)			(10.8)	(8.5)	

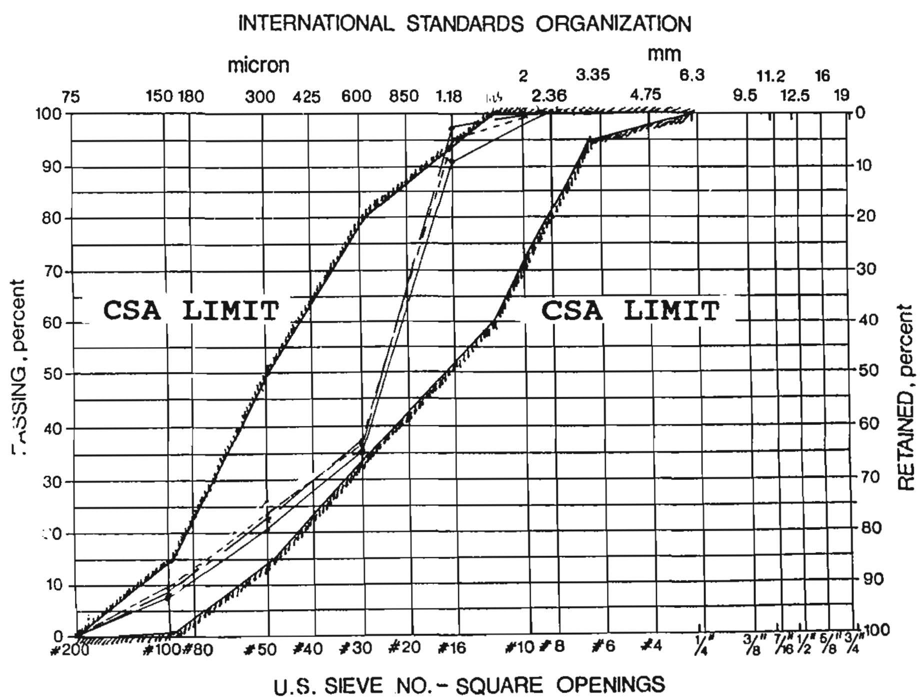


FIGURE 3.5 GRADATION CURVES FOR MASONRY SAND

content of mortar [28], whereas American standards [5] specifies a maximum of 18% for masonry cement mortar and 12% for lime- cement mortars, when used for structurally reinforced masonry. The air content values shown in Table 3.4 appear to be in line with the American requirements.

5) <u>Cube Strength</u>

Mortar cubes were tested to judge the curing progress of the wall specimens. Thus, standard moist curing by submersion in lime saturated water was not followed for all walls. Instead the cubes were cured along side the wall test specimen in the laboratory. The average cube strengths obtained for each wall are listed in Table 3.4.

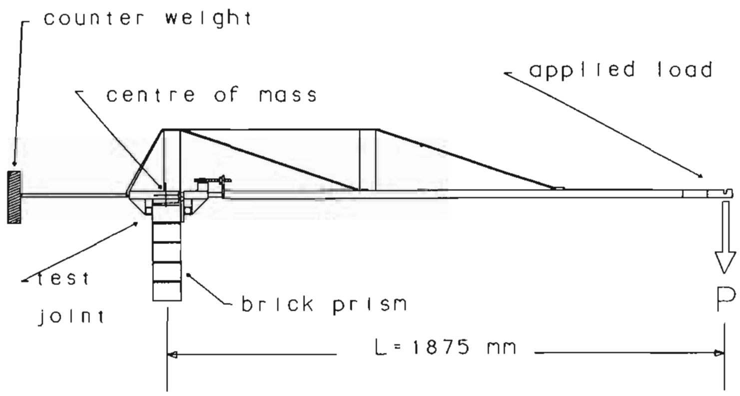
For two walls, one using lime and one using masonry cement, the effect of water curing the mortar cubes was examined. After one day of air curing, the mortar cubes were submerged in distilled water saturated with hydrated lime. For the masonry cement mortar, the results showed a reduced compressive strength whereas the lime mortar increased in strength.

3.2.5 Flexural Strength Tests

Both bond wrench [2] and beam [1] flexural tensile strength tests were conducted in accordance with standard test procedures. In addition to testing prisms built by the mason during construction of the veneer, test prisms were cut from uncracked areas of the wall specimens after failure. This practice was adopted to check the flexural strength properties of the wall specimens.

1) <u>Bond Wrench Tests</u>

Bond wrench tests were carried out using the apparatus shown in Figure 3.6. Although the lever arm distance (measured between the centre of the brick and the point of



$$F = \frac{6PL}{BDD} - \frac{(P+W)}{BD}$$

FIGURE 3.6 BOND WRENCH APPARATUS

TABLE 3.5 FLEXURAL STRENGTH TEST RESULTS

DESCRIPTION	TEST SPECIMEN				
	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5
Masonry Cement (MC) or Lime Mix	MC	Lime	Lime	MC	MC
Bond Wrench:					
Test Prisms – (MPa)	0.72	0.89	0.78	0.68	0.76
number of joints	71	68	71	70	72
COV(%)	(33.6)	(43.4)	(39.8)	(18.6)	(21.2)
Wall Specimen – (MPa)	0.70	0.80	0.70	0.62	N/A
number of joints	14	15	16	16	N/A
COV(%)	(34.2)	(33.23)	(25.4)	(24.2)	N/A
Beam Test: Perpendicular					
(MPa)	0.66	1.04		0.40	0.72
number of samples	5	5		5	5
COV(%)	(23.4)	(20.12)		(20.42)	(15.75)
Parallel					
(MPa)		2.63	3,21	2.37	
number of samples		5	4	5	
COV(%)		(28.0)	(11.16)	(14.7)	

load action) of 1875 mm does not conform to the current standard bond wrench test procedure [2] it has been established that the actual length of the moment arm does not influence the results[42].

The test procedure involved clamping the bond wrench device onto a single brick and slowly adding weight (sand) to a bucket suspended at the far end of the wrench until the bond between the brick and the mortar failed. The flexural tensile strength was determined by weighing the sand and calculating the flexural stress at the mortar joint as shown in Figure 3.6.

The test results shown in Table 3.5 are the average values from all the joints of all the prisms made for each wall specimen. To compare the results between wall specimens with various mortar compositions, the statistical variance must be considered. Typically, large coefficients of variation limit conclusions regarding the significance of differences between mean values. Not withstanding this limitation, it can be seen that the lime based mortars exhibited greater flexural bond strength than masonry cement based mortars. This was true regardless of whether the prisms where made separately or cut from the wall. In the latter case, the brickwork had been subjected to additional curing due to the rain penetration studies. It is also recognized that those prisms removed from the wall showed a decrease in flexural strength, possibly attributable to an uneven trade off between the benefits of additional moist curing conditions and poorer filling of the mortar joints.

In addition to the brick masonry prisms tested, concrete block specimens were constructed with the material used for WALL5. Although the bond wrench apparatus used to test these prisms was much sturdier, the same principles were applied. The results indicated an average flexural bond strength of 0.28 MPa with a C.O.V. of 8.5%.

2) <u>Beam Tests</u>

Beam tests on the two configurations of specimens shown in Figure 3.7 were carried out to examine flexural strengths both parallel and perpendicular to the bed joints of the veneer. These specimens were removed from the walls after failure and were cut to the required size and shape. Only for walls where two way bending was expected was tensile strength parallel to the bed joint investigated. Unfortunately, for WALL 3 excessive cracking prohibited recovery of prisms high enough for flexural strength tests perpendicular to the bed joint.

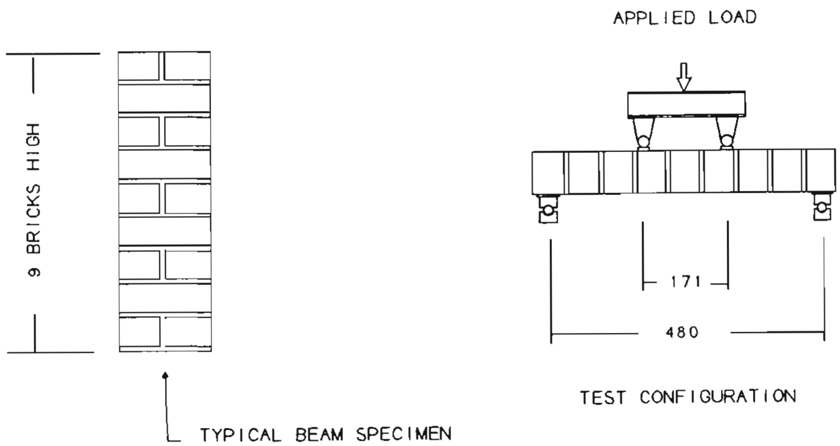
The procedures followed in the lab closely conformed to the current masonry beam test standard [1], the major exception being the specimen length when availability of uncracked portions of the wall specimen was limited. The span lengths and loading configurations are shown in Figure 3.7.

The results shown in Table 3.5 indicate that the flexural bond strength was generally higher for the bond wrench tests than the beam tests. This can be attributed to the fact that in the beam test configuration, only the critical combination of bending moment and joint strength are measured whereas the bond wrench test results include the strengths of all joints.

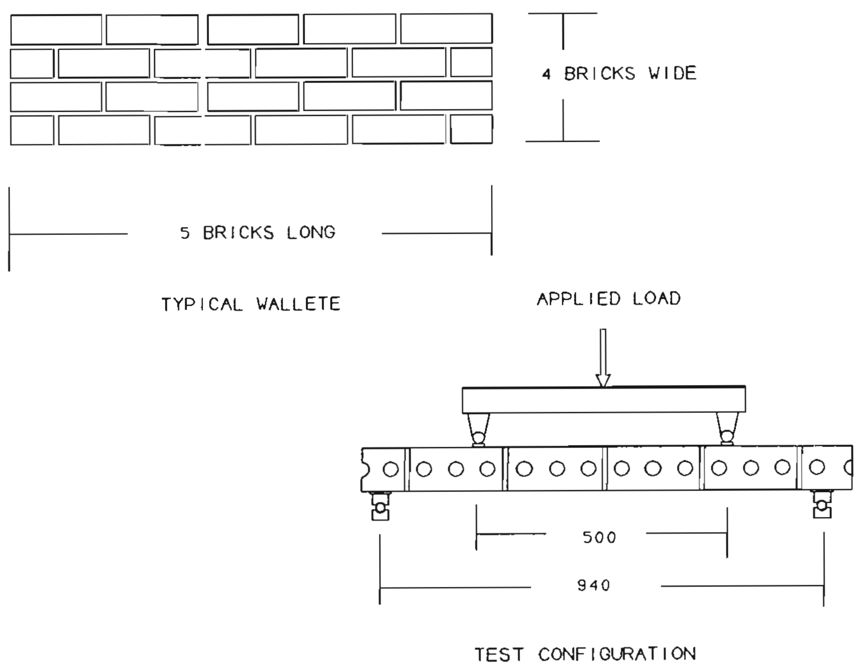
3.2.6 Compression Tests of Prisms

Prisms were cut from the failed wall specimens to obtain compressive strength (f'm) and strain properties (Em) of the brick veneer. Young's moduli, Em, was defined as the secant stiffness occurring at 25% of the compressive strength.

As shown in Figure 3.8, the specimens were gauged with linear variable potential transducers to record strain readings during testing. The gauge length of approximately 127 mm was positioned across mortar and brick in the ratio of 1:5.35 which is close to the actual material proportions of 1:5.7 present in the wall. The average results for each wall specimen



a) Tension Parallel to Bed Joint



b) Tension Perpendicular to Bed Joint

FIGURE 3.7 FLEXURAL BEAM TEST CONFIGURATIONS

TABLE 3.6 COMPRESSION PRISM TEST RESULTS

DESCRIPTION	TEST SPECIMEN				
	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5
Masonry Cement (MC) or Lime Mix	MC	Lime	Lime	MC	MC
Compression Tests:					
f'_m (MPa)	41.2	42.7	32.3	31.5	35.17
number of prisms	5	5	3	5	5
COV(%)	(2.8)	(6.9)	(5.9)	(4.0)	(6.1)
Young's Moduli: @ 25% f'_m (MPa)	13760	15500	14400	15630	11490
COV(%)	(15.9)	(11.7)	(11.9)	(3.4)	(10.5)

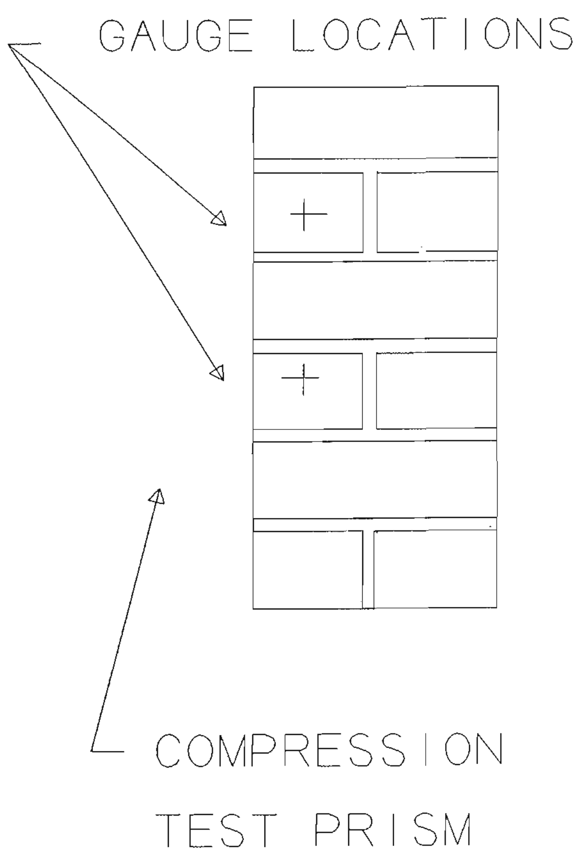


FIGURE 3.8 GAUGE LOCATION FOR PRISM TEST

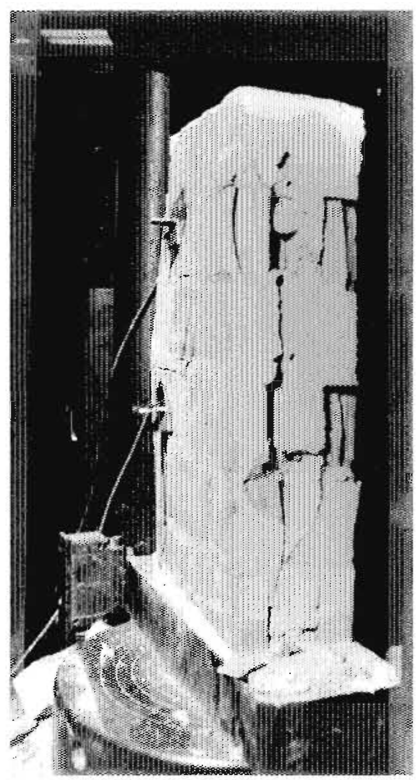


FIGURE 3.9 TYPICAL FAILURE MODE OF COMPRESSION PRISM

are shown in Table 3.6 and the individual stress-strain curves and failure loads are provided in Appendix 2. Figure 3.9 is a photograph of the typical vertical splitting failure mode.

3.3 STEEL STUD BACKUP WALL COMPONENTS

The component properties of the steel stud backup had been determined in PART 1 [33] of the CMHC/McMaster BV/SS research program. The following extracted information defines the relevant properties.

- Material Properties - Based on virgin steel tested in accordance with A.S.T.M. A370,yield stresses between 255 and 262 MPa were reported.
- Flexural Strength of Steel Stud - Using a standard two point load test on two stud sections placed back to back to eliminate twisting, an average flexural strength of 1.825×10^6 Nmm was determined for each 18 gauge 92 mm deep steel stud.
- Stiffness of Nested Top Track Connection - For the nested top track detail, average ultimate and yield loads of 2.9 and 1.9 kN, respectively, were documented. The secant stiffness at 2 mm of displacement was 517 N/mm.
- Shallow Bottom Track Connection Stiffness - For the bottom stud to shallow track connection, average ultimate and yield loads of 4.7 and 3.7 were documented. The secant stiffness at 2 mm of displacement was 964 N/mm.

3.4 BV/SS WALL TIE SYSTEMS

Strength and stiffness characteristic of the BV/SS wall tie systems used in this program had been defined by PART 4 [36] of the CMHC/McMaster BV/SS research program. In this investigation twelve commonly used wall tie systems were examined for strength and stiffness properties.

The four wall ties chosen were representative of field use and excluded the stiffest and most flexible systems. These ties, their secant stiffness ranges over their ranges of adjustability at 1.2 mm displacement, ultimate capacities and material properties are:

•	Double Leg Adjustable	– secant stiffness	= 363-608	N/mm
		– ultimate capacity	= 1678-1709	kN
		– anchor yield stress	= 283	MPa
		– wire yield stress	= 696	MPa
•	Wire Loop Anchor on Support Stand	– secant stiffness	= 428-598	N/mm
		– ultimate capacity	= 1503-1288	kN
		– anchor yield stress	= ---	
		– wire yield stress	= 613	MPa
•	Bailey Wrap Around Tie	– secant stiffness	= 691-775	N/mm
		– ultimate capacity	= 4500-2642	kN
		– anchor yield stress	= 353	MPa
		– wire yield stress	= 615	MPa
•	Posi-Tie	– secant stiffness	= 522-529	N/mm
		– ultimate capacity	= N/A-1418	kN
		– anchor yield stress	= ---	
		– wire yield stress	= 615	MPa

3.5 DESIGN AND CONSTRUCTION OF FULL-SCALE TEST WALLS

3.5.1 General

The BV/SS test results will be used as the basis for future recommendations on design and construction practices. Thus, to ensure the relevance of this work, the test specimens were designed to be consistent with present practices and they were assembled using typical construction details. The following sections contain full descriptions of the test specimens and provide summaries of the design and construction details employed.

3.5.2 Experimental Design of Test Program

Although experimental research using full scale walls imposes practical limitations on the number of tests, an attempt was made in the experimental design to provide some comparative test results. A major variable identified was the support condition of the veneer where specimens were selected to provide a comparison between one way and two way bending. One way bending of the SS backup wall was achieved by installing the end studs in a manner that allowed free out-of-plane deflection within the specimen frame. The veneer was therefore only supported at its base by the shelf angle and by the studs at the top of the wall. Two way bending was introduced by fixing the end studs to the sides of the specimen frame which allowed the veneer to act as a plate supported on four sides.

Other variables considered in the design of the specimens included the influence of a large opening in the wall, inverting the SS backup wall by positioning the movement joint at the bottom of the wall and the behaviour of a concrete block backup wall used in conjunction with the brick veneer. To incorporate these features, the specimen configurations illustrated in Figure 3.10 were designed. Brief descriptions of the wall specimens are as follows:

- WALL1 represented typical one way bending BV/SS wall construction with support of the veneer provided by the top line of ties connected to the steel stud wall and at the base by the shelf angle.
- WALL2 was very similar to WALL1 with the exception that the edge support of the steel stud wall introduced two way bending in the veneer.
- WALL3 represented a new design concept for the BV/SS wall system. The backup wall was inverted to provide the movement joint at the bottom of the wall.
- WALL4 included a large opening to investigate the adequacy of present details used to support the window and to illustrate the influence of the large opening on overall wall behaviour.
- WALL5 was constructed with a concrete block backup wall which permitted comparisons between the BV/CB and the BV/SS wall systems.

Although the structural performance and rain penetration studies in this test program included many influencing parameters within each specimen, the main comparisons between the specimens are identified in Figure 3.10 as follows:

A - one way bending vs. two way bending

B - conventional SS design vs. new inverted wall design

C - influence of a large opening

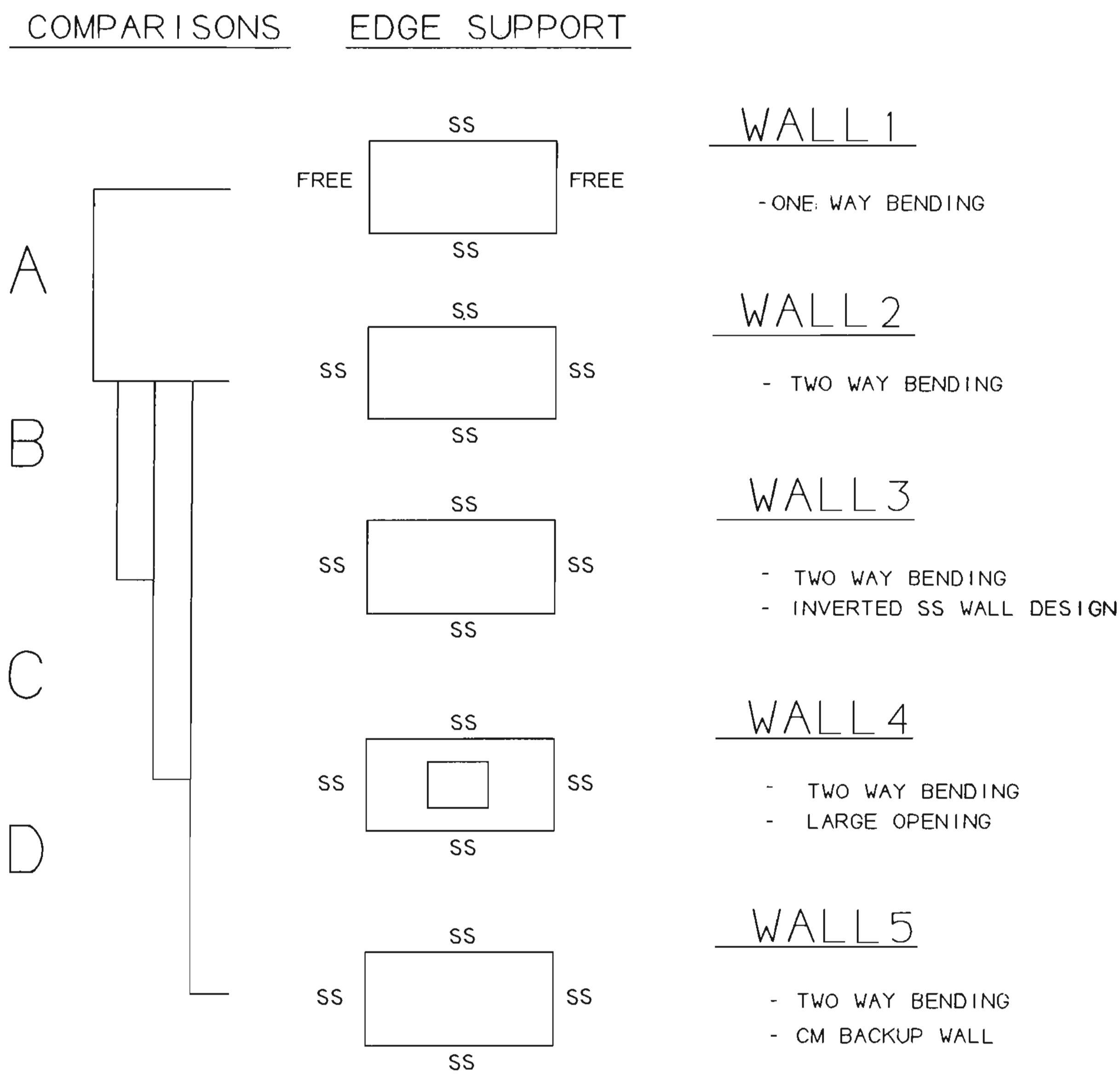


FIGURE 3.10 SPECIMEN CONFIGURATIONS

D - comparison between concrete block and steel stud backup walls

3.5.3 Structural Design of Test Specimens

1) BV/SS Wall Design

The structural design of the wall system primarily involved the selection of SS sections and their horizontal spacing. Possible load sharing by the brick veneer was not considered in the structural design of the backup wall system. This is consistent with common design practice where Masonry codes typically require that the structural backup be capable of resisting the entire applied lateral load [25]. Aside from noting the difference in stiffness between the veneer and the backup, the allowable unsupported height of a veneer wall [25] is currently limited in Canada [25].

The main criteria available for design involved limiting the out-of-plane displacement of the steel stud backup wall as an attempt to limit cracking in the brick veneer. The limits most prominently identified in the literature ranged from ratios of L/360 to L/720 where L is the height of the steel stud wall [14,19,53,62,80,81,91].

For design, the wind load was assumed to act on the horizontally spanning gypsum board sheathing and to be transferred to the load resisting vertical SS members in proportion to their horizontal spacing. Two mechanisms for load transfer were identified as either surface contact between the sheathing and the SS's or through fasteners attaching the sheathing to the SS flanges. Because of the geometric properties of the SS 'C' sections, both types of load were eccentric to the shear centre and thus produced torsion. However, from another Part [33] of the CMHC/McMaster BV/SS research program, it was established that bridging and sheathing, appropriately attached to the section, could provide adequate torsional resistance. Thus, the steel studs were designed as uniformly loaded and simply supported beams in accordance with normal bending theory.

For the design of the test specimens,a convenient stud spacing of 406 mm was chosen. The design chart in Figure 3.11 was constructed for 18 gauge 92 mm steel studs spaced at 406 mm intervals. It demonstrates that the selected 406 mm spacing naturally satisfies both the L/360 and L/720 deflection limits for design loads of approximately 2 kPa and 1 kPa respectively.

Although the structural design of the wall system only addresses the SS component of the backup wall, other details such as stud/track connections, lateral bracing, wall tie spacing and wall tie selection have all been identified as important considerations with respect to the durability and structural performance of a wall system [11,16,33,35,36,49,50,80,88,89]. In fact, the current structural design of the wall system is relatively simple compared to the amount of detailing and preparation of specifications necessary to ensure proper construction and performance.

2) BV/CB Wall Design

The current Canadian masonry code [25] allows the use of either the empirical method or engineering analysis in design. In the case of 190 mm thick hollow concrete block walls, the empirical method limits the height to 20 times thickness or 3.8 m.
(ie 20 x t).

An accurate analysis of load sharing between the BV and CB including the relative moduli of elasticity and moments of inertia of the two wythes indicated that the veneer would resist approximately 30% of the applied load. This is based on both wythes being simply supported and uncracked. Thus, allowing for load sharing, the overall design load for the system would be that which causes 1.43 times the allowable bending stress in the CB wall. Alternatively, as was the case for the SS backup walls, the CB wall could be assumed to resist the full wind load. The allowable flexural tensile stress (normal to the bed joint) for hollow

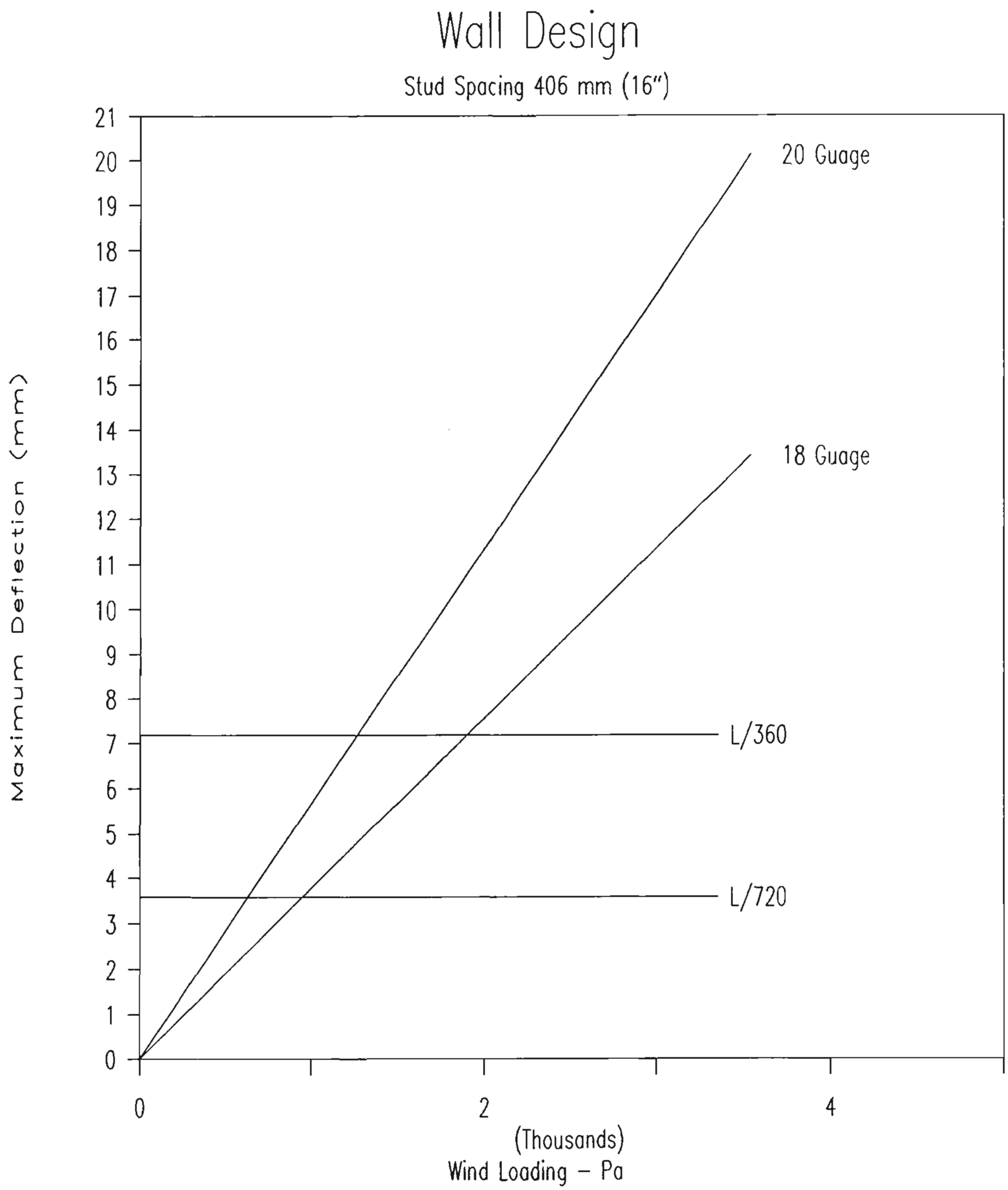


FIGURE 3.11 STEEL STUD DESIGN CHART

concrete block masonry is 0.16 MPa [25] which, for the 2.58 m wall height results in an allowable wind pressure of 1.2 kPa for load sharing and 0.84 kPa if the CB wall is assumed to resist the entire load.

3.5.4 Typical Details fo r Steel Stud Backup Walls

The following discussion covers the typical details employed in WALL1, WALL2 and WALL4. Details relevant to WALL3 and WALL5, respectively representing non-standard BV/SS practices and standard BV/CM practices are discussed separately.

Mainly 18 gauge (1.22 mm) cold formed steel components, specified as hot-dipped galvanized, were used. Pan headed TEK #6 self drilling screws were used for fastening. Since no single tradesman is responsible for the complete construction of SS backup walls, the necessary skills were assembled in house, through discussions with knowledgeable individuals and physical demonstrations in the laboratory. The only exception involved a journeyman drywall/gypsum board installer who taped the joints for WALL1 and WALL2 because proper sealing was essential for the proper performance of the air barrier.

1) <u>Top and Bottom Stud/Track Connections</u>

The standard SS connections to a shallow bottom track and the nested top track configuration, which includes a movement joint, are shown in Figure 3.12.

Movement was accommodated by providing a gap of 10-15 mm between the webs of the two nested track sections. Both stud flanges were connected to the 63.5 mm long flanges of the deep inner track which was then inserting into the shallow track (38 mm flanges) that was anchored to the test frame. Figure 3.13 contains a more detailed illustration of the required gypsum board screw locations and the required clearance provisions for the anchor bolt heads

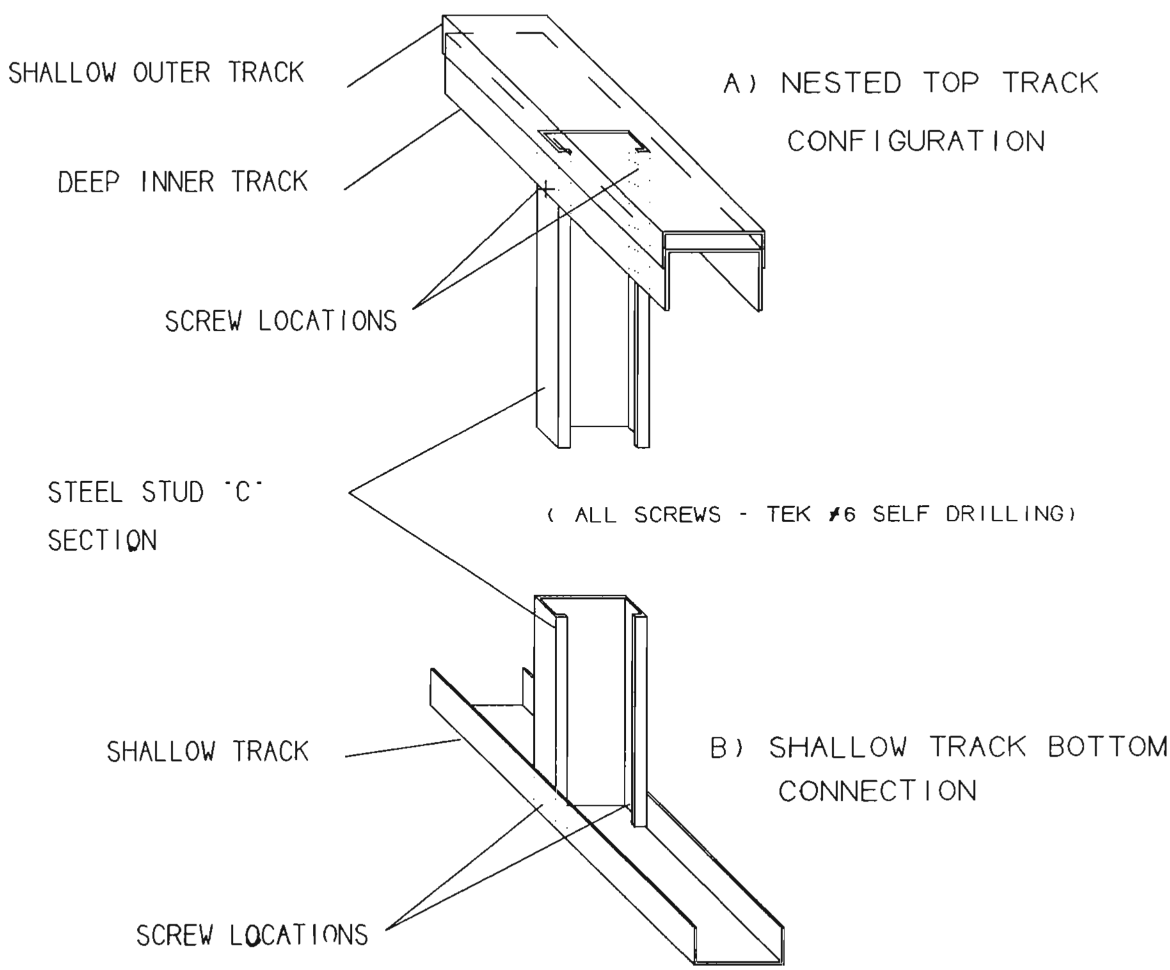


FIGURE 3.12 TYPICAL STUD/TRACK CONNECTIONS

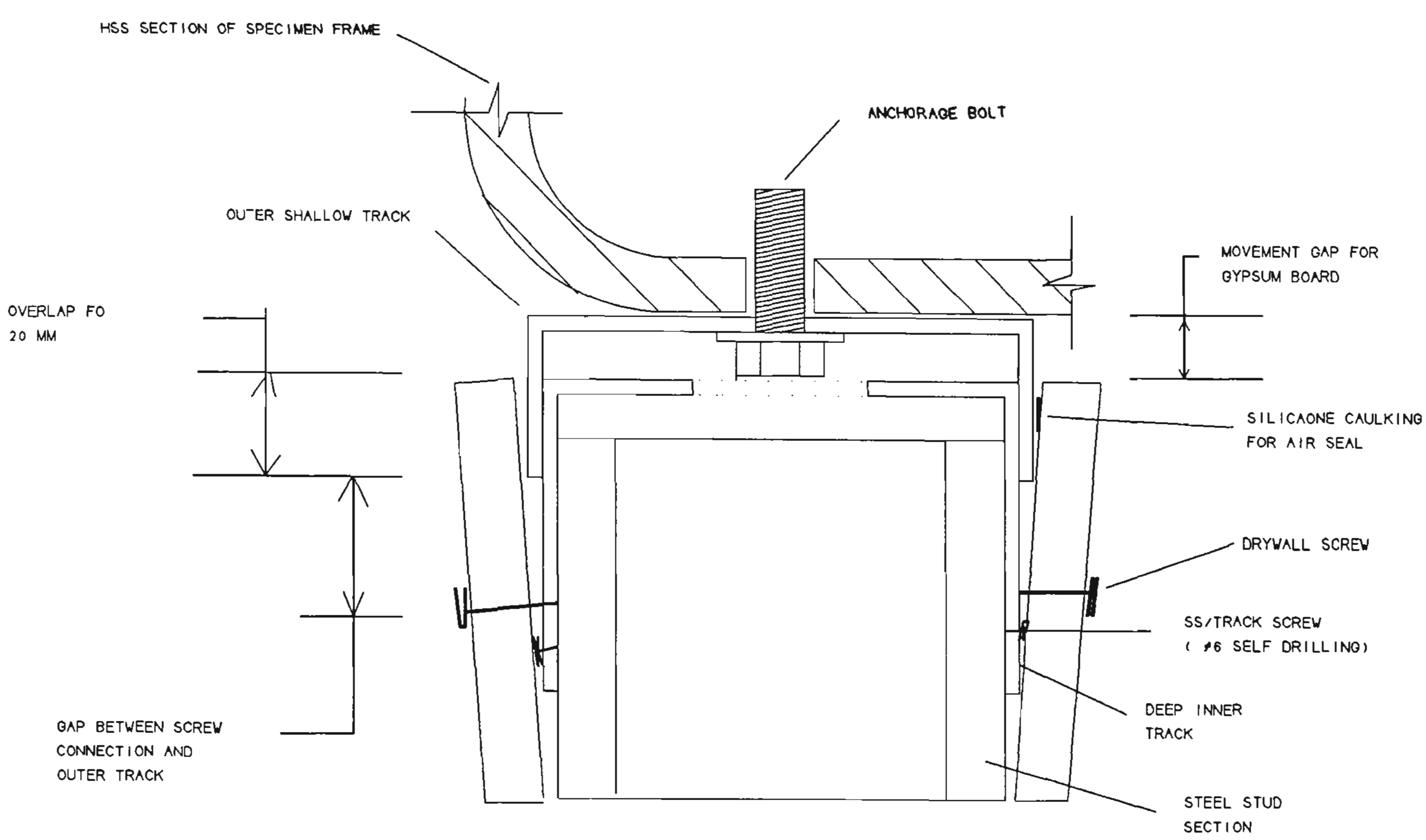


FIGURE 3.13 REQUIRED DETAILS TO MAINTAIN MOVEMENT CAPABILITIES OF THE MOVEMENT JOINT

and the gypsum board which are necessary to maintain the movement capabilities of the nested top tracks.

2) Air Barrier Design

The typical air barrier was the interior gypsum board sheathing. Interior and exterior grade gypsum board were supplied by Westrock in 1220x2440x12.5 mm thick sheets. The sheathing was attached to the studs with standard self drilling gypsum board screws spaced at 200 mm centres along each stud. Sealing of all gypsum board joints and screw hole locations with joint compound was identified as a requirement for completion of the air barrier design. Potential air leakage paths at the stud/track connections were sealed by applying a continuous bead of silicone caulking between the track flanges and gypsum boards as well as between the track and the specimen frame. Additional measures to ensure air tightness, such as painting, were not deemed necessary.

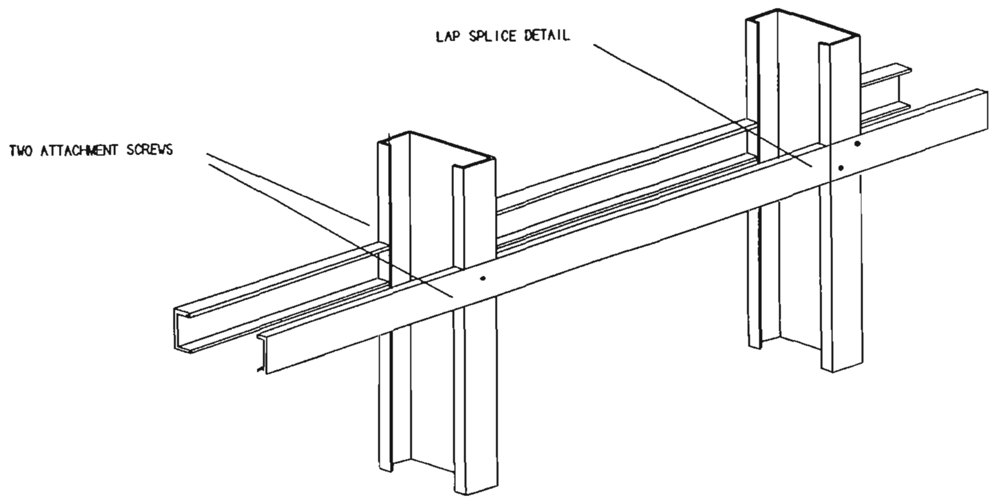
3) Details for Stud Bracing

Two forms of bracing to prevent flexural- torsional buckling of the studs, were identified in product literature [12,19,53] as representative of current practices. The typical bridging details commonly known as through-the-web bridging and external face bridging are illustrated in Figure 3.14.

Through-the-web bridging, consisting of 18 gauge channel sections (38 mm deep with a 12.5 mm flange) and 16 gauge clip angles (38x38 mm), was used in WALL1 and WALL4. An important detail involved the use of two fastening screws to attach the clip angle to the stud and to the bridging. This detail is essential for the bridging to resist twisting of the steel studs.

External face bridging, consisting of 18 gauge channel sections (38 mm deep with a 19 mm flange) with 35 mm lengths of flange removed at 406 mm intervals to facilitate connection

a) External Face Bridging



b) Through-the-Web Bridging

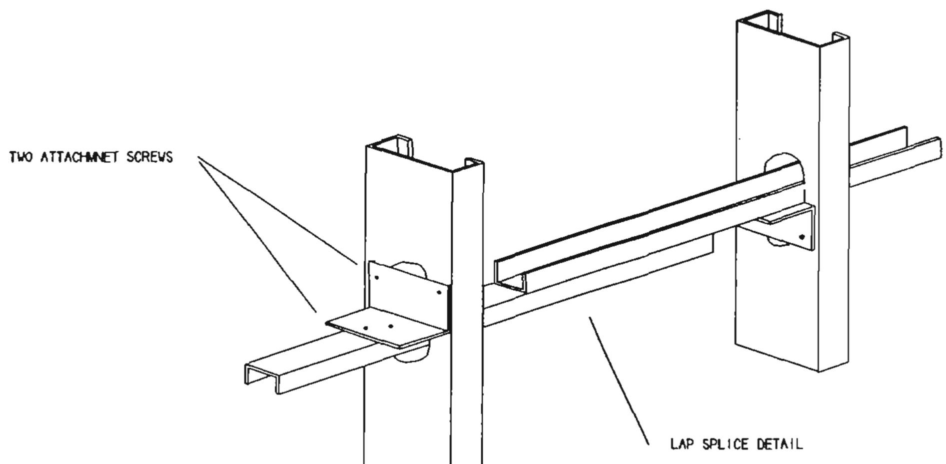


FIGURE 3.14 TYPICAL BRIDGING DETAILS

to the SS, was employed in WALL2. For this bridging to function as intended, it must be installed in a continuous manner. Since the channel sections were approximately 3 m in length, lap slices were required over the 5.2 m wall length. As shown in Figure 3.14, splicing of the channel section at a stud location ensured continuity. Splice details have typically not been dealt with in product literature.

3.5.5 Typical Details for Brick Veneer

To avoid repetition, details and construction considerations common to all veneer wall panels are presented in this section. The typical veneer panel dimension consisted of 41 courses of 26 units with an average joint thickness of 9.85 mm. Accurate course markings and vertical guide angles attached to the specimen frame ensured proper dimensions and plumb construction. Construction of the veneer was specified to provide either a 25 mm or 50 mm cavity formed between the veneer and the outer layer of exterior gypsum board sheathing on the backup wall.

Type S mortars were used in all walls and bricks were conditioned in the laboratory for a period of not less than 5 days to reach a reasonably dry state prior to laying.

1) <u>Construction Methods</u>

To ensure consistency between wall properties and those obtained from auxiliary prism testing, the experienced mason constructed both bond wrench and compression specimens along side the veneer wall. The construction period ranged from 2 to 3 days depending on the number of auxiliary test prisms required. Specific practices were as follows :

- A maximum placement of mortar sufficient for three bricks was placed before laying the bricks.
- Brick ends were fully buttered before placing.

- Only shallow furrowing of the bedjoint was allowed.
- Units moved after placement were discarded and replaced with new units and fresh mortar.
- The mortar was notretempered.
- Mortar was kept covered at most times to prevent drying out.
- Mortar not used within 2 hours was discarded.
- Chipped or excessively firecracked bricks were discarded.
- Saw cutting was used to make half units.
- Exterior joints were tooled with a cylindrical jointer.
- Interior joints were either left undisturbed or struck off with the mason's trowel.

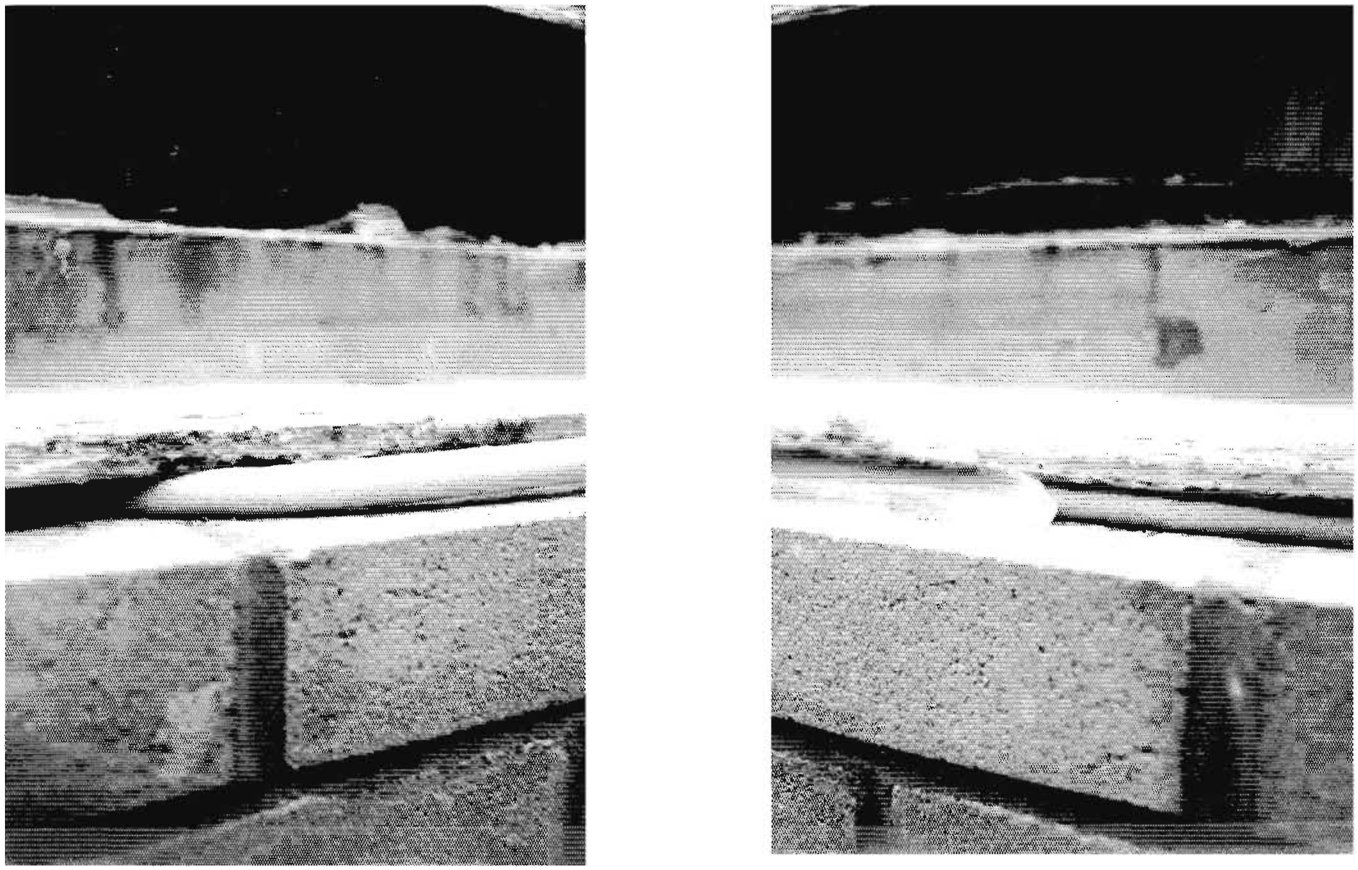
2) <u>Top Movement Joint</u>

Allowance for typical movements of 10 to 15 mm were provided by soft joints between the top veneer courses and the underside of the shelf angles as illustrated in Figure 3.15. Packing of the backer rod into the joint supports the silicone caulking used to provide a watertight seal.

The influence of the movement joint on durability and rain penetration has been addressed in the past [35,80]. However, its influence on the structural behaviour has not been established experimentally. Because the relative diameter of the backer rod with respect to the joint size is not standardized, little attention was paid to this detail in constructing the first wall specimen. From the result, it was established that a tightly packed movement joint could provide a support condition for the veneer. For other specimen, the relative size of the backer rod and movement gap were altered to further examine this feature.

3) <u>Bottom Shelf Angle Detail</u>

The first course of brick veneer was bedded in a layer of mortar on the shelf angle. The only deviation from common practise was the exclusion of flashing usually placed directly on the shelf angle. Also, to accommodate the drainage system required for collection of water in



a) Initial Packing of Backer Rod

b) Silicone Sealant

FIGURE 3.15 CONSTRUCTION OF TOP VENEER MOVEMENT JOINT the cavity, the shelf angle was positioned with the vertical leg down and shimmed out 19 mm from the specimen fame.

4) Veneer Ends

At the end of the veneer wall, saw cut bricks provided both a smooth face and a uniform veneer surface for the running bond construction. To avoid air leakage around the ends of the wall, either torched on or cold adhesive bituminous membranes were used to span the joint between the veneer and the specimen frame. This provided resistance to air movement without introducing restraint to wall displacement. Because of the time and effort required for the torch applied product, it was used for WALL1 only and an adhesive product was adopted for the remainder of the specimens.

5) Wall Ventilation

The empty head joint weep holes and vents described in Section 2.2.6 were respectively located three courses from the top and no closer than 5 courses from the bottom. As previously discussed this unconventional positioning of weep holes accommodated cavity water collection. The number of weep holes and vents were varied in the test program to study the effects on cavity pressurization.

3.6 DETAILS OF WALL1

3.6.1 Steel Stud Backup Wall

The steel stud framing for WALL1 consisted of fourteen, 18 gauge studs at 406 mm spacing except at the wall ends where 350 mm spaces were provided. Through-the-web bridging at the knock out hole located 950 mm from the bottom of the SS wall was installed using the screwed chip angle attachment shown in Figures 3.16. A photograph of the shallow

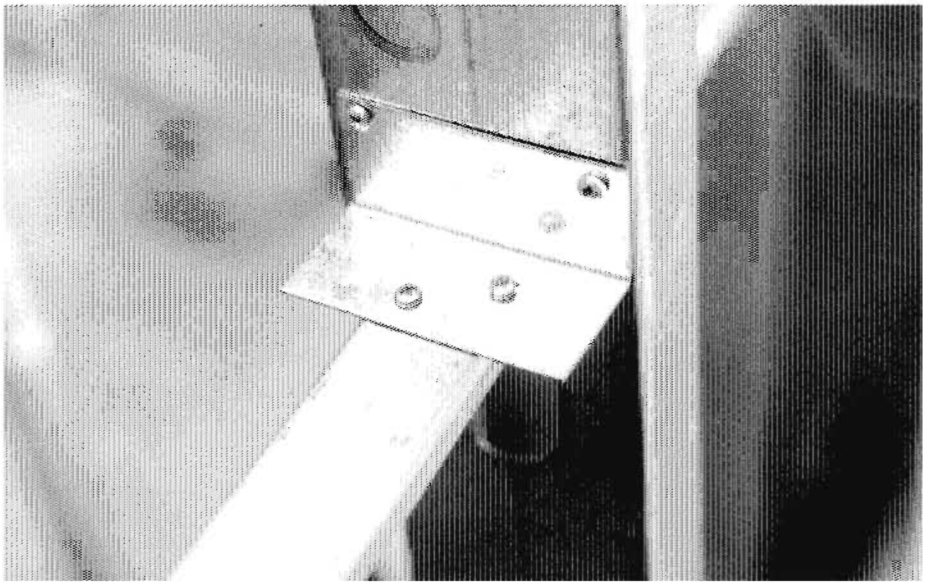


FIGURE 3.16 THROUGH-THE-WEB CLIP ANGLE ATTACHMENT DETAIL

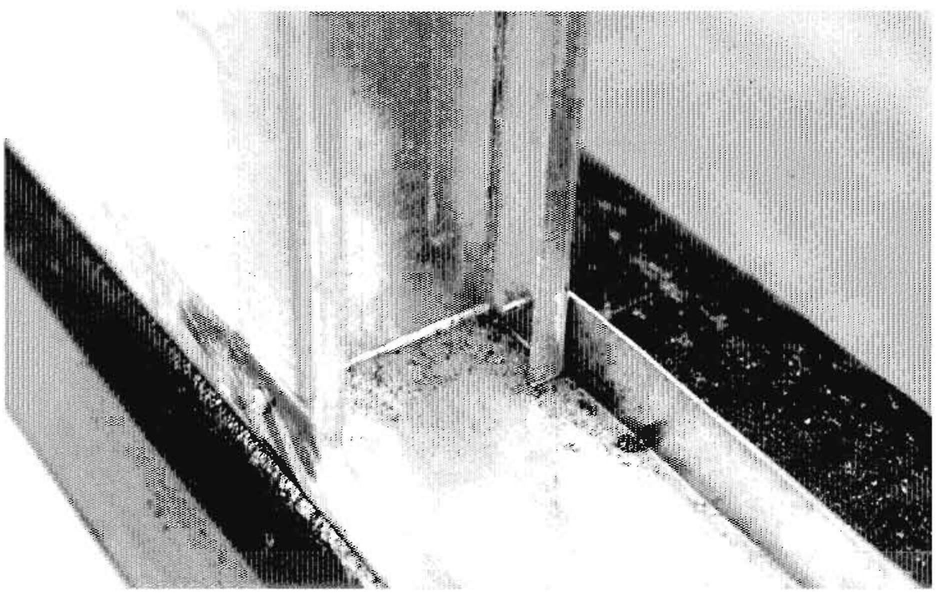


FIGURE 3.17 SHALLOW TRACK CONNECTION

bottom track connection is shown in Figure 3.17. A vertical section of the complete wall system shown in Figure 3.18, contains notes on other construction details.

1) Wall Ties

The wall tie system selected was the wire loop adjustable tie mounted on the brick veneer tie support also shown in Figure 3.18. The 75 mm wire tie length accommodated the specified 25 mm air space in the cavity and placed the anchor legs of the tie within the middle third of the brick veneer. Accurate installation of the ties was completed before constructing the veneer.

The vertical tie spacing for WALL1 satisfied the recommended 200 mm edge distance [14,15], but the maximum tributary area per tie was 0.245 m^2 instead of the recommended 0.2 m^2. However the spacing does satisfy the more practical limit of 0.267 m^2 recommended for walls with cavities less than 25 mm [14,15].

2) Air Barrier Design

The interior gypsum board air barrier had properly taped joints and sealed screw holes but no special attention was given to caulking details. Instead the gypsum board was placed tightly up against the perimeter of the specimen frame in a manner that appeared snug with no gaps.

3.6.2 Brick Veneer Wall

The brick veneer was constructed with undisturbed mortar fins in the cavity. The 25 mm air gap between the veneer and the exterior sheathing plus the 92 mm air space between the exterior and interior gypsum board sheathing provided an air volume of 1.60 m^3.

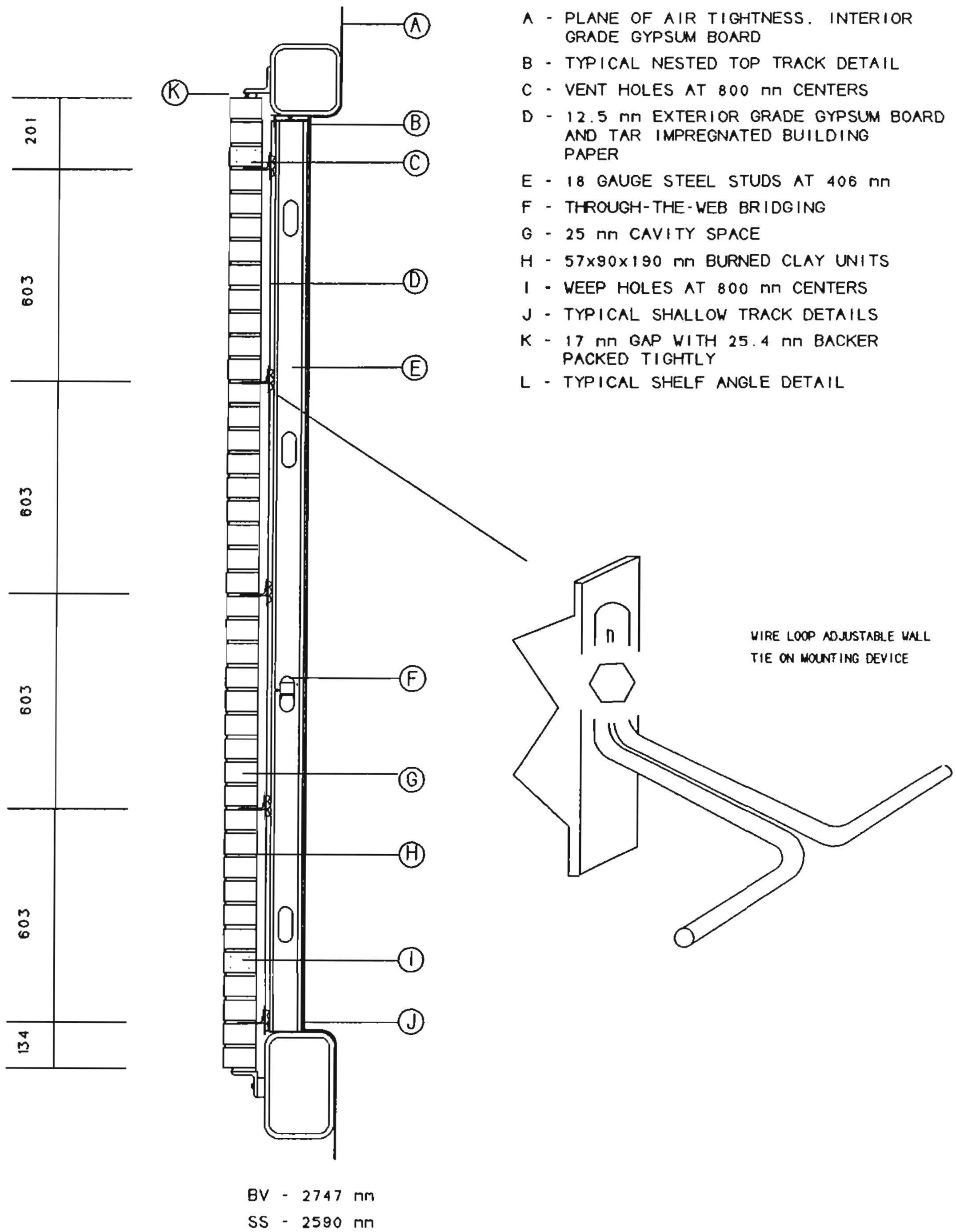


FIGURE 3.18 WALL1 DETAILS AND NOTES

The movement joint for WALL1 consisted of a 17 mm gap into which was forced a 25.4 mm diameter backer rod. Silicone caulking was used to seal the joint.

3.7 DETAILS OF WALL2

3.7.1 Steel Stud Backup Wall

Two way bending was created by bolting the end studs to the specimen frame at 600 mm spacing. External face bridging was located 1295 mm from the bottom of the SS wall and was attached as shown in Figure 3.14(a). For this wall, all caulking and sealing details were followed to complete the air barrier. Figure 3.19 is a vertical section of WALL2 and includes a list of the construction details.

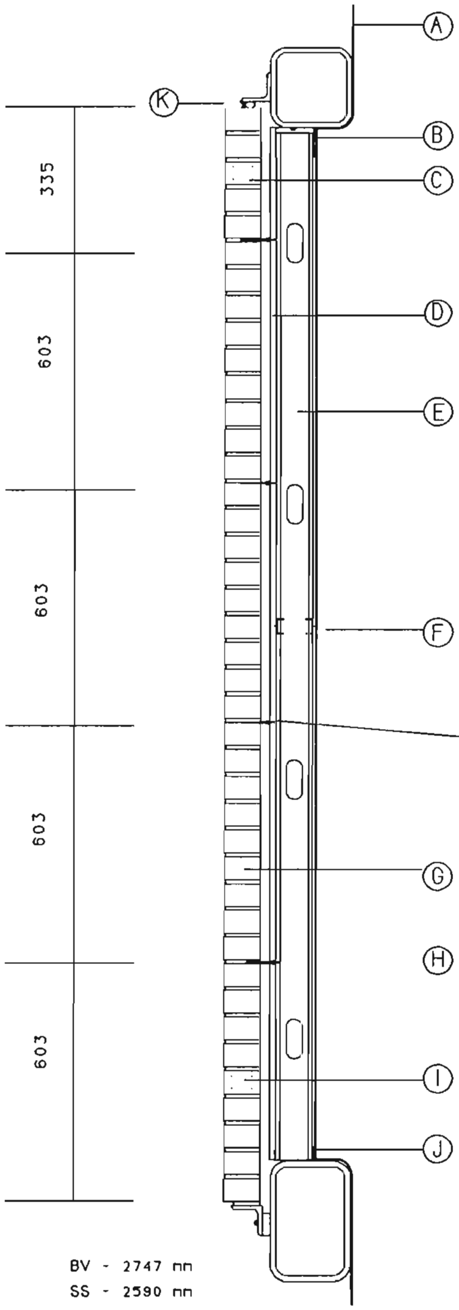
The selected tie system consisted of a single leg wire pintle in combination with the self drilling Posi-Tie anchor drawn in Figure 3.19. For the 25 mm cavity width, the 75 mm wire tie length resulted in the tie being embedded within the middle third of the brick veneer. Adjustments to match brick coursing were minimized by accurate installation of the self drilling portion of the tie prior to construction of the veneer.

Although the basic tie spacing of 406 mm horizontally and 603 vertically for WALL2 closely resembles that of WALL1, the maximum distance of 200 mm from a tie to the top or bottom of the wall was not adhered to for this specimen.

3.7.2 Brick Veneer Wall

Construction of the brick veneer was identical to WALL1 except that weep holes and vents were spaced horizontally at 1000 mm.

The movement joint for WALL2 is illustrated in Figure 3.20 (a) along with the joint installed for WALL1. However, installation of the joint sealing material was delayed until an initial loading cycle of the wall specimen was completed. This procedure was followed to



GENERAL NOTES

A - PLANE OF AIR TIGHTNESS, INTERIOR GYPSUM BOARD
B - TYPICAL NESTED TOP TRACK DETAIL
C - VENT HOLES AT 1000 mm SPACING
D - 12.5 mm EXTERIOR GRADE GYPSUM BOARD AND TAR IMPREGNATED BUILDING PAPER
E - 18 GAUGE STEEL STUD AT 406 mm SPACING
F - EXTERNAL FACE BRIDGING
G - 25 mm CAVITY SPACE
H - 57x90x190 BURNED CLAY UNITS
I - WEEP HOLES AT 1000 mm SPACING
J - TYPICAL SHALLOW TRACK DETAIL
K - 10 mm GAP FILLED WITH 12.5 mm BACKER ROD
L - TYPICAL SHELF ANGLE DETAIL

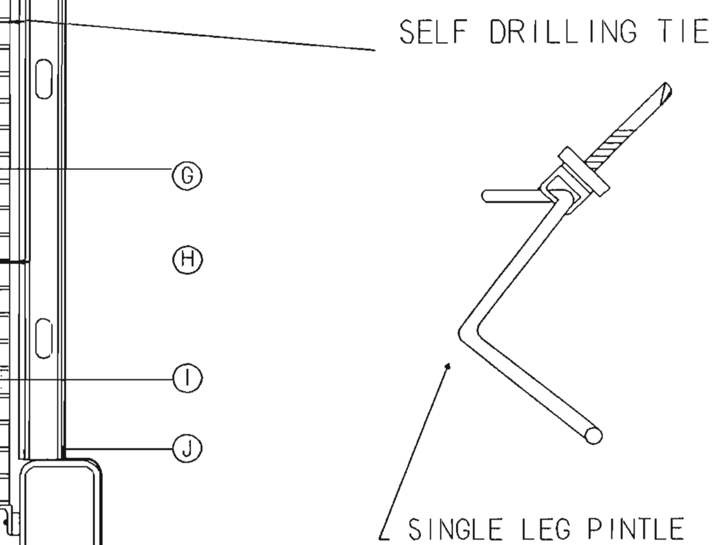
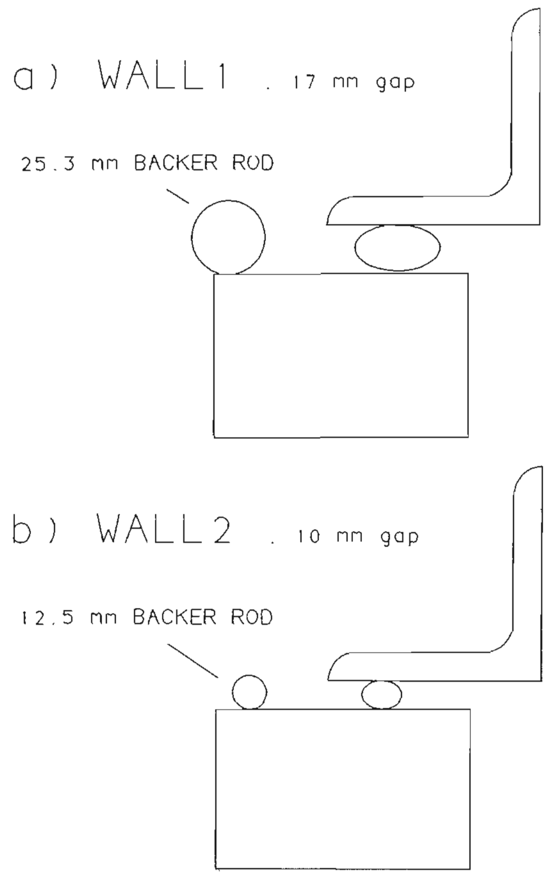
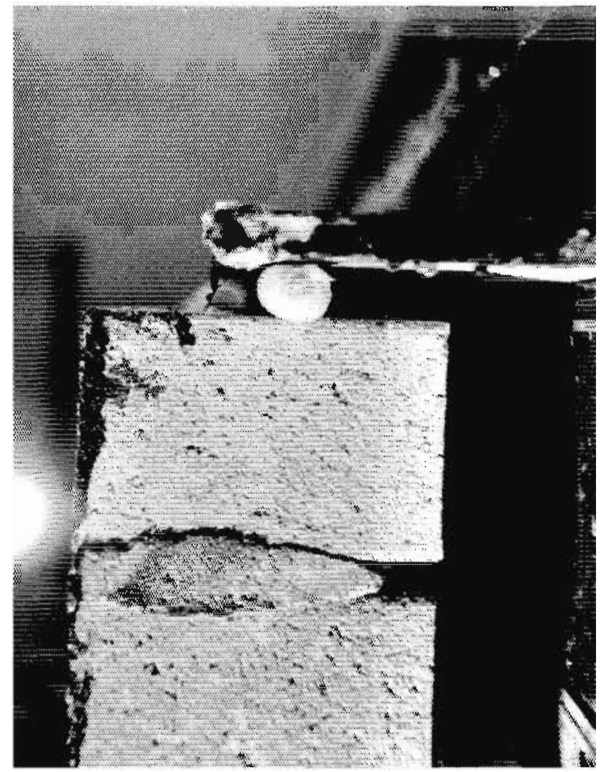


FIGURE 3.19 WALL2 DETAILS AND NOTES



a) Comparison of WALL1 and WALL2 Top Joint Details



b) Actual Construction of WALL2 Movement Joint

FIGURE 3.20 VENEER MOVEMENT JOINT DETAILS FOR WALL2 examine the influence of the top joint on the structural behaviour of the wall system. A 12.5 mm diameter foam backer rod was forced into the 10 mm gap. Silicone caulking was used to seal the joint. In Figure 3.20 (b) the marginal compression of the foam backer rod and the location of the silicone caulking are shown.

3.8 DETAILS OF WALL3

3.8.1 Steel Stud Backup Wall

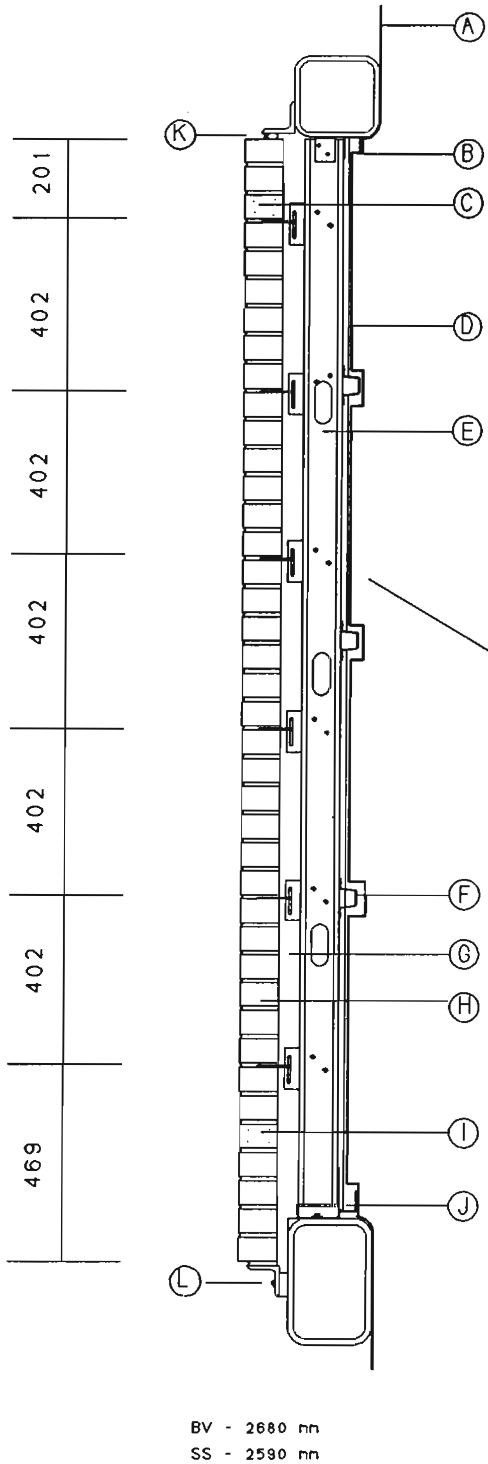
WALL3 represented non-standard BV/SS wall construction and provided an opportunity to investigate a new design concept. The design calls for double steel stud sections with the 2 studs placed back to back to form a symmetric element which was not subject to flexural-torsional buckling and therefore did not require bridging. The double section allowed the spacing to be doubled to 800 mm.

If the air barrier is located on the interior of the backup wall, the veneer construction can be scheduled before it is installed and the veneer can be inspected from both sides as construction progresses. This has the added advantage of allowing the cavity to be cleaned out before closing in the backup wall. This practice also allowed the veneer to be built from inside the building in an overhand fashion..

Other than the double stud configuration, the main difference between WALL3 and the other SS specimens was the location and details of the movement joint and stud supports. A vertical section of the wall system is shown in Figure 3.21, along with notes on other construction details to be discussed below.

1) <u>Movement Joint Details</u>

The movement joint for the backup was located at the bottom of the wall. Movement was accommodated by hanging the studs from upper Tee brackets and fitting them into Base



GENERAL NOTES

A - PLANE OF AIR TIGHTNESS. EXTERIOR GYPSUM BOARD
B - TEE BRACKET TOP DETAIL
C - VENT HOLES AT 800 mm SPACING
D - 12.5 mm EXTERIOR GRADE GYPSUM BOARD
E - DOUBLE 18 GAUGE STEEL STUDS AT 813 mm
F - HAT CHANNEL SECTION
G - 50 mm CAVITY SPACE
H - 57x90x190 mm BURNED CLAY UNITS
I - WEEP HOLES AT 800 mm SPACING
J - BASE SHOE CONNECTION
K - 10 mm GAP FILLED WITH 12.5 mm BACKER ROD
L - TYPICAL SHELF ANGLE DETAIL

BAYONET TYPE WALL TIE WITH TRIANGULAR WIRE TIE

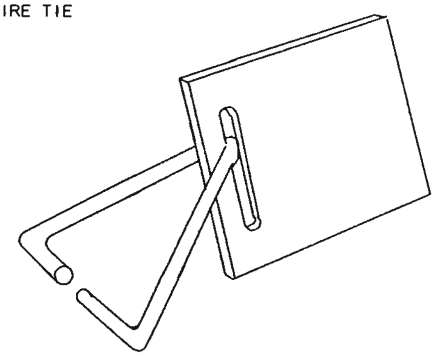


FIGURE 3.21 WALL3 DETAILS AND NOTES

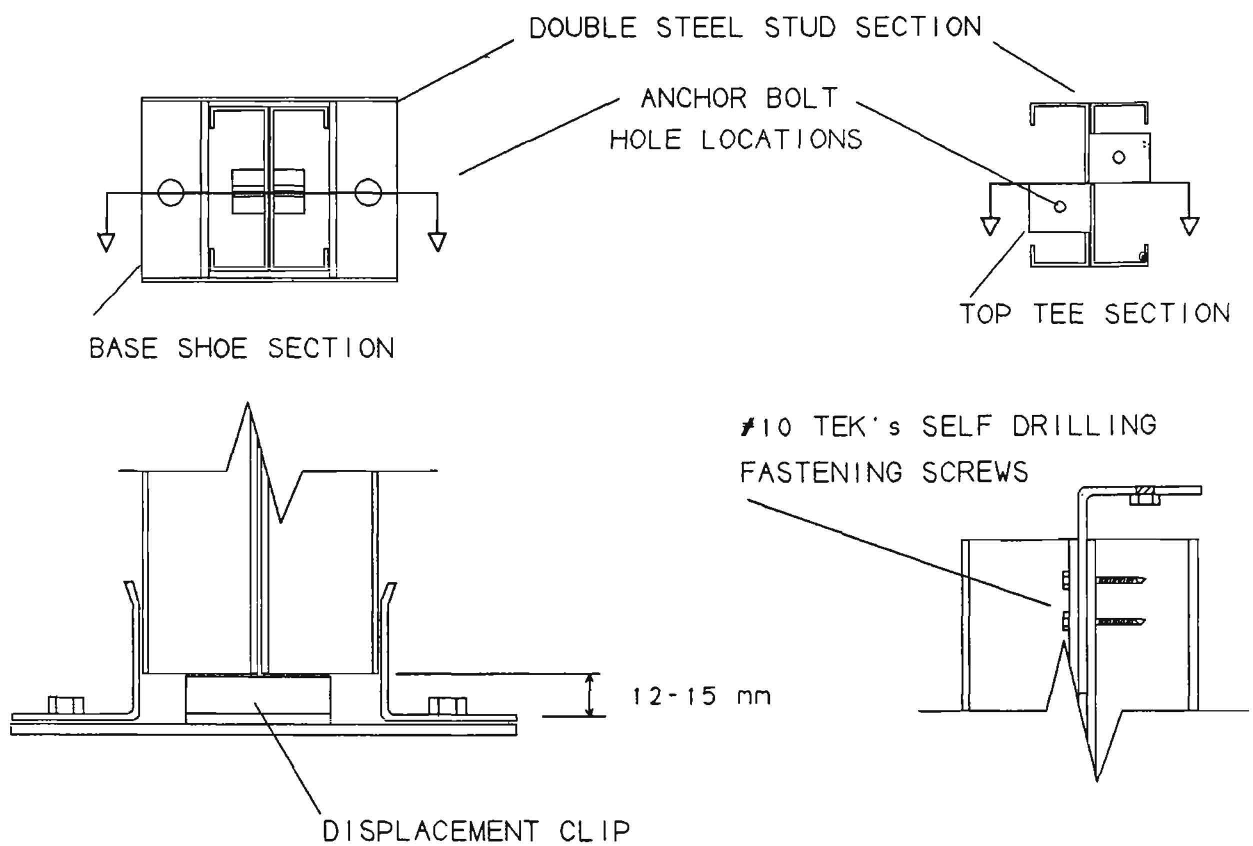
Shoe sections which provided lateral restraint while allowing 12-15 mm of vertical movement. A compressible displacement clip, located underneath the double steel stud within the Base Shoe section was used to maintain the movement gap during construction. Construction details of the Tee and Base Shoe sections, including the movement joint, are illustrated in Figure 3.22.

2) Wall Ties

In addition to providing a symetric section, fastening two steel stud 'C' sections back to back also facilitated installation of the wall tie between the two studs as shown in Figure 3.23 (a). The horizontal stud spacing of 813 mm and the vertical spacing of 400 mm produced a maximum tie tributary area of 0.325 m^2. The 75 mm long triangular wire tie used in conjunction with the bayonet tie and a 50 mm cavity resulted in the tie being embedded within the middle third of the brick veneer as shown in the photograph in Figure 3.23 (b).

3) Air Barrier Support

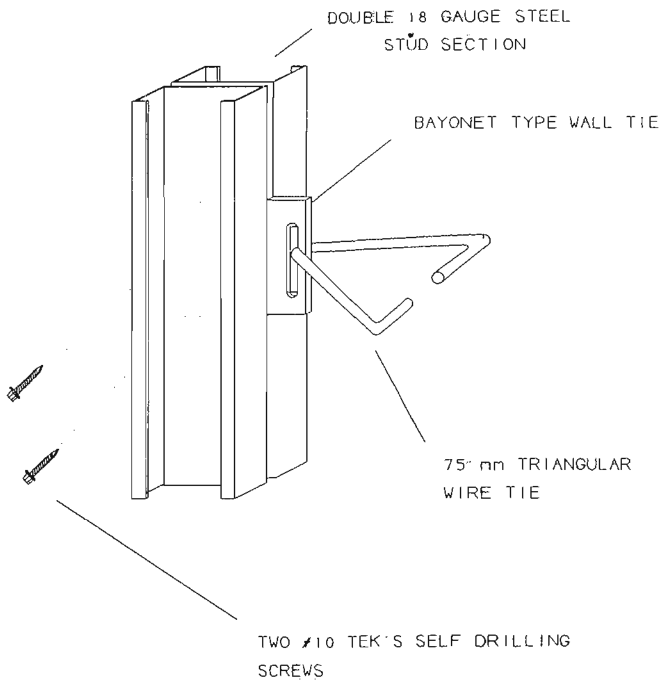
Although the symmetric 'I' section does not require any bracing for lateral support, hat sections placed horizontally were provided at 600 mm centres to support the interior gypsum board. In addition, 'J' sections were installed at both the top and bottom of the wall section to provide edge support for the gypsum board. The vertical spacing of these sections was designed to offset the large horizontal spans of gypsum board between lines of studs. The flanges of the hat and J sections were also positioned to accommodate proper sealing of the gypsum board in order to form a plane of air tightness. These details and the caulking locations to provide the plane of air tightness are illustrated in Figure 3.24.



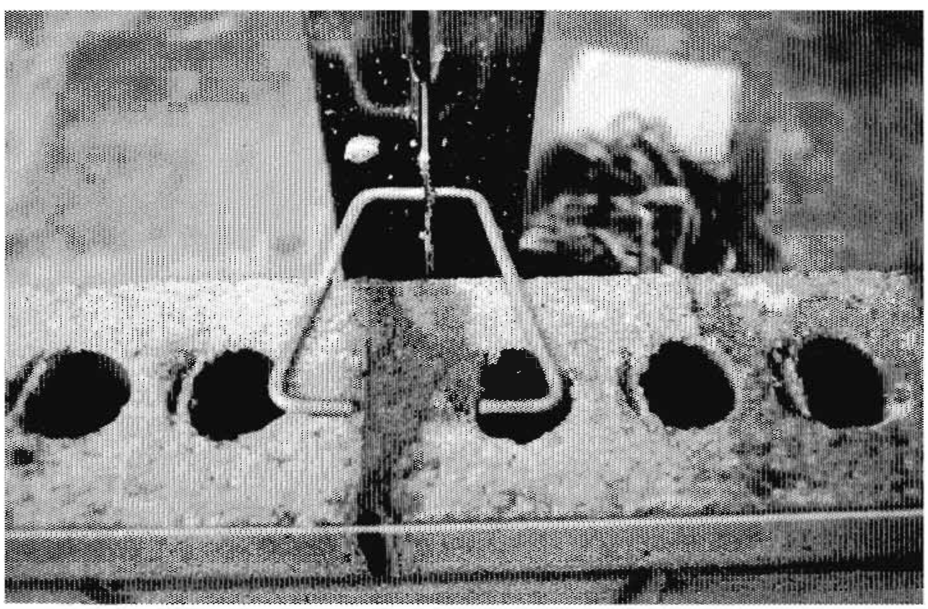
a) Base Shoe Detail

b) Top Tee Section Detail

FIGURE 3.22 BASE SHOE AND TOP TEE SECTION DETAILS



a) Double Stud and Wall Tie Assembly



b) Placement of Wire "V" Tie in Masonry

FIGURE 3.23 WALL TIE SYSTEM DETAILS FOR WALL3

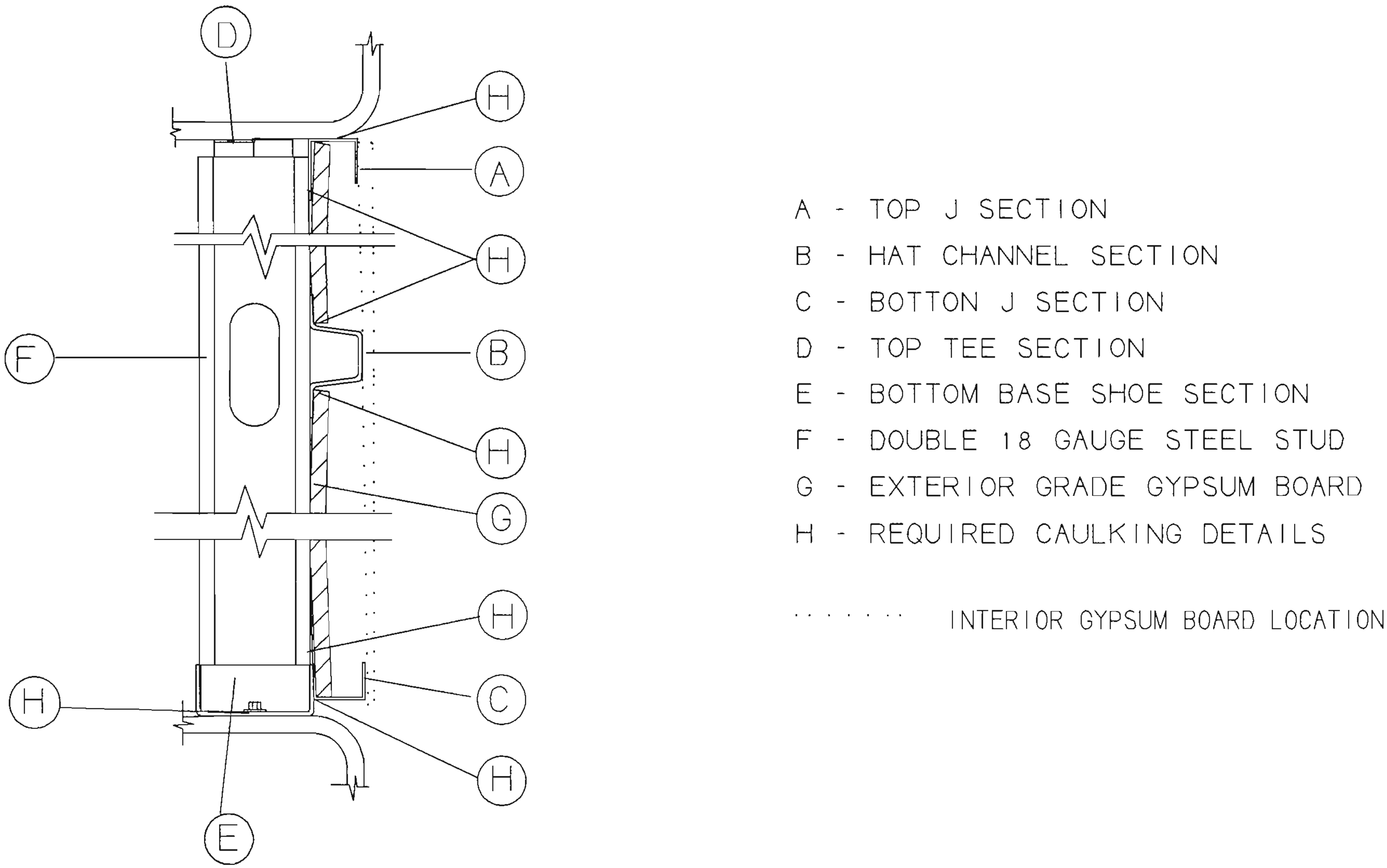


FIGURE 3.24 AIR BARRIER DETAILS FOR WALL3

3.8.2 Brick Veneer Wall

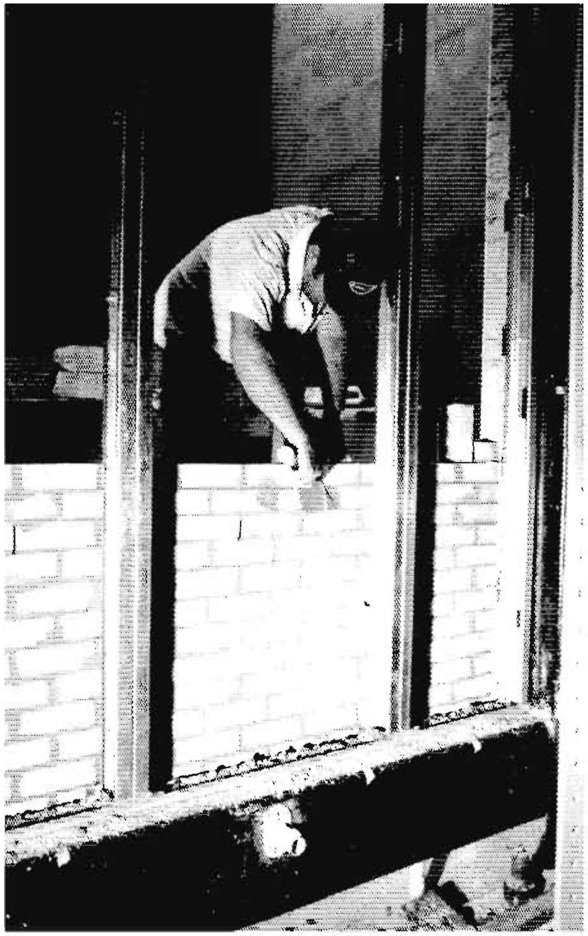
The brick veneer for WALL3 consisted of 40 courses of 26 bricks. Dimensionally the wall measured 2680 mm high by 5200 mm long with an average mortar joint thickness of 9.85 mm. The veneer was constructed at a distance of 50 mm from the exterior flange of the steel studs. This 50 mm cavity and the 92 mm inter stud cavity created by the interior sheathing air barrier, provided a cavity air volume of 1.94 m^3. Ventilation of this air space was achieved with weep holes and vents spaced horizontally at 800 mm centres and located in the typical manner. The movement joint installed for WALL3 was identical to that of WALL2.

Because of the unique design of the SS backup wall, the veneer could be constructed from either side of the backup wall. Construction of the BV from the inside of a building reduces scaffolding costs on low rise projects and swing stage costs on high rise buildings. This practice is not foreign to traditional brick/block cavity wall construction methods employed in the Toronto area. The mason was asked to lay bricks from both sides of the wall and to comment on the feasibility of such a practice in BV/SS wall systems. The photographs in Figure 3.25 show the mason laying bricks from both sides of the backup wall prior to placing the gypsum board air barrier.

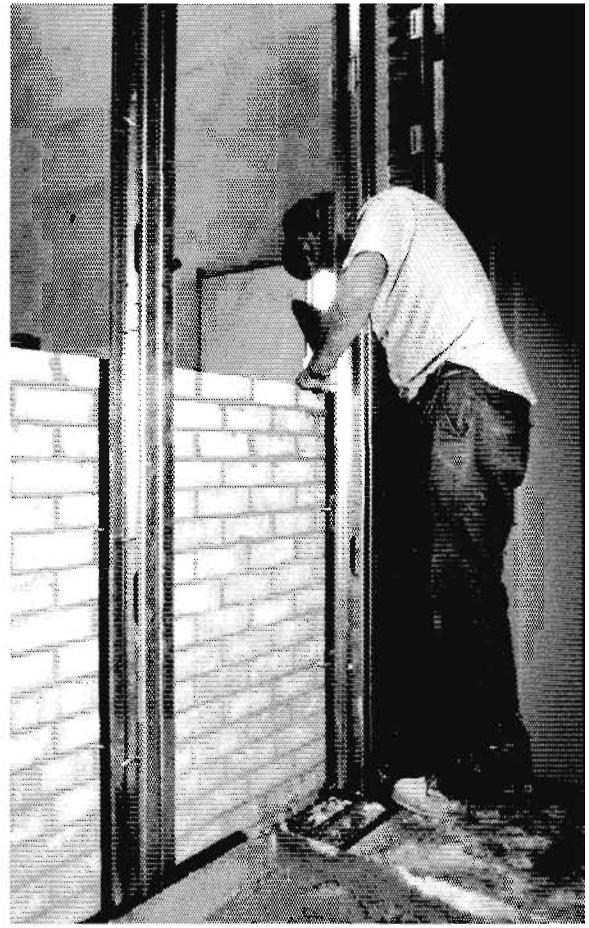
3.9 DEATILS OF WALL4

3.9.1 Steel Stud Backup Wall

WALL4 was constructed with a 2170 mm wide by 1790 mm high window. The high quality window was supplied within a wood-framed test buck by the Building Performance Division at ORTECH. WALL4 was constructed with typical top and bottom track/stud connections and through- the-web bridging. The bridging was located at the centre of the 2.59 m studs and fastened using the typical detail. Vertical sections of the wall system in Figures 3.26 and 3.27 were also used to illustrate other details discussed below.



a) Construction from Exterior



b) Construction from Interior

FIGURE 3.25 CONSTRUCTION OF VENEER FOR WALL3

1) Wall Ties

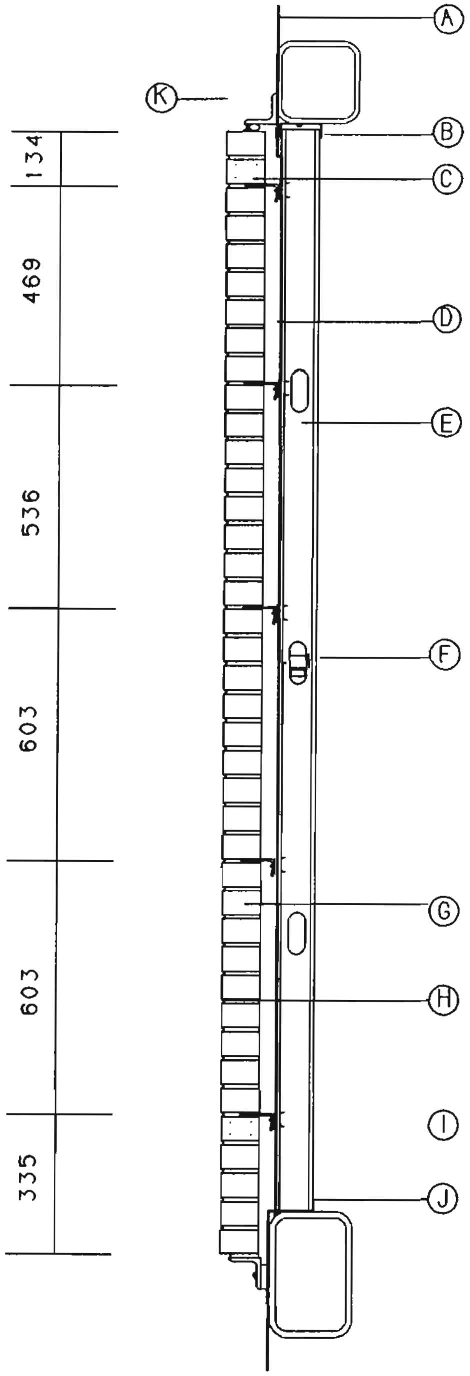
The double leg adjustable anchor shown in Figure 3.26 was chosen where the 100 mm length of wire pintle, resulted in the anchor length of the tie being located within the middle third of the brick veneer, as shown in Figure 3.28 for the 50 mm cavity. The ties were installed to strict tolerances which limited the amount of adjustment necessary to match the brick courses when the veneer was constructed later.

Horizontal and vertical tie spacings were set as roughly 406 mm and 603 mm, respectively. However, because of the large opening, placement of additional ties was required around the perimeter. Doubling of the studs in the vicinity of the opening was also necessary to maintain a design strength comparable to the other wall specimens. The arrangement of wall ties and studs are shown in Figure 3.29.

2) Details Related to the Window

To support the window in the steel stud backup wall, special details involved welded double steel studs on each side of the window for support, track lintels above and below the window, and small stud sections below the window. The double studs are shown in Figure 3.29. Anchors used to attach the window to the wooden buck and the wooden buck to the SS frame were spaced at approximately 200 mm.

The photograph in Fig 3.30 shows the window fitted into the backup wall before the brick veneer was constructed. Whether the window was installed before or after the veneer was constructed was not thought to be particularly significant. However, it was necessary that this window be installed prior to laying the bricks so that the previously documented high performance of the wood-framed window assemblage would not be diminished.



BV - 2680 mm
SS - 2590 mm

GENERAL NOTES

A - PLANE OF AIR TIGHTNESS. BITUTHENE MEMBRANE
B - TYPICAL NESTED TOP TRACK DETAIL
C - VENT HOLES SPACED AT 800 mm CENTRES
D - 12.5 mm EXTERIOR GRADE GYPSUM BOARD
E - 18 GAUGE STEEL STUD SECTION
F - THROUGH-THE-WEB BRIDGING
G - 50 mm CAVITY SPACE
H - 57x90x190 mm BURNED CLAY UNITS
I - WEEP HOLES SPACED AT 800 mm CENTRES
J - TYPICAL SHALLOW TRACK CONNECTION
K - 10 mm GAP FILLED WITH 12.5 mm BACKER ROD
L - TYPICAL SHELF ANGLE DETAIL

DOUBLE LEG ADJUSTABLE WALL TIE

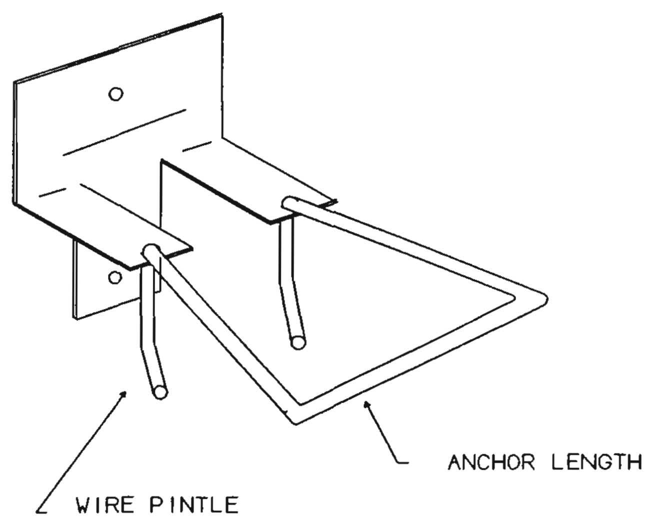
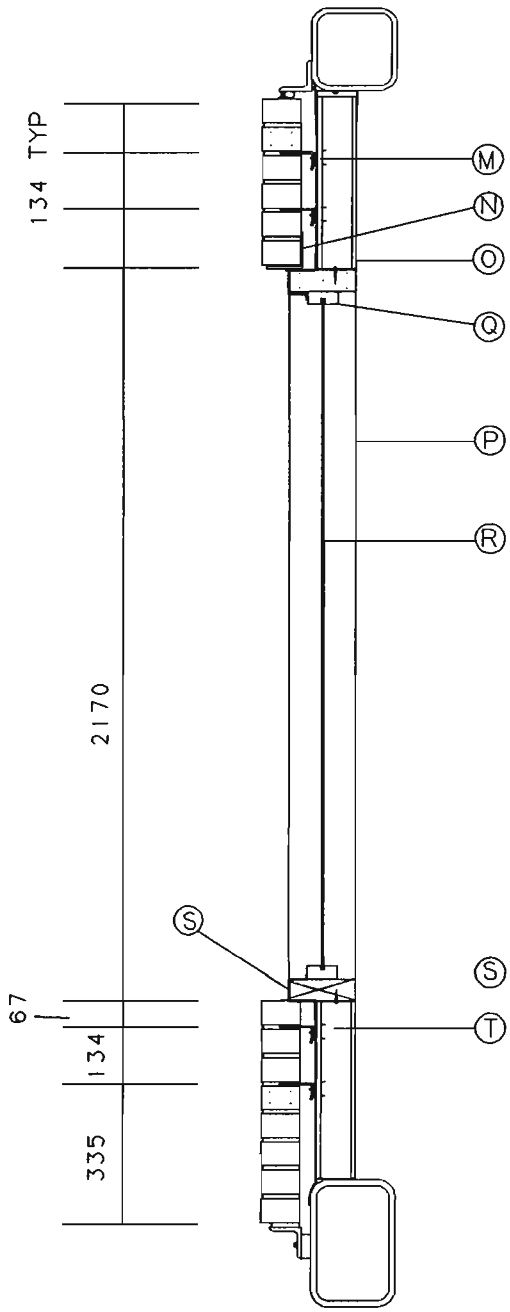


FIGURE 3.26 WALL4 DETAILS AND NOTES



GENERAL NOTES

M - ADDITIOAL WALL TIE
N - STEEL ANGLE FOR VENEER LINTEL
O - SS/TRACK LINTEL FOR SS WALL
P - WOOD-FRAMED WINDOW BUC
Q - PLASTIC FRAME FOR GLASS
R - WINDOW GLASS
S - BITUTHENE AIR BARRIOUR
T - ADDITIONAL WALL TIE

FIGURE 3.27 WALL4 DETAILS AND NOTES AT SECTION THROUGH WINDOW OPENING

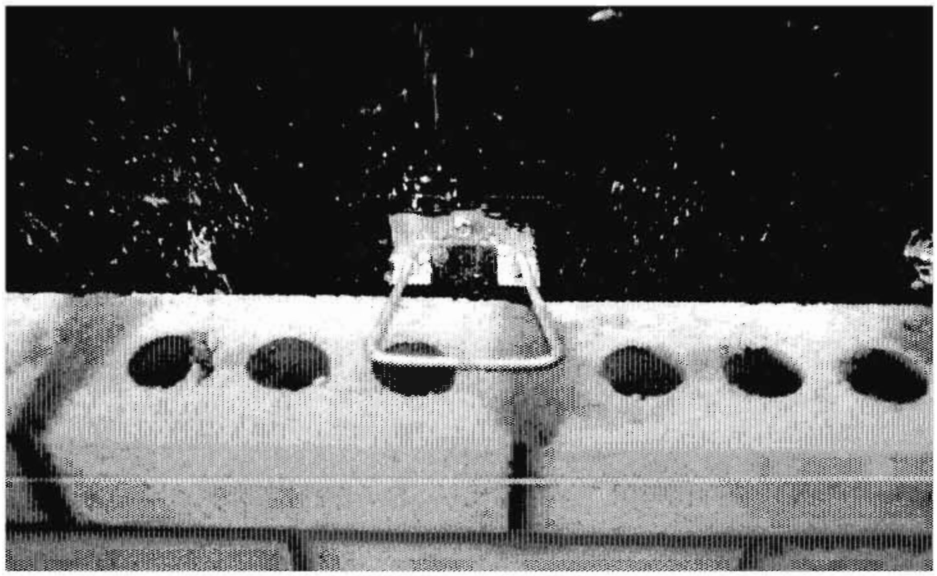


FIGURE 3.28 POSITION OF WALL TIE SYSTEM IN VENEER

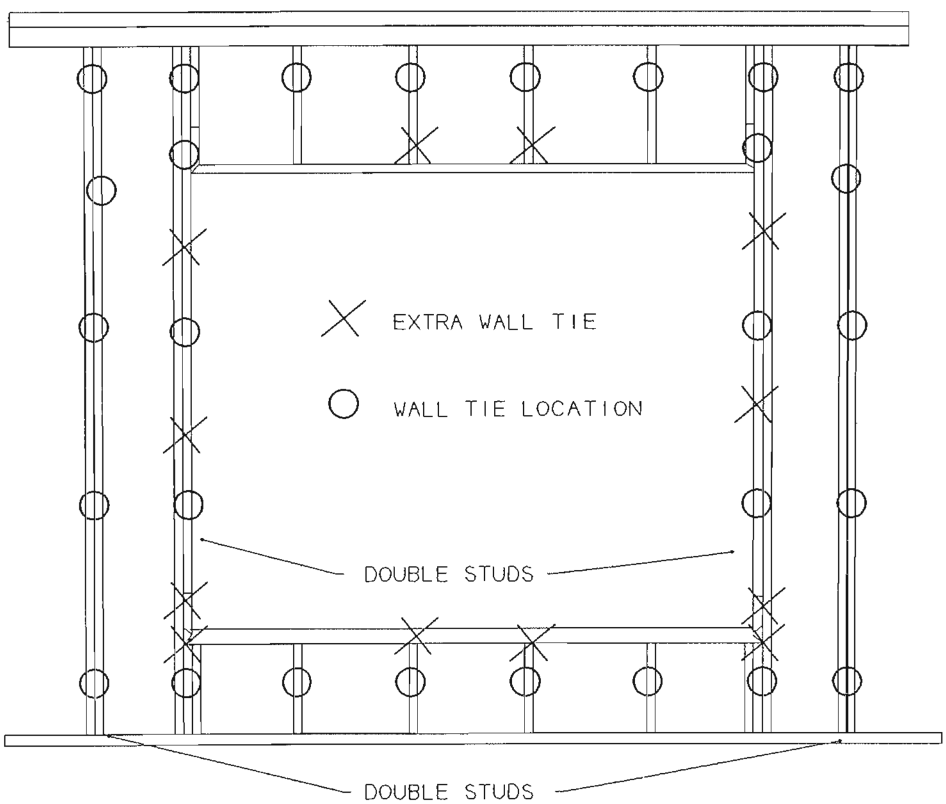


FIGURE 3.29 ARRANGEMENT OF WALL TIES AROUND WINDOW

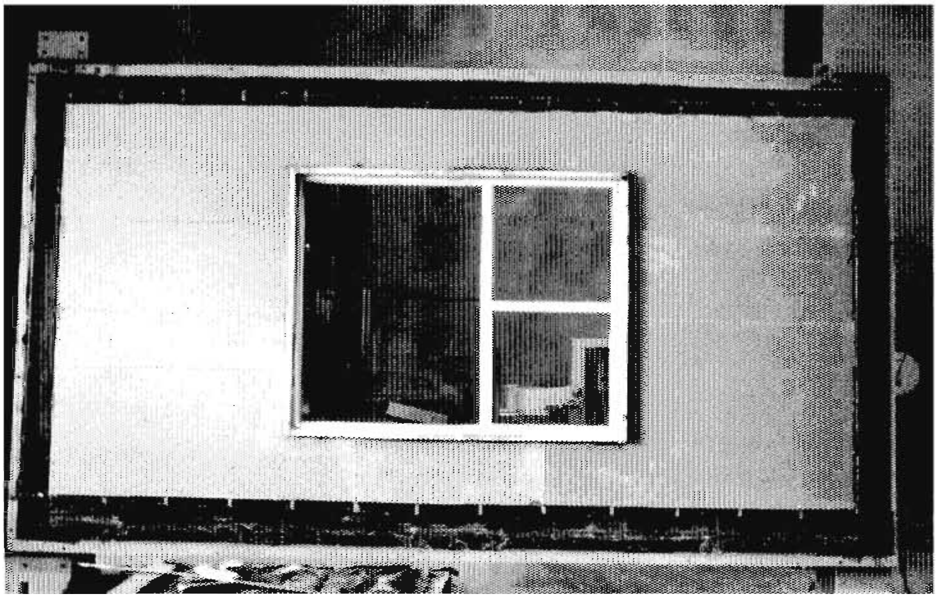


FIGURE 3.30 PLACEMENT OF WINDOW WITHIN BACKUP WALL

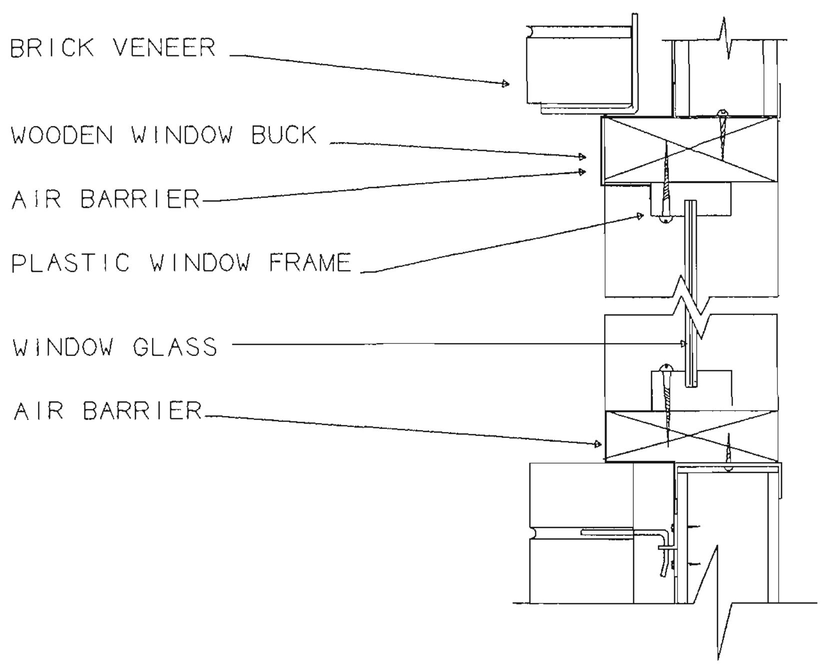


FIGURE 3.31 SECTION THROUGH WINDOW SHOWING CONTINUITY OF AIR BARRIER DESIGN

The construction procedure involved erecting the steel stud backup wall around the window, fastening the gypsum boards in place, installing the cold adhesive air barrier and finally placing the brick veneer.

3) Air Barrier Design

For WALL4 the air barrier design consisted of a cold adhesive membrane supplied by Grace Ltd. and identified as Bituthene Perm-A-Barrier. An important detail involved the continuity of the air barrier around the window frame. The details of the interface between the SS wall and the window frame are illustrated in Figure 3.31. The membrane was easy to work with and could be wrapped around the exposed edges of the wood- framed window buck without any difficulty.

Installation of this air barrier involved application of a primer solution to prepare the surface for adhesion. This coating was applied to the gypsum board with hand brushes a half hour prior to adhering the membrane. The material was positioned in strips stretching from one edge of the specimen frame to the centre of the wall. In the middle of the wall a 150 mm overlap joint was provided.

3.9.2 Brick Veneer Wall

The veneer was constructed a distance of 50 mm from the surface of the exterior gypsum board sheathing. This 50 mm cavity provided a cavity-air-volume of 0.70 m^3. Ventilation of this air space was achieved with weep and vent holes spaced horizontally at 800 mm centres.

The 402 mm height of brick veneer over the window was supported on a 90x90x6 mm steel lintel angle spanning 2200 mm. The ends of the loose lintel were embedded 300 mm into the veneer at both ends. Bricks were laid on the angle in a bed of mortar and the angle was laid directly on the supporting veneer at each end.

3.10 DETAILS OF WALL5

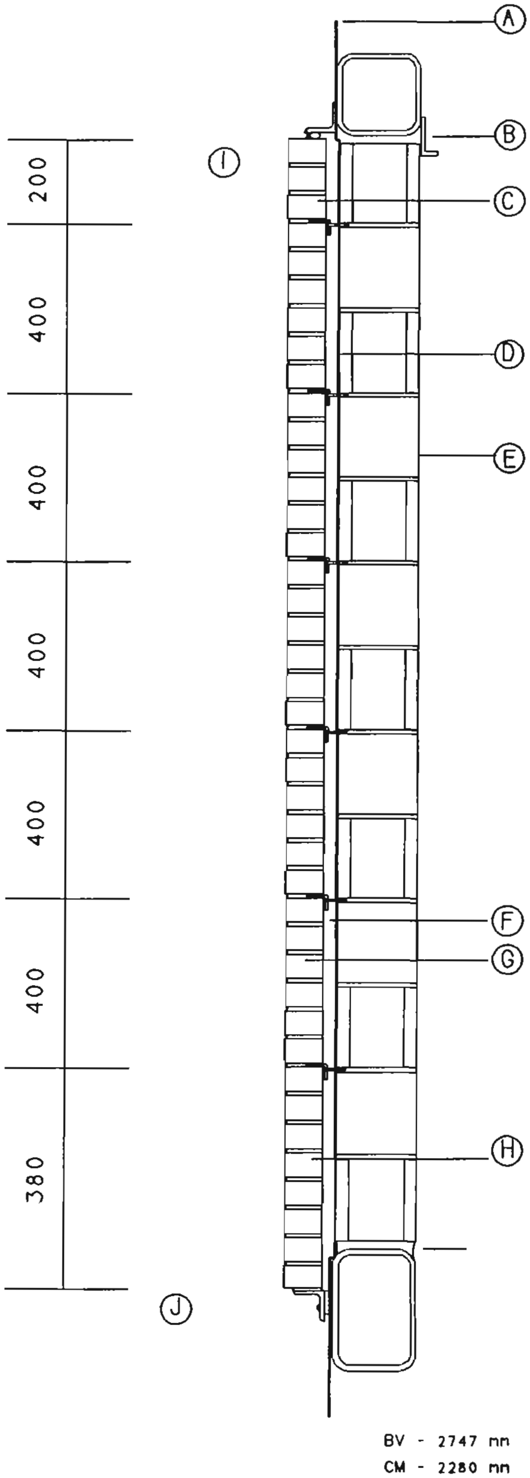
3.10.1 Concrete Masonry Backup Wall

The concrete blocks previously described, were of good quality and with 10 mm face shell mortar joint provided a working module of 400x200 mm. This resulted in the backup wall measuring 5.20 mm in length and 2.59 mm in height being constructed directly within the specimen frame.

All support conditions were consistent with field practices. The bottom course was laid on a bed of mortar and the edges of the wall were built up to the specimen frame. Also a top movement joint of no more than 10 mm was provided, similar to that provided in actual construction to accommodate differential movement. Top support of the concrete block wall was provided by welding 300 mm long clip angles onto the specimen frame at 800 mm centres. Also similar edge support at each end of the concrete wall panel was provided to produce two way bending behaviour in the masonry. The vertical section of the complete wall system shown in Figure 3.32 includes additional details.

1) Wall Ties

The wall tie system consisted of the rectangular tie with cross bar attached to the ladder joint reinforcement in the backup wall as shown in Figure 3.33 plus, for adjustment, a bent rectangular tie that was positioned through the slot in the first component and anchored in the middle third of the veneer thickness as shown in Figure 3.34. These wall ties were spaced at 400 mm centres horizontally and vertically. Because of the non-standard



GENERAL NOTES

A - PLANE OF AIR TIGHTNESS. BITUTHENE MEMBRANE
B - CLIP ANGLES SPACED AT 300 nn
C - VENT HOLES AT 800 nn CENTRES
D - BITUTHENE AIR BARRIOUR MEMBRANE
E - 190x190x390 nn CONCRETE BLOCKS
F - 50 nn CAVITY SPACE
G - 57x90x190 nn BURNED CLAY UNITS
H - WEEP HOLES SPACED AT 800 nn CENTRES
I - 10 nn GAP SEALED WITH BITUTHENE MEMBRANE NO BACKER ROD
J - TYPICAL SHELF ANGLE DETAIL

FIGURE 3.32 WALL5 DETAILS AND NOTES

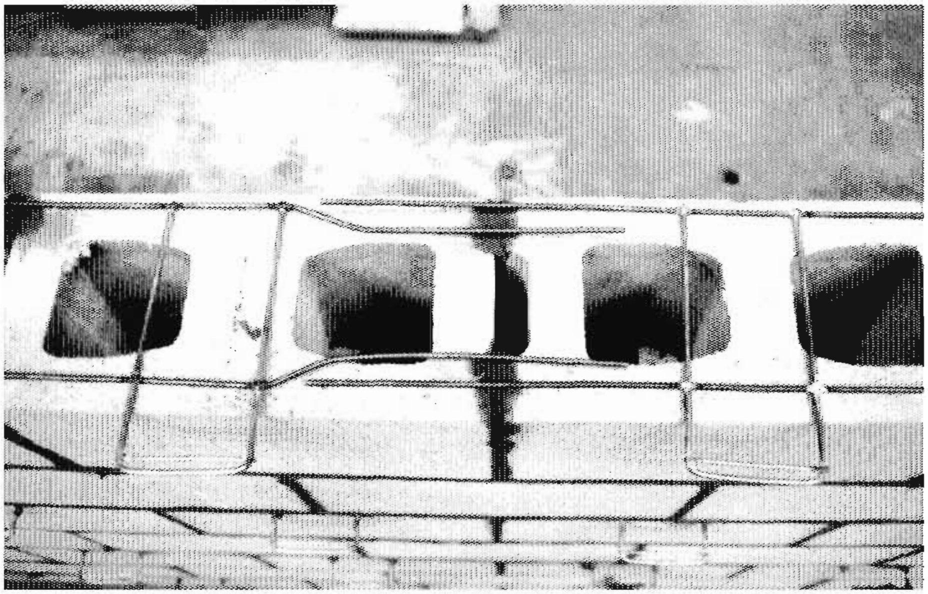


FIGURE 3.33 LAP SPLICING OF CONTINUOUS REINFORCEMENT USED IN WALL5

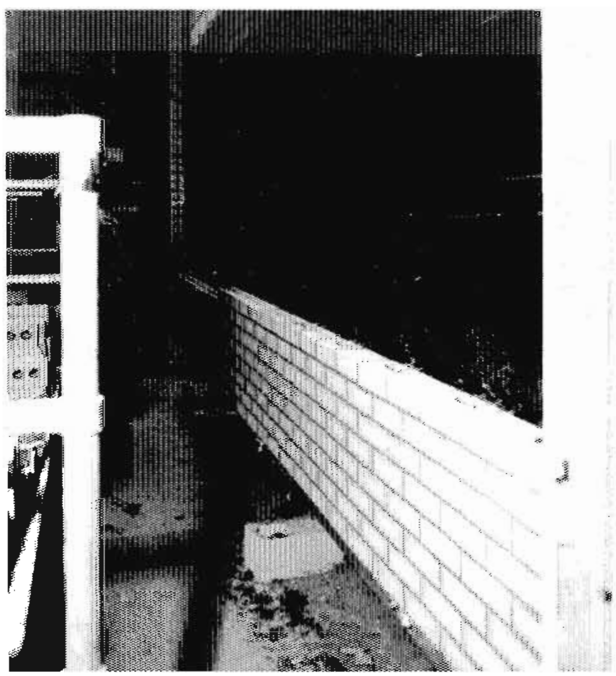


FIGURE 3.34 PLACEMENT OF THE WALL TIE IN THE VENEER FOR WALL5

classification of the adjustable wall tie, the vertical spacing was set conservatively at 400 mm as opposed to the recommended 600 mm spacing for a standard tie used in a similar manner [22].

The rectangular wire component protruded from the block wall and passed through the air barrier membrane. To ensure air tightness black mastic caulking was applied to openings caused by the wires at these locations.

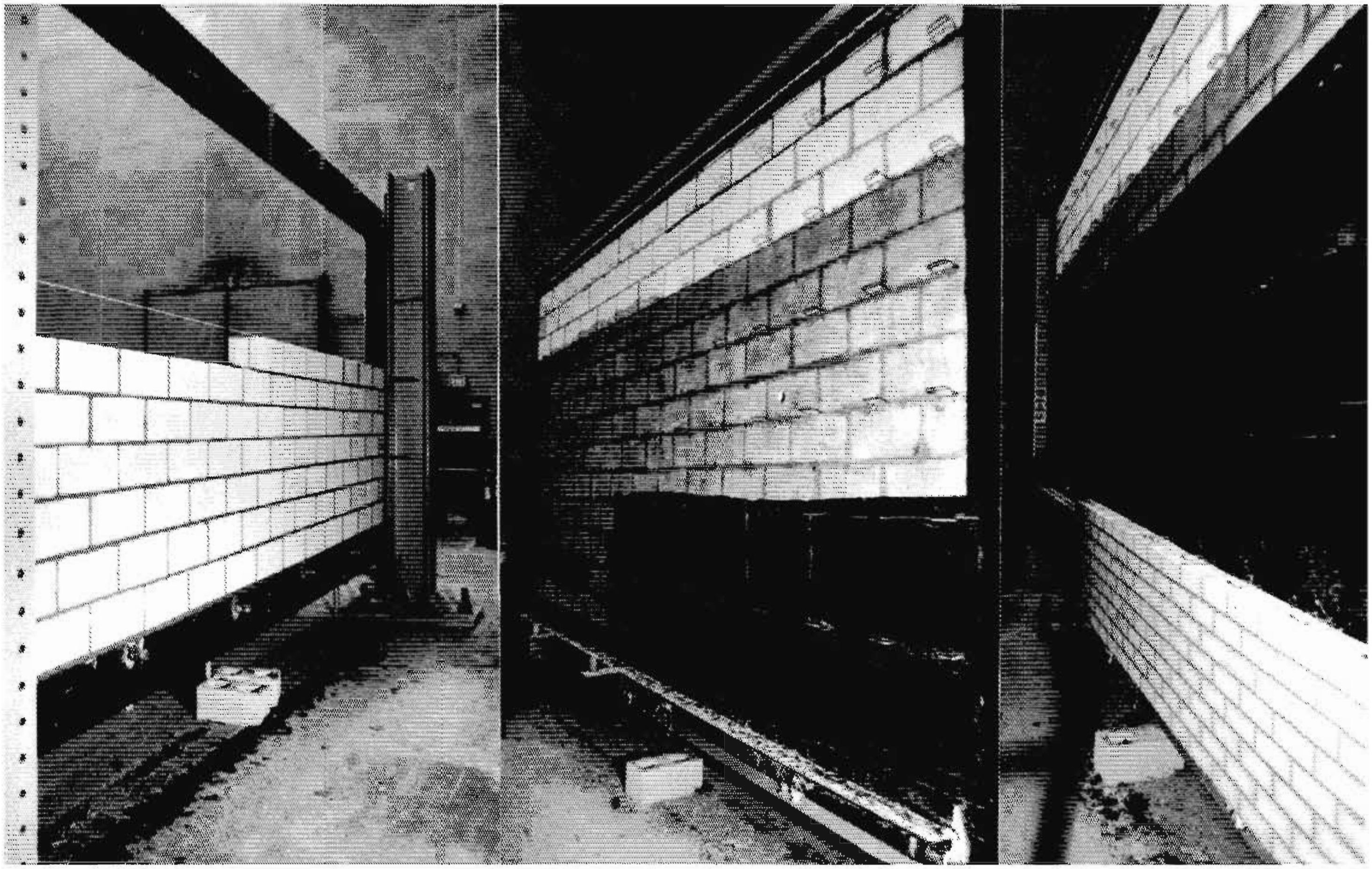
3) <u>Air Barrier Design</u>

The air barrier system for WALL5 was similar to that for WALL4. The Bituthene Perm-A- Barrier membrane was adhered to the concrete blocks in the same manner as for the gypsum boards of WALL4.

The construction stages for the BV/CB wall specimen are shown in Figure 3.35. First the concrete blocks were laid in running bond within the specimen frame. The blocks were then coated with a primer solution to prepare the surface for adhesion of the air barrier membrane, as shown for the middle courses of the block wall in Figure 3.35 (b). The bituminous membrane was applied to the prepared surface over the bottom courses of the block wall as shown in the photograph in Figure 3.35 (b). The photograph is Figure 3.35 (c) provides a composite illustration of all the wall system components from the bottom up including, clay bricks, ties, bituthene membrane, primer solution, ladder joint reinforcement and concrete masonry.

3.10.2 Brick Veneer Wall

The veneer was constructed in a manner identical to that described for WALL1 with the exception that a 50 mm cavity and 12.5 mm movement joint were provided.



a) Block Wall Construction   b) Air Barrier Membrane Installation   c) Construction of Veneer

FIGURE 3.35 CONSTRUCTION SEQUENCES FOR BV/CB WALL SYSTEM

3.11 SUMMARY

Design and construction details for the five wall specimens are summarized in Table 3.7 for easy future reference. The following legend of abbreviated terms will prove useful when referring to the table:

AT TOP	–	movement joint located at top of SS wall
AT BOT	–	movement joint located at bottom of SS wall
BBT	–	Bailey Bayonet Type wall tie
DLA	–	Double Leg Adjustable wall tie
EFB	–	External Face Bridging
HAT	–	Hat shaped connection
N/A	–	Not Applicable
SDT	–	Self Drilling Type wall tie
SHOE	–	bottom base Shoe connection
TEE	–	top Tee connection
LADDER	–	adjustable double leg Continuous welded wire Ladder tie system.
TWB	–	Trough Web bridging
TYP	–	TYPical detail
WLA	–	Wire Loop Adjustable wall tie

TABLE 3.7 SUMMARY OF SPECIMEN DETAILS

Design and Fabrication Details	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5	Units
Brick Veneer Walls						
Cavity Width	25	25	50	50	50	mm
No of Courses	41	41	40	41	41	
Free Gap at Top	17.0	10.0	10.0	10.0	10.0	mm
Dia. of Backer Rope	25.4	12.5	12.5	12.5	12.5	mm
Weep/Vent Spacing	800	1000	800	800	800	mm
Brick Veneer Height	2747	2747	2680	2680	2680	mm
Steel Stud Walls						
Stud Gauge	18	18	18	18	N/A	
Stud Spacing	406	406	813	406	N/A	
Top Track Connection	TYP	TYP	TEE	TYP	N/A	
Bot. Track Connection	TYP	TYP	SHOE	TYP	N/A	
Bridging	TTW	EFB	HAT	TTW	N/A	
Movement Joint	AT TOP	AT TOP	AT BOT	AT TOP	AT TOP	
Wall Tie System	WLA	SDT	BBT	DLA	LADDER	
No. of Wall Ties	70	56	48	72	78	
Max. Vert. Spacing	603	603	400	603	400	mm
Max. Horiz. Spacing	406	406	813	406	400	mm
Max. Tributary Area	0.245	0.245	0.325	0.245	0.16	mm^2
Max. Tie Edge. Dist.	200	603	342	335	400	mm
No. of Studs	14	14	14	14	N/A	
Design Details						
Design Load					1.0	kPa
(L/360 Limit)	2.0	2.0	2.0	2.0	N/A	kPa
(L/720 Limit)	1.0	1.0	1.0	1.0	N/A	kPa
Air Barrier	Interior drywall (poor)	Interior drywall	Interior drywall	Exterior membrane	Exterior membrane	
Major Variable	One Way Action	Two Way Action	Inverted Wall Design	Large Opening	Concrete Masonry Backup	

CHAPTER 4
RAIN PENETRATION TEST PROGRAM

4.1 INTRODUCTION

The rain penetration test program was designed to examine the rain screen performance of BV wall systems. The effectiveness of such a design for masonry veneer walls is of great importance to their long term satisfactory performance. Full scale tests under standardized conditions of air pressure and rain load have been undertaken in response to the many moisture problems identified in rain screen walls [31,65,66,70,76]

The program consisted of testing the five wall specimens previously described in Chapter 3 under the conditions outlined in Chapter 2. The observations and results are provided in the following sections along with discussion of the performance of the rain screen in brick veneer wall systems. A summary of the major observations is included later in the report.

4.2 TEST PROGRAM OBJECTIVES AND EXPERIMENTAL DESIGN

The objectives of the rain penetration test program were to quantitatively and qualitatively assess the leakage characteristics and performance of the wall specimens. Specifically the objectives can be summarized as follows:

- Determine the time at which water penetrates into the cavity under pressurized and depressurized conditions.
- Identify the leakage paths and examine their uniformity over the wall specimen.
- Determine the influence of the position of the pressure gradient on the rain screen performance.
- Examine the impact of veneer cracking on the performance of the rain screen.
- Examine the sensitivity of leakage to variations in air pressure.
- Examine the significance of compartmentalization in the performance of the rain screen.

- Investigate the influence of workmanship.
- Determine the time required to pressurize the air cavity.

Because of to the limited number of test specimens, the investigations were planned to obtain the most information from each wall. To satisfy all of the objectives listed, it was not possible to address all issues in each wall specimen. The experimental design for the program is outlined in Table 4.1 where the objectives addressed for each wall specimen are indicated. For each wall, a sequence of testing was devised within the framework of the test protocol and is provided in Appendix 2.

4.3 STANDARD RAIN PENETRATION TEST RESULTS

4.3.1 General

From Chapter 2, it may be recalled that typical experiments were conducted by loading the wall specimen with a 4 hour rain under a pressure of approximately 500 Pa. During the test, the applied air pressure and horizontally directed water spray were independently controlled and water reaching the cavity was collected continuously and recorded at 30 minute maximum intervals. Thus leakage rates quoted in the figures and sections to follow generally represent average flow rates over the 30 minute period.

It should be noted that the experimental objectives were both qualitative and quantitative in nature, making visual observations as significant as measured quantities. Although leakage rates are used to comparatively examine many influences, it must be stressed that these values are particular to each specimen and are not necessarily representative of all brick veneer wall constructions. Thus, wherever possible, inferences are drawn from within test comparisons. However, when general trends in rain screen performance or leakage characteristics are observed, the results are examined collectively.

TABLE 4.1 EXPERIMENTAL DESIGN OF RAIN PENETRATION TEST PROGRAM

	WALL 1	WALL 2	WALL 3	WALL 4	WALL 5
INITIAL LEAKAGE TIME	X	X	X	X	X
UNIFORMITY OF LEAKAGE		X	X		X
RESPONSE TO PRESSURE VARIATIONS		X	X		X
INFLUENCE OF VENEER CRACKING	X	X	X		
INFLUENCE OF PRESSURE GRADIENT		X	X		X
INFLUENCE OF COMPARTMENTALIZATION	X	X	X		
DYE TRACING OF LEAKAGE PATHS		X			
INFLUENCE OF POOR CONSTRUCTION DETIALS	X	X			X

The test results and observations are presented as they relate to the outlined test objectives. A complete record of leakage data for individual tests and major observations are included in Appendix 3 as a permanent record.

4.3.2 Leakage Through Initially Dry Veneer

An important observation was the initial sighting of dampness and leakage through the veneer wall. This information together with descriptions of the initial dampness patterns and eventual leakage paths provides valuable insight into the rain penetration characteristics of brick veneer walls. In order to collect this information, observation ports were installed in the backup wall. These viewing ports, positioned between the vertical steel stud members, consisted of plexiglass sheets sealed to the drywall to prevent air leakage.

WALL1, WALL2 and WALL3 were outfitted with viewing ports but the unique features of WALL4 and WALL5 prevented their installation. Specifically the latter two wall specimens possessed exterior air barriers, located within the wall's cavity, making sealing of the viewing ports too difficult. Thus only the time to initial leakage was recorded for WALL4 and WALL5. Dampness patterns and leakage times were collected for the other specimens.

The practice of testing half walls to examine uniformity in the wall specimen accommodated tests of initially dry sections of the walls under both cavity pressurized and depressurized conditions. The leakage times obtained in the laboratory are summarized in Table 4.2 and the general observations recorded during the tests are summarized as follows:

- Initial signs of dampness were located at the bases of head joints.
- Head joints became nearly 100% damp in less time for the cavity depressurized condition than for the pressurized condition.
- Head joints were nearly 100% damp before neighbouring bed joints showed signs of dampness.

TABLE 4.2 INITIAL LEAKAGE TIMES

Design and Fabrication Details	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5
CAVITY PRESSURIZED					
damp	60	40	25	N/A	N/A
leakage	90	60	+240	N/A	+240
CAVITY DEPRESSURIZED					
damp	10	12	5	4	N/A
leakage	90	20	10	9	45

time in minutes

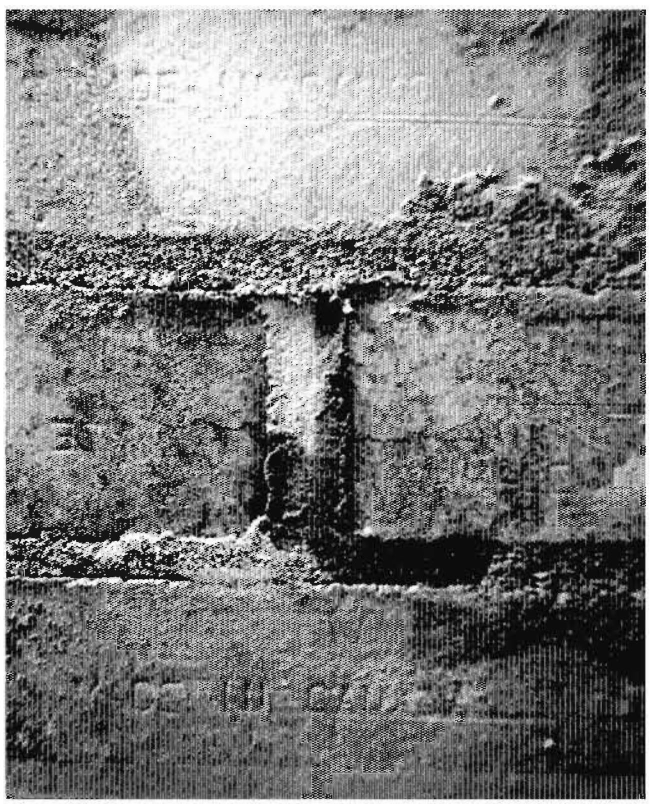


FIGURE 4.1 INITIAL SIGHTING OF DAMPNESS IN HEAD JOINT

- Leakage occurred after head joints became damp but not necessarily before bed joints became damp.
- The major portion of leakage originated at head joint-bed joint intersections.
- Leakage at the bottom shelf angle/brick veneer interface was only observed during the cavity depressurized testing of WALL3.
- A considerable time lag existed between discernable moisture on the inside face of the veneer and actual cavity water leakage when the cavity was pressurized.
- Protruding mortar fins and wall ties were observed to act as wicks for extracting water from saturated mortar joints, particularly under the cavity depressurized condition.

An important observation made during all the tests was the initial dampness in the head joint and early leakage from the intersection between the head joint and the bed joint. Figure 4.1 is a photograph of the typical dampness observed in the head joint. Although very few leakage studies exist on brick masonry, the head joint has been identified as a large contributor to leakage [63,68].

4.3.2.1 Leakage of WALL1 and WALL2 (Initially Dry)

Considering the lack of driving force present in the cavity pressurized condition, the leakage response might be expected to only involve mortar dampness and veneer saturation. However, WALL1 and WALL2 exhibited slight cavity leakage after 90 minutes and 60 minutes respectively. The recorded leakage for both walls was attributed to the substandard sealing details in the air barrier and top movement joint, which allowed large air flows through the veneer even under cavity pressurized conditions. Nonetheless the amount was quite small.

The effect of features of the brick veneer on the leakage reported during the pressurized cavity test must be considered carefully. For WALL1, a poorly sealed air barrier existed and large air movements through the wall system were observed. The air movements into the cavity were observed to cause leakage at weep hole and vent locations. For WALL2, leakage occurred as a result of poor sealing details in the veneer movement joint. Although this leakage was easily recognizable at the top of the wall and was separated from the dampness observations, it could not be separated from recorded leakage rates. The significance of the construction details studied in WALL1 and WALL2 are discussed later in the report.

For the cavity depressurized tests of both specimens, initial dampness in the mortar joints was observed at 10 and 12 minutes respectively. Within minutes from observing dampness in the head joints, water was seen trickling down the inside face of the veneer. The major sources of leakage were identified as isolated head joint bed joint interfaces intermittently spread across the surface of the wall.

4.3.2.2 Leakage of WALL3 (Initially Dry)

Large viewing ports in WALL3 allowed excellent observation of the progress of dampness in mortar joints during the test. Also, both dampness and water leakage were more easily seen because of the clearly struck mortar joints on the inside of the veneer.

The pattern of dampness recorded through one observation port at three instances during the initial cavity pressurized test are shown in Figure 4.2. Examination of this pattern supports the observation of initial dampness in the head joints as opposed to bed joints.

After testing half of the specimen in the cavity pressurized condition, the whole wall was retested in the cavity depressurized condition. Almost immediately leakage from the wet side was recorded as water flowed through the previously damp locations on the veneer. On the dry side, dampness was observed within 5 minutes and leakage was recorded in 15 minutes.

It was also observed that significant leakage occurred at the veneer/shelf angle interface. This leakage was not uniform along the wall length and was isolated in distinct locations.

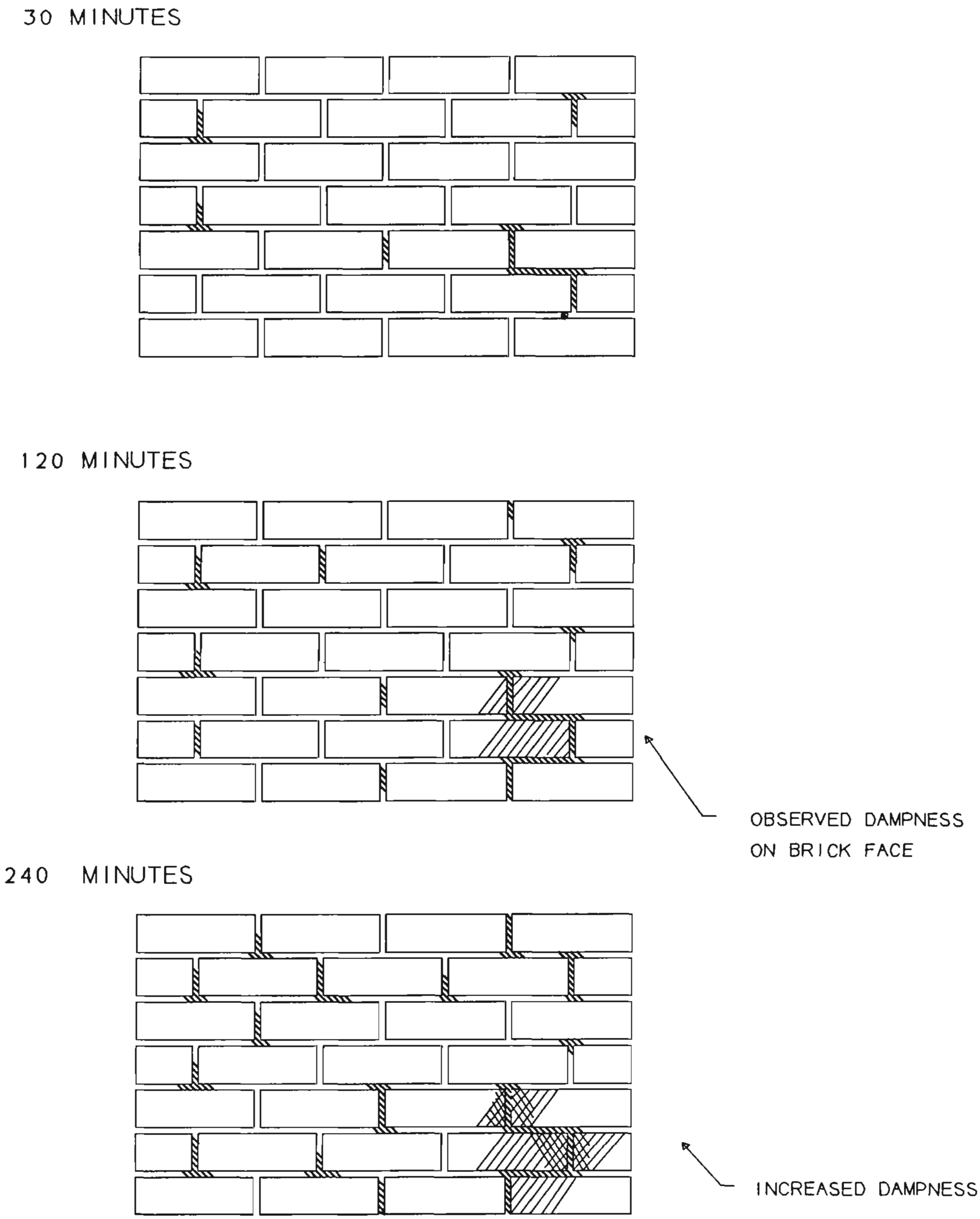


FIGURE 4.2 PROGRESS OF DAMPNESS IN JOINTS DURING THE CAVITY PRESSURIZED TEST OF WALL3

4.3.2.3 Leakage of WALL4 and WALL5 (Initially Dry)

The loading sequence for WALL4 precluded observation of the initial leakage time for cavity pressurized conditions. Also, because viewing ports were not provided in either WALL4 or WALL5, observations of dampness and leakage were not possible. However, the times to initial leakage were recorded.

It should be noted that for WALL4, examination of the mortar joints after the test revealed many workmanship deficiencies.

4.3.3 Uniformity of Leakage Paths

Because of normal variations in workmanship, some poorly filled head joints or deeply furrowed bed joints could be anticipated. Since a single large leakage paths could bias the test results, a feature of the test program was to provide a within test comparison and verification of leakage rates.

Verification of uniformity of leakage was achieved through separate rain penetration tests of each half of the wall. By comparing the two leakage rates, differences could reveal locations of lower quality construction. Half of the wall was tested by covering the other half with a plastic sheet. The tests were conducted under the cavity depressurized condition which best accommodated comparison because this arrangement produced the largest leakage rates.

It was generally observed that, within the 4 hour rain session, a relatively steady state leakage rate was reached. Most half wall tests were conducted on initially dry specimens as opposed to the initially wet condition for tests of the whole wall. Of the five test specimens, the effects of poor construction details in WALL1 and WALL4 forced their exclusion from this study.

WALL3 and WALL5 both had very uniform leakage properties and, as illustrated in Figure 4.3, similar leakage responses were obtained for tests of both half and whole walls. By

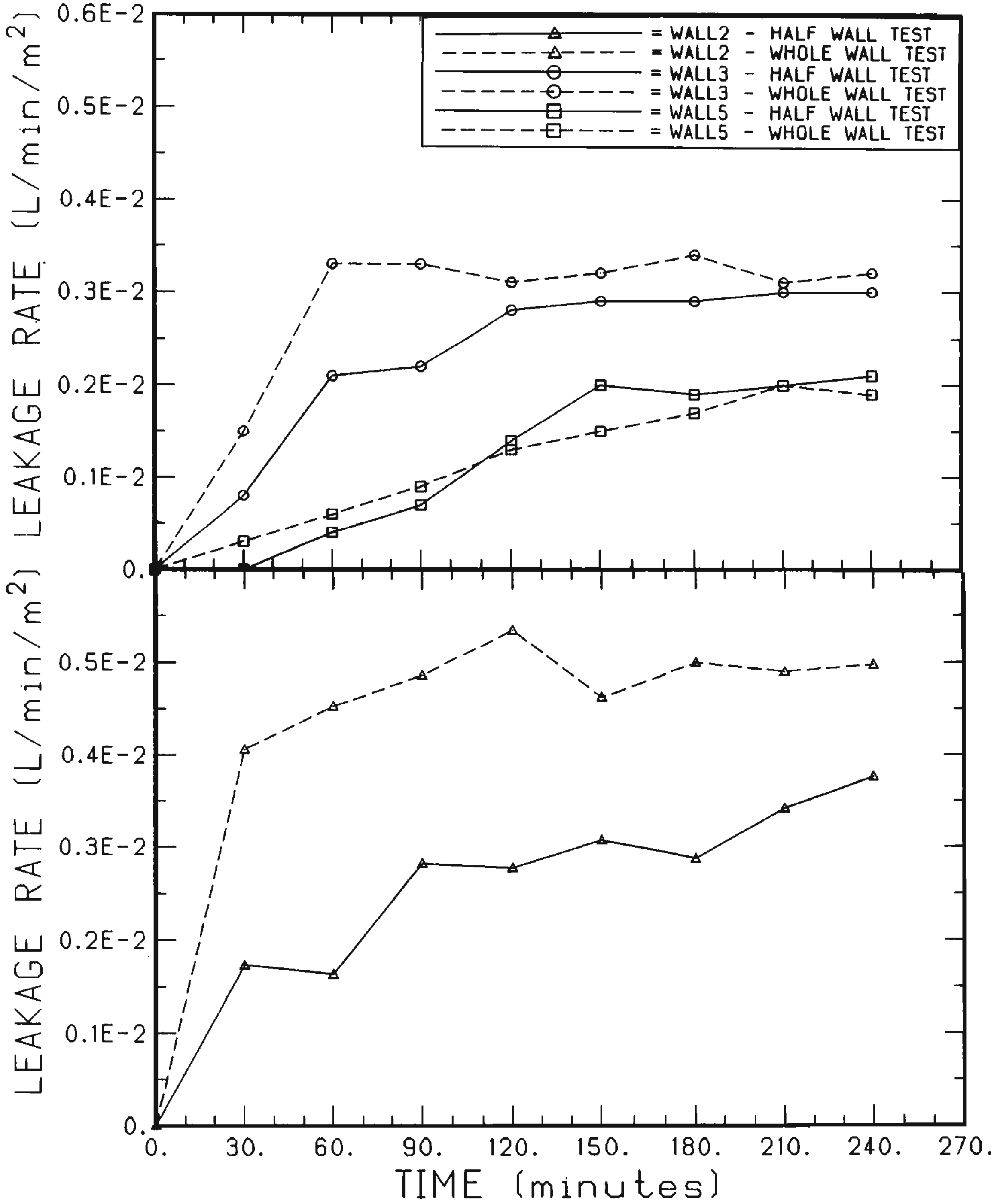


FIGURE 4.3 UNIFORMITY OF LEAKAGE

contrast, WALL2 had non-uniform leakage as shown in Figure 4.3 by the different leakage rates recorded for the half and whole walls. The unequal amount of leakage paths was confirmed by the visual observation of early dampness then leakage at two head joints within the second test half of the veneer

4.3.4 Influence of Air Pressure Gradient Across the Veneer

The influence of the position of the air pressure gradient on rain penetration was examined by varying its magnitude across the veneer. With the cavity pressurized, the air pressure difference across the veneer was minimal whereas the cavity depressurized condition produced the maximum difference. Pressure differences of 300 Pa and 150 Pa were also included to provide intermediate points to further examine the relationship.

The leakage rates studied were those obtained after relatively steady leakage rates had been achieved for both uncracked and cracked conditions. These are shown in Figure 4.4 for WALL1, WALL2, WALL3 and WALL5. The test sequence for WALL4 did include the influence of pressure gradient and initial cracking of the concrete backup wall for WALL5 precluded any further leakage investigation.

The leakage rates were not as sensitive to the magnitude of the pressure gradient for the uncracked condition as for the cracked condition. However, leakage rates for very small pressure differences across the veneer were not so markedly influenced by the cracked condition of the veneer. It should be noted that, although each wall possessed unique leakage characteristics, the general relationships discussed above were consistent for all specimens.

4.3.5 Influence of Cracking of the Veneer

Discussions regarding the vulnerability of brick veneer wall systems to deterioration due to rain penetration often focus on the effect of cracking of the veneer. With a flexible

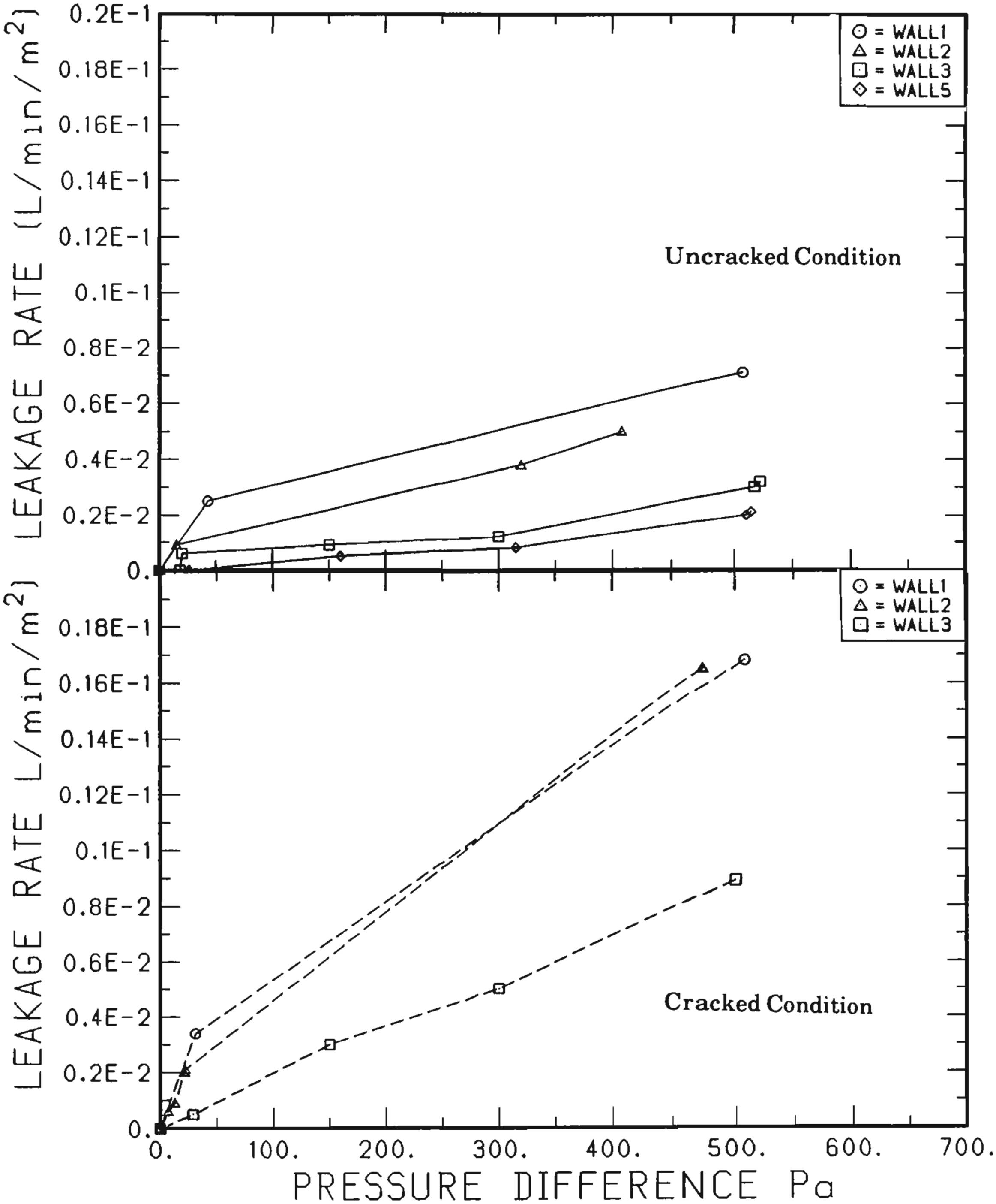


FIGURE 4.4 INFLUENCE OF PRESSURE GRADIENT

backup system such as steel stud construction, there is greater potential for flexural cracking to occur than where a rigid backup is used. However, increased vulnerability of the system to excessive leakage and moisture damage as a direct result of flexural cracking has not been demonstrated.

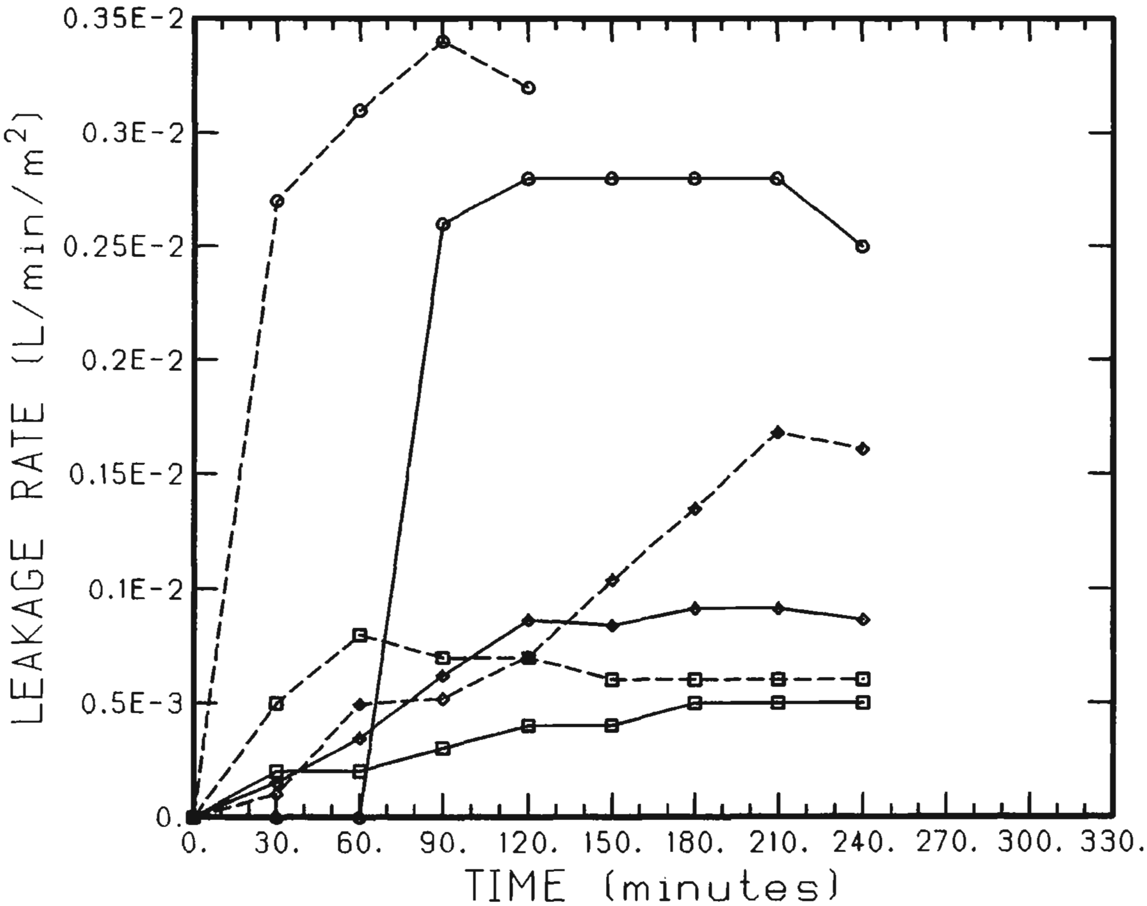
To examine the influence of cracking on leakage rates through the veneer, the wall specimens were tested both before and after cracking for WALL1, WALL2 and WALL3. The effects of poor construction in WALL4 and the initial cracking of the backup wall in WALL5 prevented their inclusion in this phase of the investigation.

4.3.5.1 Cavity Pressure Condition

When the cavity is depressurized, the entire pressure difference is across the brick veneer and this results in larger leakage rates than for the cavity pressurized condition with the pressure difference across the backup wall and away from the wet surface. This observation was supported by the data plotted in Figure 4.4 as well as by the results related to the influences of cracking of the veneer shown graphically in Figure 4.5. It should be noted that the vertical scales for the two cavity pressure conditions are different in order to present the data in a clearer fashion.

1) Cavity Pressurized

As shown in Figure 4.5(a), for the cavity pressurized condition, a crack in the veneer did result in increased leakage but this was characterized as marginal. WALL1 provided consistent trends with respect to the influences of pressure gradients and cracking of the veneer but the leakage rates were higher than for others walls. The greater rain penetration can be attributed to the effects of the poor construction details included in WALL1.



a) Pressurized Cavity

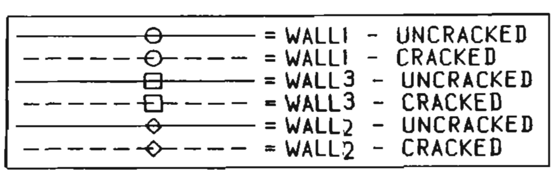
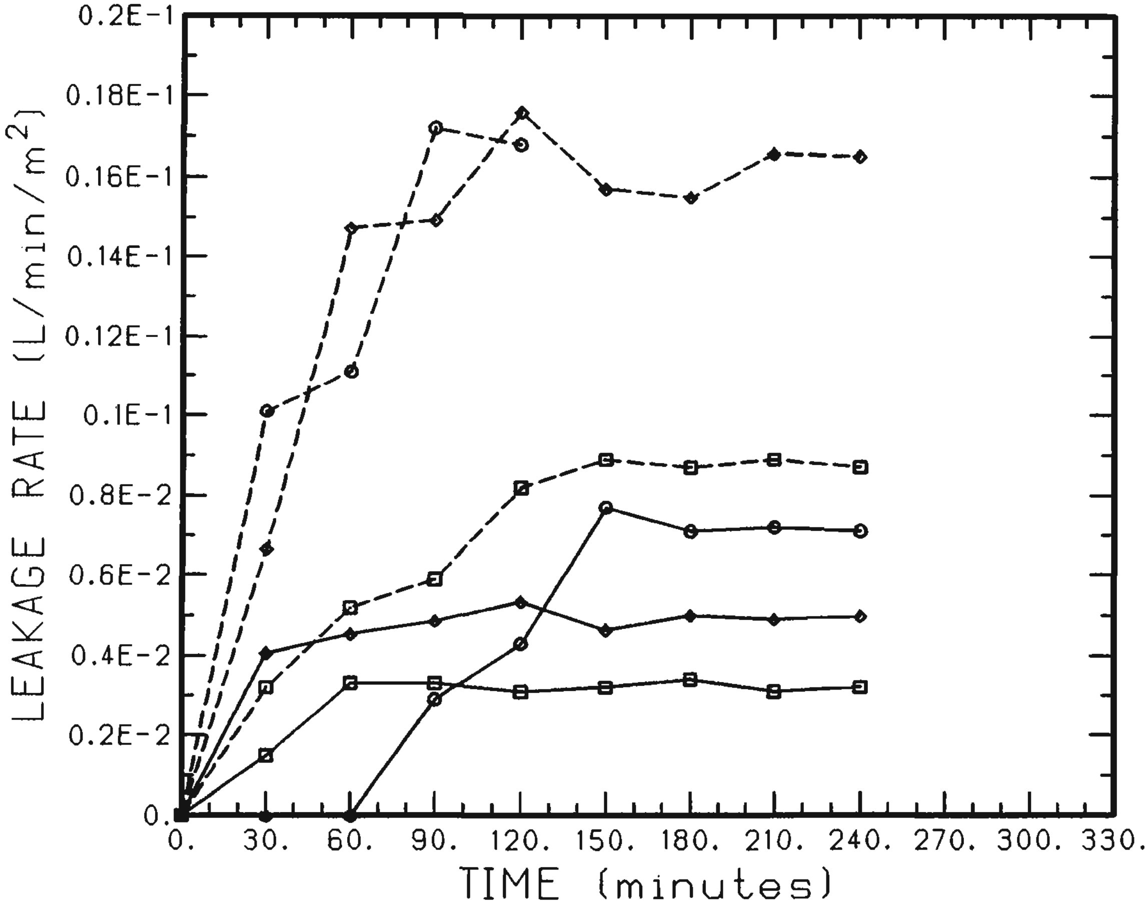


FIGURE 4.5 INFLUENCE OF CRACKING OF THE VENEER



b) Depressurized Cavity

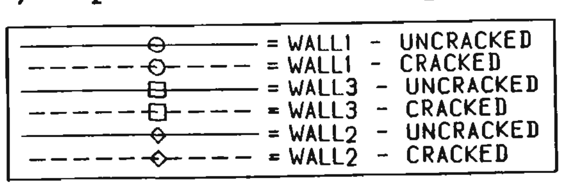


FIGURE 4.5 INFLUENCE OF CRACKING OF THE VENEER

2) <u>Cavity Depressurized</u>

For the depressurized cavity condition, as shown in Figure 4.5(b), the leakage rates increased dramatically following cracking of the veneer. At steady state the leakage rate after cracking of the veneer was approximately 2.5 to 3.0 times greater than before cracking.

During the tests of WALL2 and WALL3, it was noticed that increased leakage occurred in the region where the wall was expected to crack. One viewing port in WALL2 offered a clear view of a cracked bed joint and a cracked head joint near the central portion of the wall. Water filled this opening and the volume of water was great enough to cause water droplets to drip off mortar fins and splash on mortar fins and wall ties below.

The location and magnitude of leakage after cracking was also noted during the WALL3 test. Water was seen running down the back face of the veneer from the middle portion of the wall in a manner not observed for the uncracked condition.

4.3.5.2 Crack Width

For WALL3, a total of 6 joints over the central height of the veneer were fitted with LPDT's positioned to measure the relative movement between successive brick centre lines. This measurement was interpreted as the cracking size occurring in the bed joint between the two bricks. The contribution of strain in the brick units was neglected because of the very low tensile stresses.

Fortunately, for WALL3 the combination of large viewing ports and cleanly struck mortar fins allowed a faint crack line to be identified. At 500 Pa air pressure, the recorded crack width was approximately 0.023 mm. After cycling the wall system through 50 load applications of 1000 Pa and 1500 Pa under both cavity pressurized and depressurized conditions (200 total cycles) the crack displacement spread to include 5 of the gauged joints.

The total crack width at a load level of 500 Pa was then recorded as 0.18 mm with a maximum individual crack width of 0.05 mm.

4.3.6 Effect of Magnitude of Air Pressure

The responses of the steady state leakage rates, attained during the 4 hour rain sessions, to variations in the magnitude of the air pressure were investigated. The applied pressure was reduced to 300 Pa and 150 Pa and maintained for an additional 4 hours each. The time required to re-establish steady state leakage rates and the response to sudden changes in pressure were of particular interest.

The tests were conducted with the cavity depressurized because the higher leakage rates best accommodated comparisons. Furthermore, at pressures below the standard of 500 Pa, the leakage rates for the of cavity pressurized condition were not very sensitive to changes in pressure. In fact for WALL2, pressures of 750, 500 and 250 Pa were applied with the cavity pressurized after the veneer had been cracked and leakages rates of 0.0021, 0.0007 and 0.0006 $L/min/m^2$ respectively were recorded.

The results for WALL3 and WALL5, which were subjected to this 12 hour test prior to cracking, are shown in Figure 4.6. For both walls, the recovery time was less than 1 hour at each pressure change and the response of the leakage rate was immediately noticeable. In Figure 4.6 the effect of wall saturation on the leakage response is evident. WALL3 was saturated when tested whereas only half of WALL5 had been previously exposed to water. As a result WALL3 reached a steady condition within 1 hour as opposed to WALL5 which took nearly the full initial 4 hour period.

After cracking, WALL3 was subjected to the same 12 hour rain test again with the cavity depressurized condition. The results of this test are also plotted in Figure 4.6. Increased leakage rates were recorded but there was no observable difference in recovery time for the

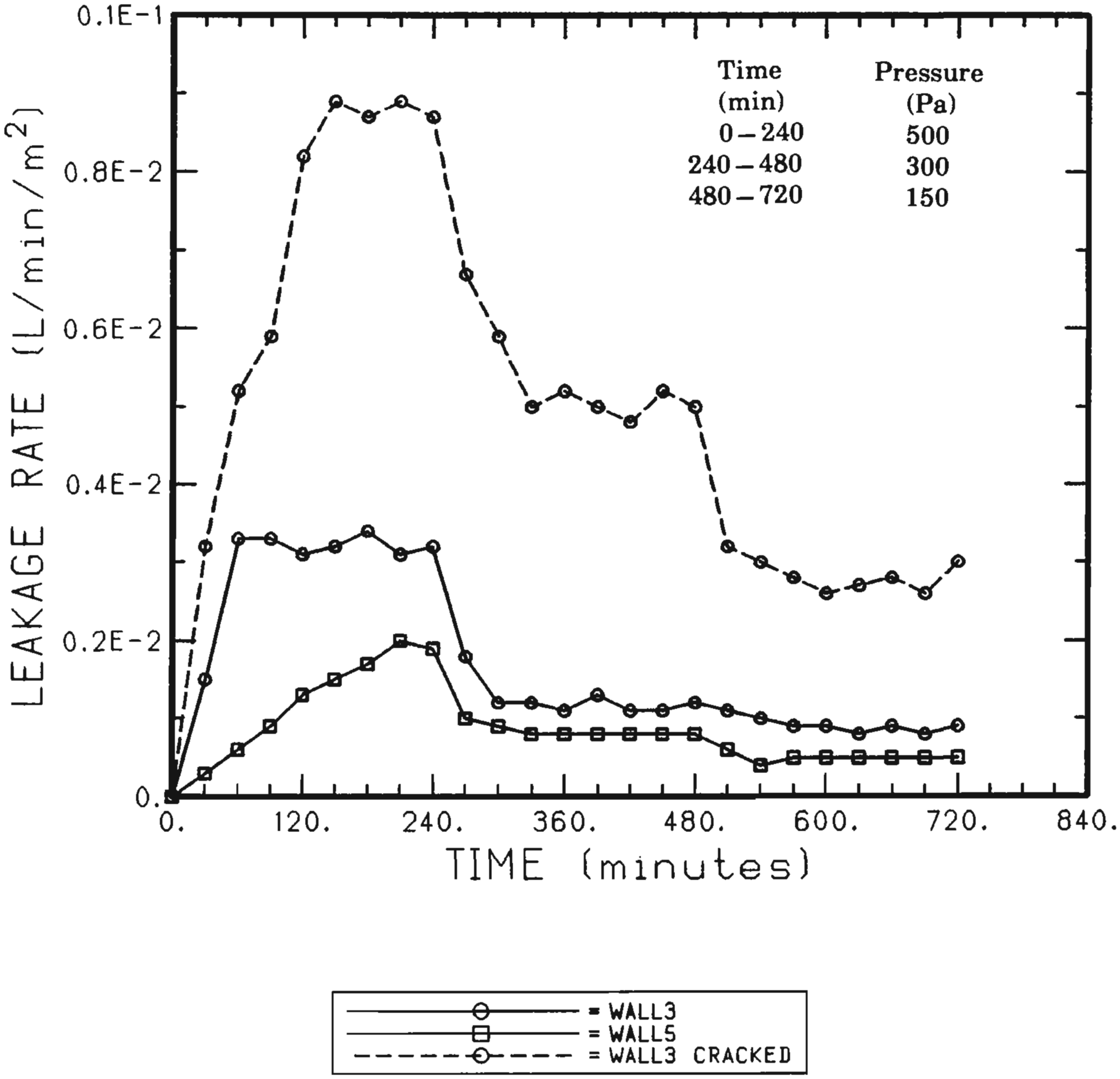


FIGURE 4.6 VARIATION IN LEAKAGE RATE WITH MAGNITUDE OF AIR PRESSURE (Cavity Depressurized Condition)

steady state leakage rate. For the cracked veneer, an increased sensitivity to variations in pressure is evident.

4.3.7 Dye Tracing of Leakage Paths

As an exercise to attempt to mark leakage paths, the water supply for WALL2 was dyed blue. Although this did provided permanent evidence of water penetration through the veneer, the extensive cleaning of the apparatus and potential damage to the pipe network precluded further dye tracing studies for other wall specimens.

In previous discussions it was noted that the pressure difference across the brick veneer significantly influenced the leakage characteristics of the veneer wall. Figure 4.7 is a photograph of a head joint that was removed from the wall after testing for 1 hour with the cavity depressurized and using the dyed water. The air pressure was greatest at the exterior face of the veneer and reduced to atmospheric conditions at the back face. The influence of this pressure gradient on the leakage through the head joint is evident in the photograph. Where the pressure was greatest at the exterior, the penetration occurred over the full height of the head joint. The height of the leakage path decreased with decreasing pressure toward the cavity. The mortar -brick interface appears to provide the least resistance to rain penetration both before and after cracking Similar patterns of staining were observed in a number of head joints but certainly not in the majority of those broken open.

The photograph in Figure 4.8(a) illustrates the typical staining pattern observed on the rear face of the units. The dark lines indicate water paths down the face of the bricks and over protruding mortar fins. The dye pattern on the broken head joint indicates that the uncompacted mortar at the cavity side of the wall more readily allowed passage of water.

No staining was observed along the bed joints at the exposed face of the veneer. However staining was noted at the cavity side of the joint. The staining was most noticeable in

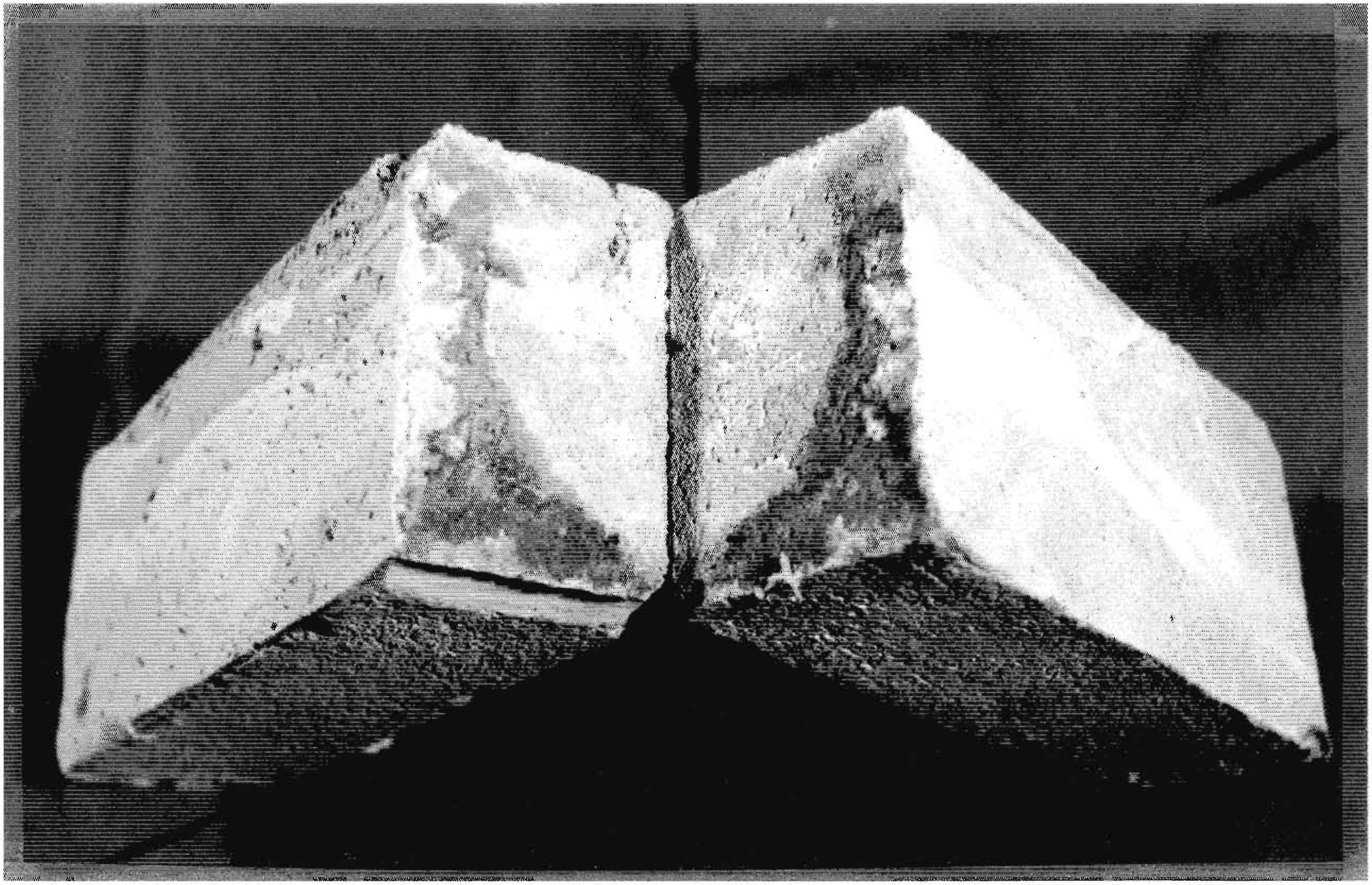
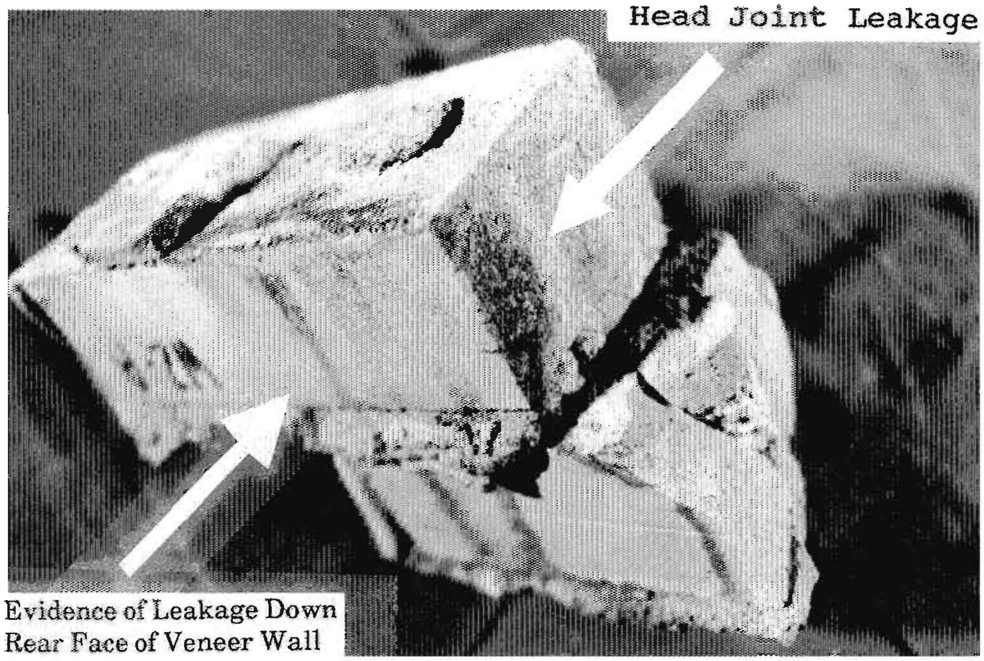
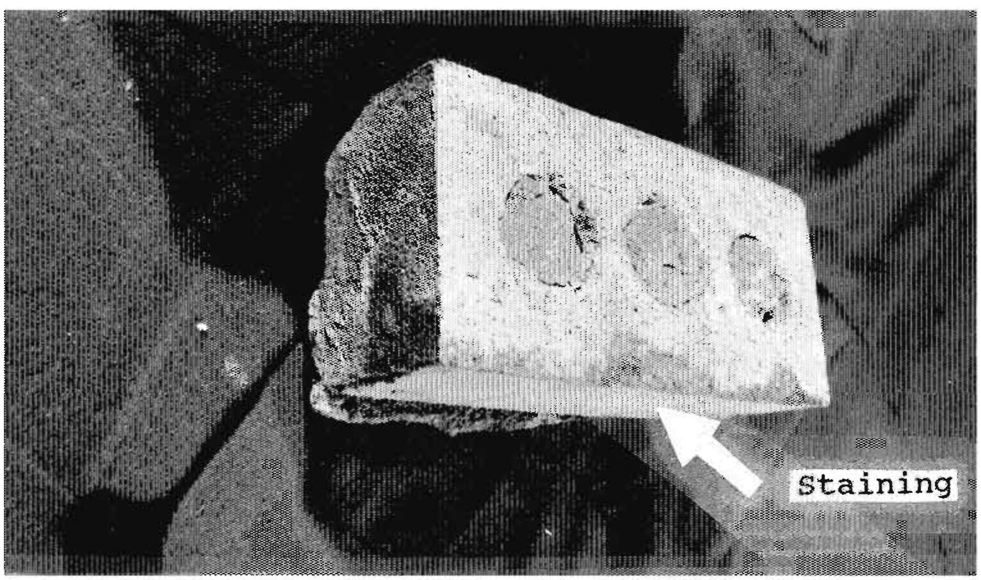


FIGURE 4.7 DYE PATTERN IN A HEAD JOINT (DEPRESSURIZED CAVITY CONDITION)



a)



b) Stained Area Indicating Leakage

FIGURE 4.8 LEAKAGE PATHS OBSERVED FROM DYE STAINING

areas that had experienced heavy head joint leakage. Therefore, it is questionable whether this staining was a result of direct leakage through the bed joint or of water from the leaking head joints migrating back into the wall. The photograph in Figure 4.8(b) shows the limited staining occurring in a typical bed joint removed from the wall. Again the leakage occurring in the head joint is evident from the staining pattern which is more concentrated near the mid length of the brick.

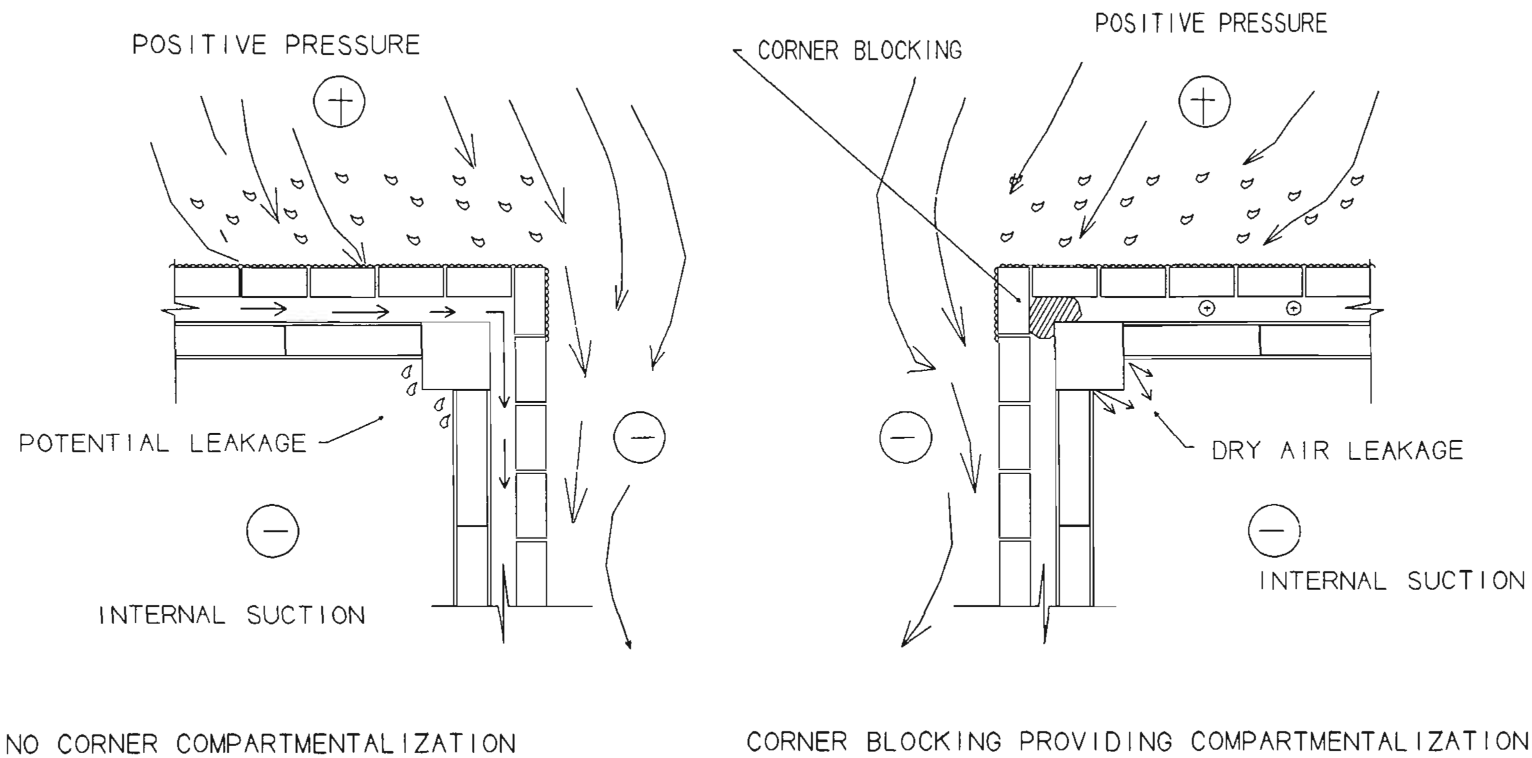
4.4 STUDY OF COMPARTMENTALIZATION

4.4.1 General

Compartmentalization of the cavity is a requirement for proper performance of the open rain screen design. To achieve proper rain screen performance, a contained compartment of air must be pressurized to the external pressure level and located between the wind driven rain and vulnerable building materials.

If the cavity is not comparted, then positive and negative wind pressure can cause air movements within the cavity and prevent equalization of the cavity pressure with the external pressure. In practice the most critical wall locations for compartmentalization are at building corners. At these locations air movement due to pressure differences and wind turbulence can draw rain into the cavity and expose potential leakage paths in the backup wall to moisture, as shown in Figure 4.9.

Compartmentalization can be achieved in the field by partitioning the cavity horizontally at floor levels with shelf angle details, and vertically within storey heights at intersecting walls and at building corners with a closed cell compressible filler or solid metal flashing spanning between the backup wall and into vertical movement joints. Discussions with many visitors to the laboratory revealed a fairly wide spread lack of concern for this important detail in either the design or construction stages of brick veneer walls.



a) No Corner Compartmentalization

b) Corner Blocking for Compartmentalization

FIGURE 4.9 ROLE OF COMPARTMENTALIZATION IN THE RAIN SCREEN PRINCIPLE

4.4.2 Tests Results

4.4.2.1 WALL1

After opening the vents in the backup wall, the cavity pressure dropped and a pressure gradient of 400 Pa was measured across the veneer. The resulting rain leakage rate after 1 hour of testing was 0.015 L/min/m^2. This rate is comparable to the 0.017 L/min/m^2 obtained under a pressure gradient of 500 Pa in an earlier test of WALL1.

4.4.2.2 WALL 2

For WALL2, an attempt was made to study the leakage response to variations in the degree to which compartmentalization had been achieved. A steady leakage rate was reached at an air pressure of 750 Pa with a gradient of 21 Pa across the veneer. After 2 hours of testing, the backup wall vents were slightly opened while maintaining the 750 Pa load. The pressure gradient across the veneer increased to 100 Pa and the steady state rain leakage rate rose from 0.0020 to 0.0045 L/min/m^2. The results are shown in Figure 4.10.

4.4.3 Significance of Compartmentalization Test Results

The fact that recorded rain leakage rates were comparable to those obtained from previous tests with similar pressure gradients does not detract from the importance of compartmentalization. The significance of these tests relates to the increased pressure gradient and reduced performance of the rain screen, both directly resulting from a loss of compartmentalization. The study is one of cause and effect. The effect of a pressure gradient on the leakage response of the wall system was previously determined. A possible cause of a pressure gradient has been identified as a loss in compartmentalization. The similarity of results

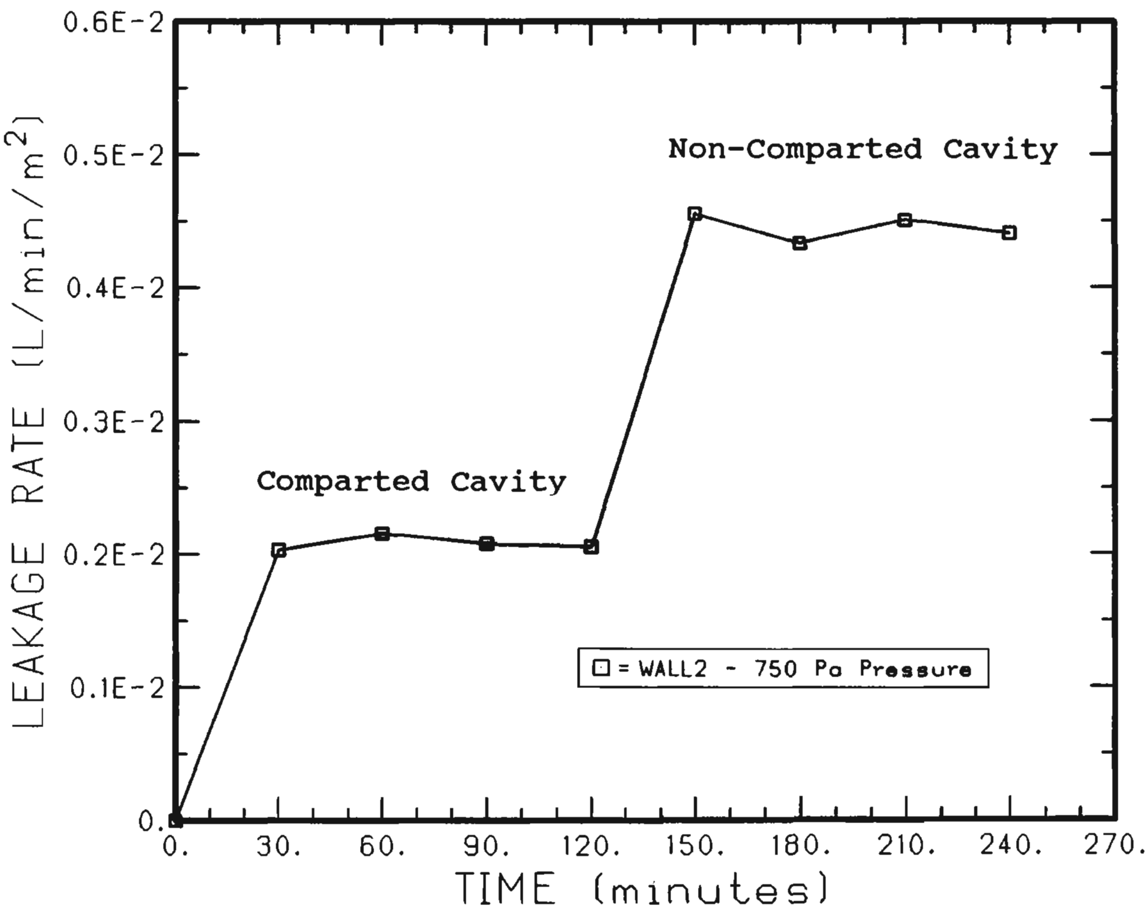


FIGURE 4.10 INFLUENCE OF COMPARTMENTALIZATION

between these studies serves as a verification of the experimental findings and as reinforcement of the need for compartmentalization.

4.5 INFLUENCE OF CONSTRUCTION QUALITY

4.5.1 General

The influence of workmanship is difficult to quantitatively examine because of the difficulty in defining quality of workmanship. If the poor workmanship identified in these tests is not representative of possible construction practices, the findings are of limited use. Also, if the construction deficiencies are too extreme, the sensitivity of the system to other influencing parameters may be masked.

The areas of interest addressed in the design of the test program included improper sealing of the perimeter air barrier and the veneer movement joint in WALL1 and WALL2, respectively. In addition to this, the mortar joints of WALL4 were found to be poorly constructed when examined after testing. The influence of these construction deficiencies with respect to their impact on rain penetration are presented in the following sections.

4.5.2 Perimeter Sealing of Air Barrier

The interior drywall air barrier for WALL1 was installed with properly taped joints and sealed screw holes. Sealant was also placed between the interior drywall and perimeter track and stud flanges. However no sealant was placed between the perimeter members and the specimen frame or the exterior drywall. This resulted in air leakage paths through the backup wall. Site visits and discussions with laboratory visitors both indicated that these details were often neglected in actual practice and were difficult to inspect after construction.

Tests were conducted in the standard manner with both the cavity pressurized and depressurized at an applied pressure of 500 Pa for a periods of 4 hours. The leakage rates measured during the test do not totally reflect the significance of these construction details. Leakage rates were determined from the water collected in the cavity, however addition leakage through the backup wall bypassing the collection system was observed. Leakage of this nature is termed "Through Wall" rain penetration [41,74] and is considered the most damaging.

During the test, water was observed as bubbling under the bottom track and running from upper track locations down the interior face of the backup wall. Also leakage between the end members and the specimen frame was noted and in all cases deterioration of the gypsum board was observed. In addition to these leakage paths, observation through viewing ports revealed that water was carried up between the exterior gypsum board and the bottom track flanges and deposited in the track. This finding is quite significant considering the potential for moisture build up in the bottom of the cavity.

The leakage paths observed during the test are illustrated in Figure 4.11. After the initial tests, the perimeter of the specimen was properly sealed to the specimen frame, thereby preventing further damage from water penetration. Tests of the repaired system continued after cracking of the veneer and no "Through-Wall" rain penetration was observed.

4.5.3 Sealing of Veneer Movement Joint

In the construction of the movement joint at the top of the veneer, it is necessary to seal the foam backer rod to provide a weather tight joint. When this joint is recessed, it is more susceptible to rain penetration than otherwise. To determine the significance of this detail on the rain penetration of the wall system, WALL2 was tested with both a fully and a poorly

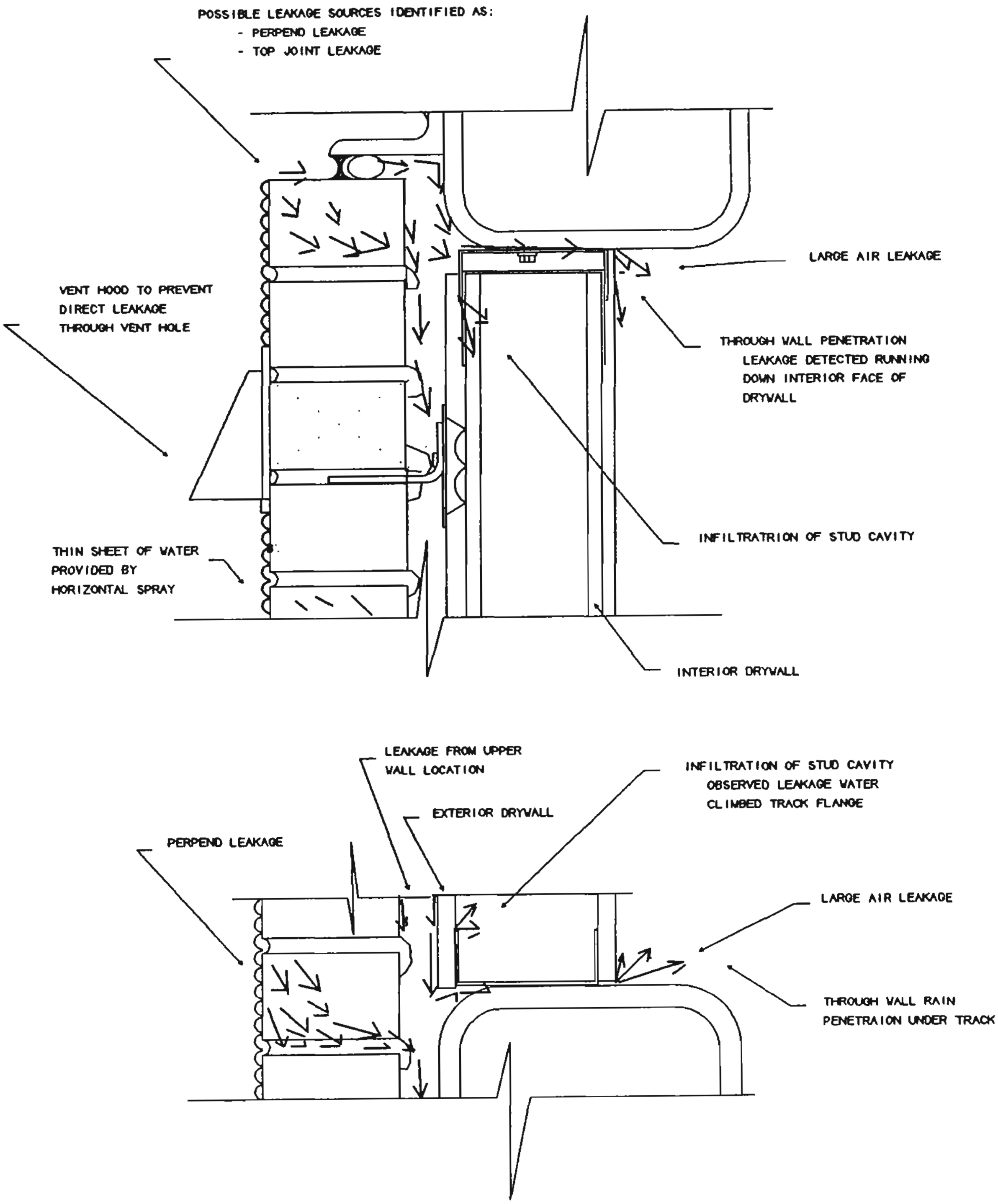


FIGURE 4.11 OBSERVED LEAKAGE PATHS DURING TESTING WITH SUB-STANDARD PERIMETER SEALING OF THE AIR BARRIER IN WALL1

sealed joint. The poorly sealed joint was constructed by improperly caulking in front of the foam backer rod. Both the fully and poorly sealed details are shown in Figure 4.12.

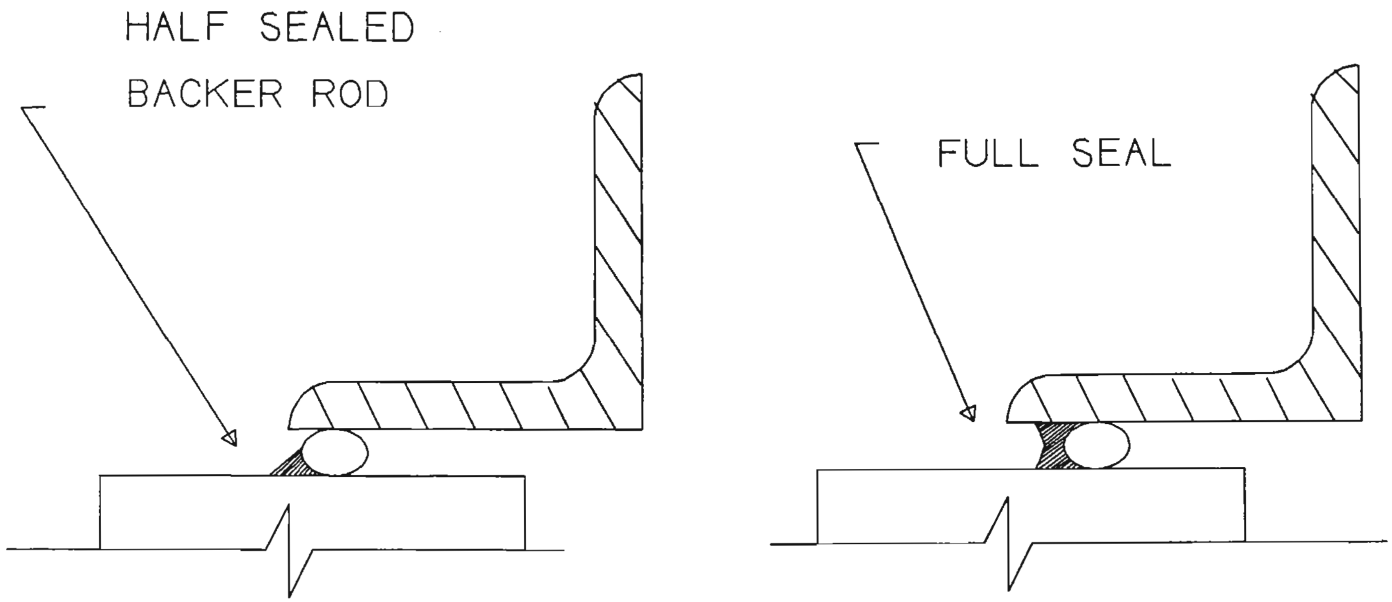
At 500 Pa air pressure, water was observed tricking down the cavity face of the veneer in the early stages for both the cavity pressurized and depressurized conditions for the test with the poorly sealed top joint. The results presented in Figure 4.13 show that in all cases the leakage rates were greater than those obtained after the joint was fully sealed. Possibly more significant than the actual leakage rates recorded were the observations of water in the stud cavity (ie. between the gypsum board sheathings).

When the cavity was pressurized, the poorly sealed top joint allowed penetration of water into the cavity along the under side of the top shelf angle. The presence of water in this location combined with the effects of gravity flow and a small driving pressure force led to infiltration of the stud cavity. Although the observed leakage was very small and basically un-measurable, it does indicate a vulnerability to moisture related problems.

With the cavity depressurized, the pressure difference acted across the veneer and, although greater leakage was recorded, no moisture was observed in the stud cavity. This might initially seem like a contradiction in results but the result helps points out the need for air tight backup walls both to achieve pressurization of the cavity and to prevent air leakage from carrying water into the backup wall.

4.5.4 Mortar Joint Workmanship

During the rain penetration testing of WALL4, it was observed that the leakage rates were significantly higher than those obtained for the other specimens. The leakage rates are shown in Figure 4.14 for both cavity pressure conditions and the responses obtained from WALL2 and WALL3 are also included for comparison.



a) Poor Seal

b) Full Seal

FIGURE 4.12 SEAL DETAILS FOR VENEER MOVEMENT JOINT FOR WALL2

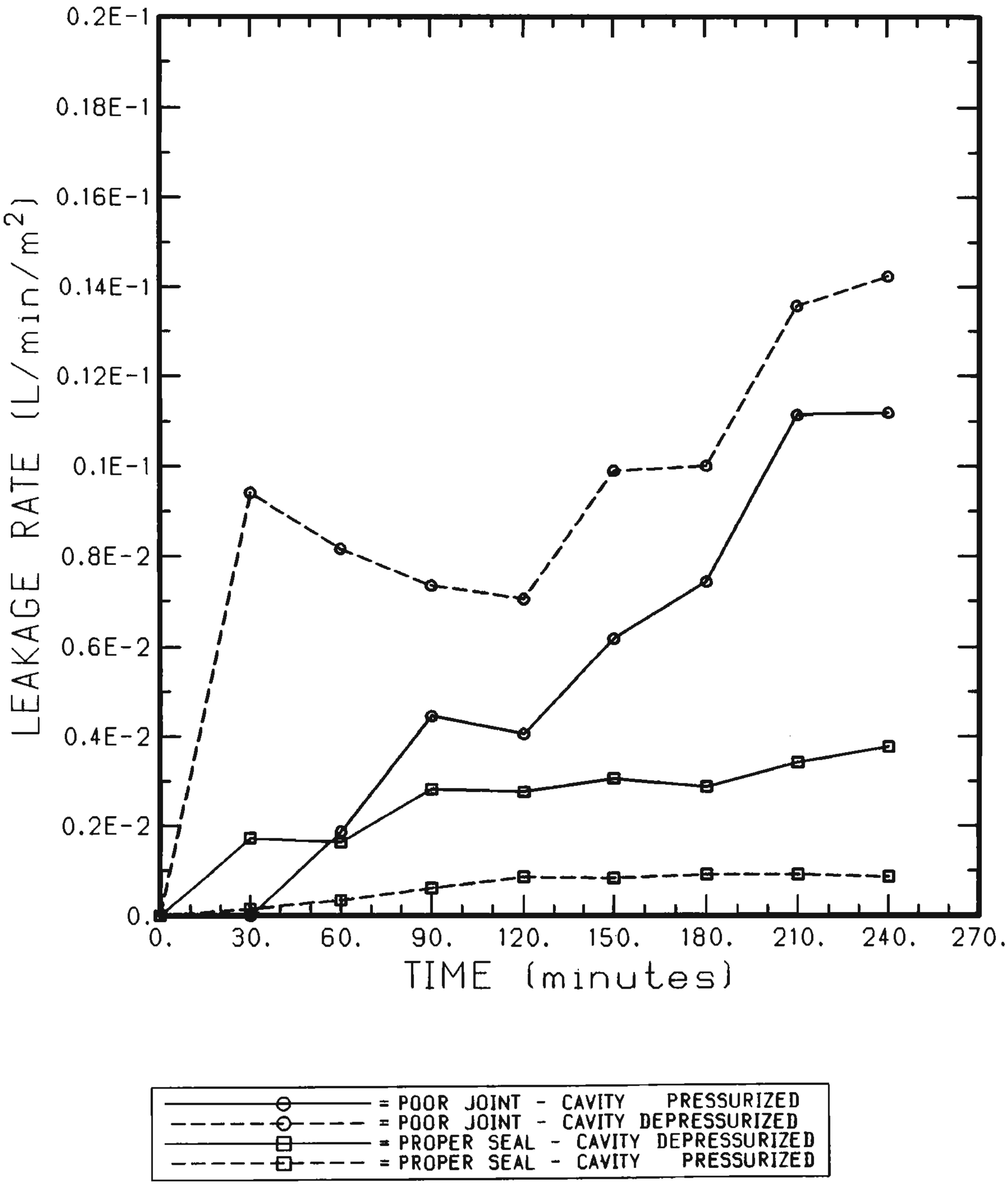


FIGURE 4.13 INFLUENCE OF POOR MOVEMENT JOINT DETAIL ON LEAKAGE RATE

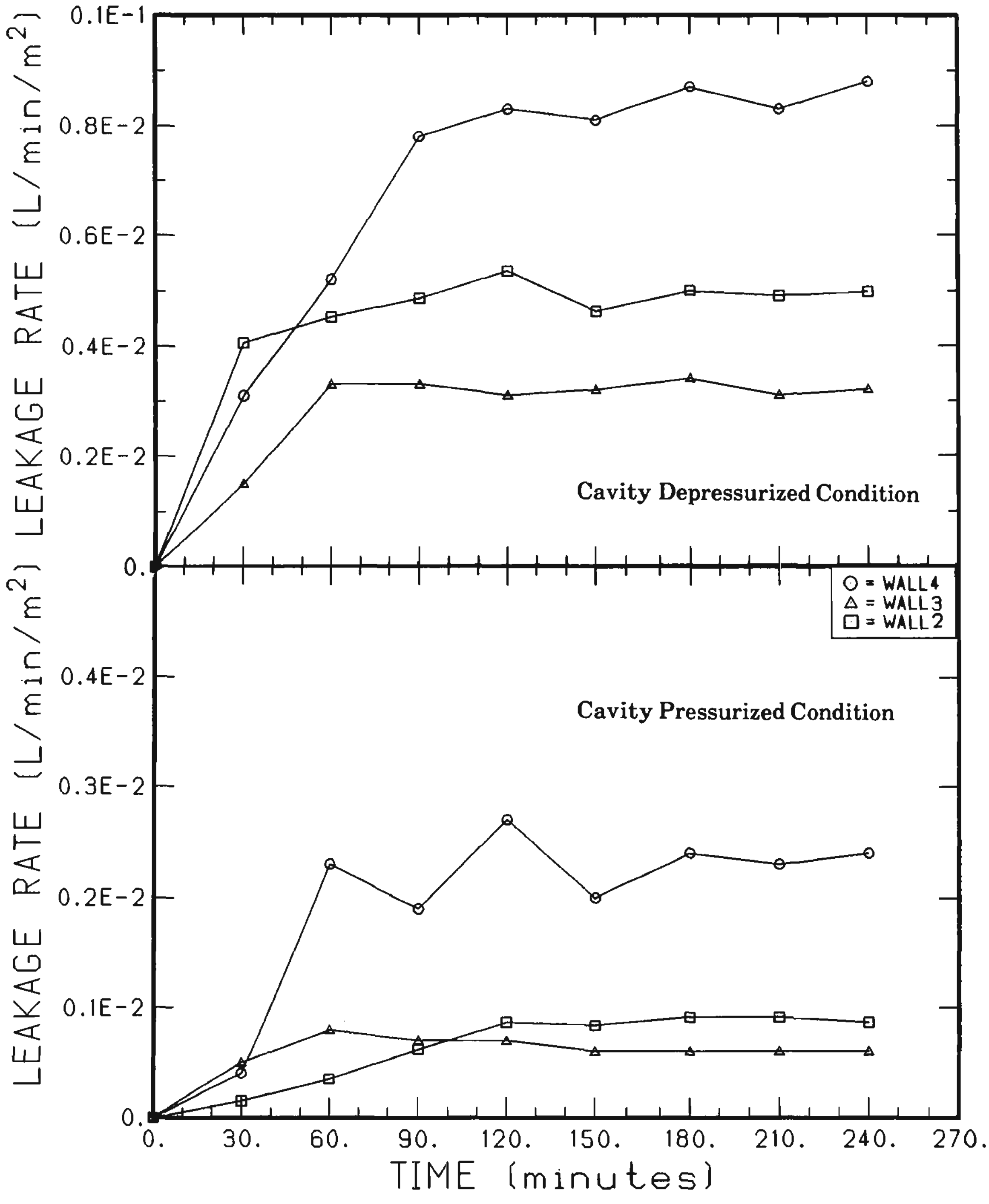


FIGURE 4.14 INFLUENCE OF POOR MORTAR JOINT ON LEAKAGE RATE

WALL4 incorporated a large window, but every effort was made to provide proper sealing around the window's exterior perimeter to prevent rain penetration. In fact the window was covered with a plastic sheet which was sealed to the exterior face of the brick preventing wetting of the window. Investigation of the relatively excessive leakage revealed that the possible sources were likely either the mortar joint above the window, between the loose lintel angle and the bricks, or at partially filled mortar joints. Figure 4.15(a) is a photograph of the lintel where the ends of the steel angle were laid on bare brick. An example of the partially filled mortar joints found in the wall is shown in Figure 4.15(b).

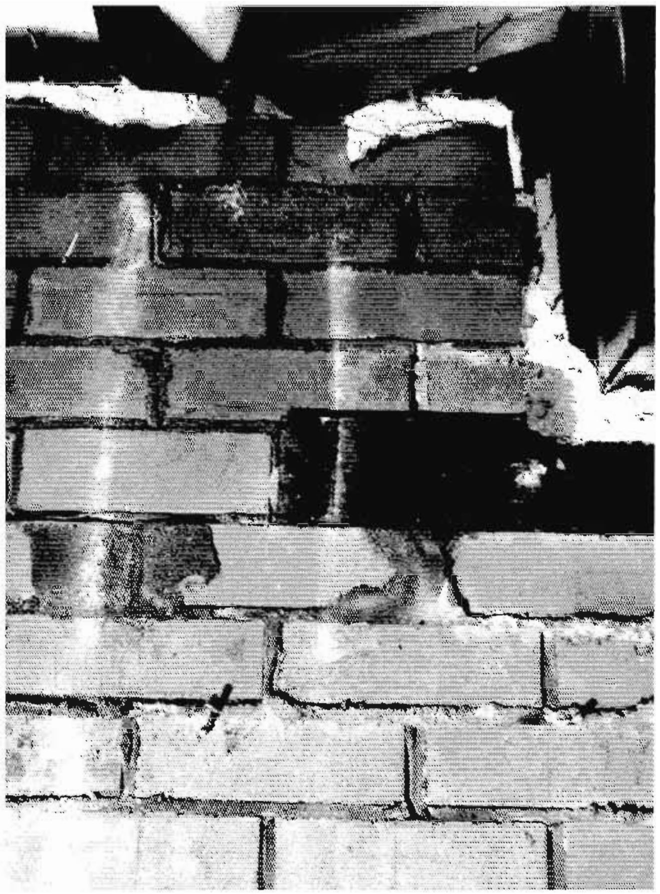
The exact contribution of each source could not be determined. However previous observations of leakage from well constructed mortar joints supports the suggestion that even more leakage would occur through partially filled joints. A close examination of the joint conditions in the wall revealed numerous deficiencies.

Photographs of particularly poorly filled head joints on the cavity side of the veneer were taken during an examination of the joint conditions before removal from the wall. The joint shown in Figure 4.16(a) has sizable areas devoid of mortar. Surprisingly the head joint located directly below was buttered over thereby hiding any such voids. It should be noted that regardless of the buttering with mortar, the joint was found to be quite damp and leakage was evidence. The worst case identified in the wall was in fact only half filled with mortar and without close examination closely resembled a weep hole. This joint is shown in the photograph in Figure 4.16(b).

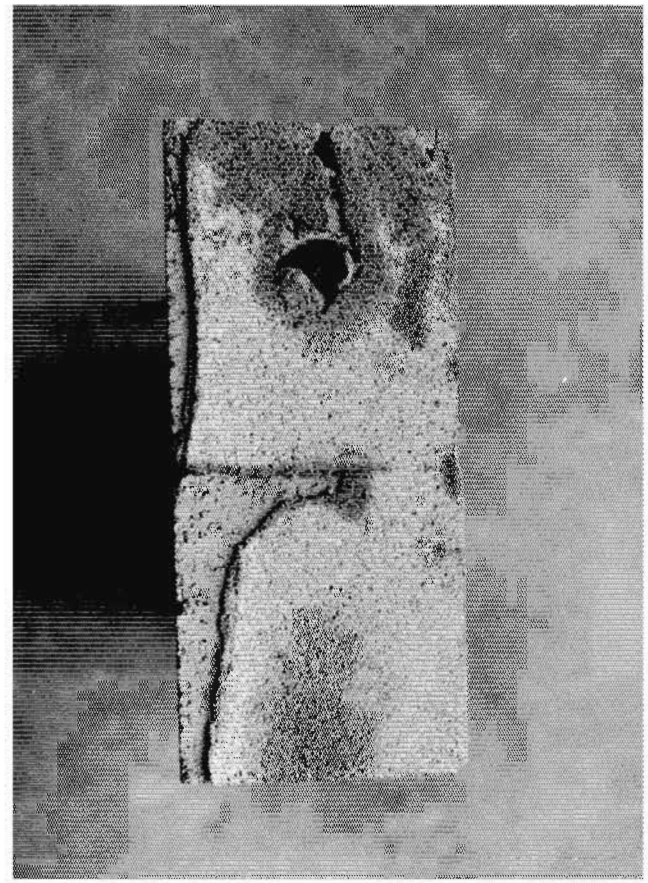
4.6 CAVITY PRESSURIZATION TIME

4.6.1 General

It has been shown that the influence of cavity pressure significantly affects the leakage response of the wall system. During the tests, the air pressures were held constant.

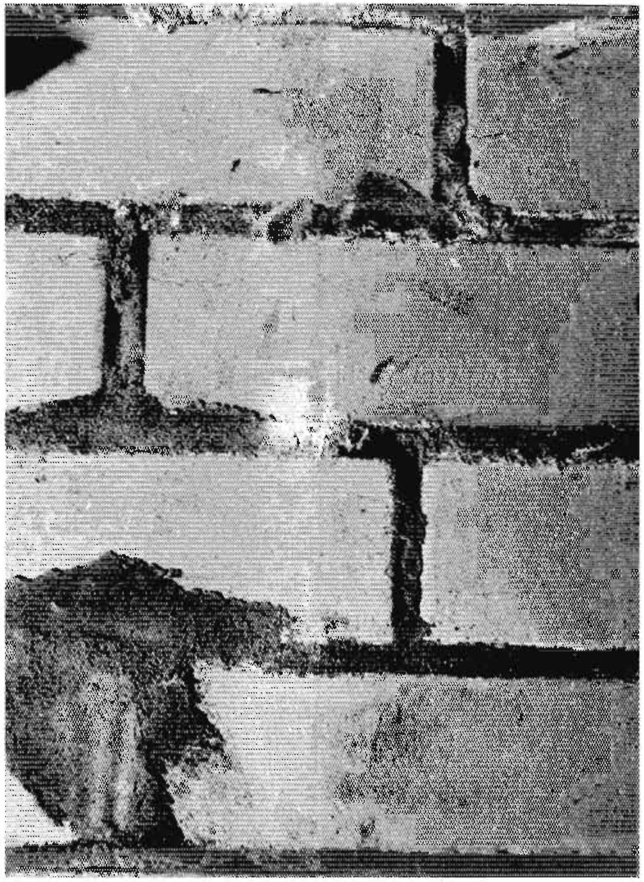


a) Loose Lintel Built Into Veneer Wall

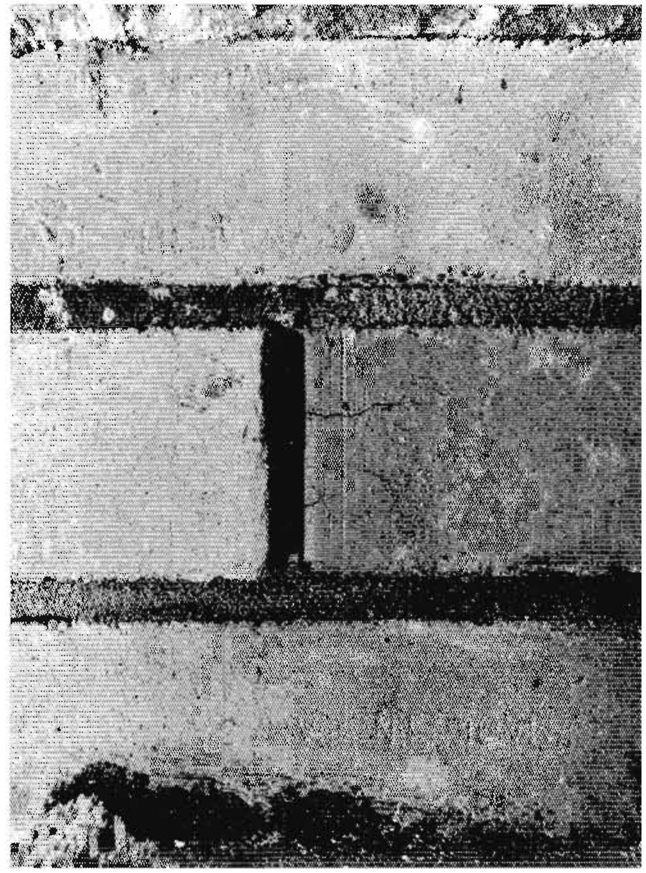


b) Partially Filled Bed Joint and Heavy Furrowing

FIGURE 4.15 SOURCES OF ADDITIONAL LEAKAGE IN WALL4



a) Poorly Filled Head Joint and Buttered Over Joint



b) Half Empty Head Joint Heavily Contributing to Leakage

FIGURE 4.16 PARTIALLY FILLED MORTAR JOINTS IN WALL4

However in practice these pressures are non-uniform and vary with time. In order to examine the response of the cavity pressure to changes in external air pressures, a series of pressure tests were undertaken.

The pressure tests were conducted on two specimens with different air volumes in the cavity. The specimens and their respective cavity volumes were as follows:

- WALL2 - cavity air volume = 1.60 m^3
- WALL3 - cavity air volume = 1.95 m^3

It should be noted that both the location of the air barrier and the cavity width influenced the cavity air volume. Another variable in the test series involved the vent area of the veneer wall. The vent areas provided during the test were as follows:

- WALL2 - vent area = 0.01224 m^2
  - vent area = 0.00612 m^2
- WALL3 - vent area = 0.00918 m^2

The vent area was controlled by the spacing between weep holes and vents in the veneer. For WALL2 half of the weep holes and vents were sealed and the wall was retested.

The test procedure was very simple and involved loading the specimen to approximately 1 kPa at full speed and then abruptly stopping the fan and allowing the apparatus to depressurize. The data collected during the test included continuous recording of external pressures and internal cavity pressures. The data logger was capable of recording the two pressures into its internal memory at a rate of two samples every 0.08 seconds. For each specimen the test was repeated five times and the results for all tests are were then averaged.

4.6.2 Test Results

Collectively the test results were intended to provide insight into both the required time to reach peak load and the response of cavity pressure to changes in external pressure levels.

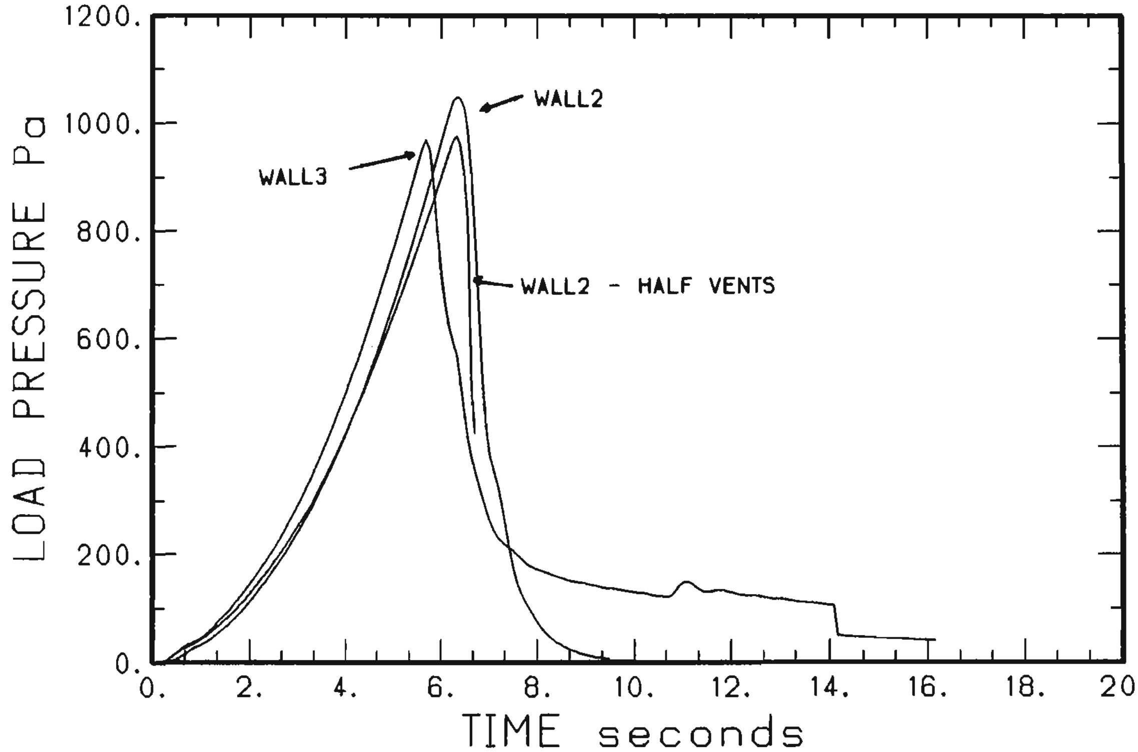
It was initially thought that the time to reach peak load would be governed by the fan's physical limitations. The test results showed that a time of approximately 6 seconds was required for the fan to build up 1 kPa load in the pressure chamber. This time was observed for all specimens regardless of the cavity air volume. It is not surprising that the cavity air volumes, which differed by as much as 1.25 m^3,barely influence the pressurization time of the approximately 12 m^3 pressure chamber. The cavity air volume did however have an impact on the response of the cavity pressure to changes in external pressure.

The average test curves obtained are shown in Figure 4.17. Although the external pressure loads shown in Figure 4.17(a) were similar in all cases, the pressure difference between the pressure chamber and the cavity, shown in Figure 4.17(b) varied between specimens.

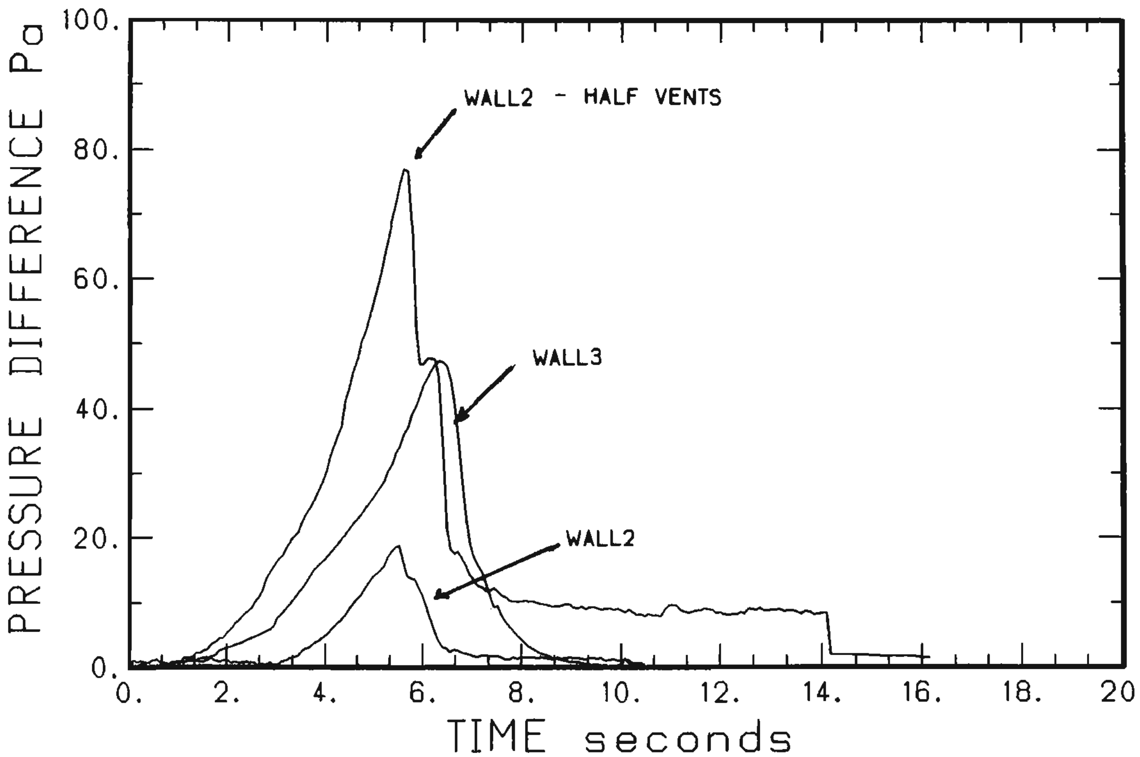
The relationship between peak pressure difference and ratio of cavity air volume to vent area is shown in Figure 4.18. As the ratio increased the ability of the cavity to rapidly adjust to the external pressure levels decreased and higher pressure differences were experienced.

4.7 CLOSURE

The rain penetration test results discussed in this chapter will be summarized later. However it should be noted that the majority of the finding were related to one of three major areas of interest. These areas of interest included cavity pressurization, veneer cracking and the significance of air tightness in the backup wall.



a) External Pressure



b) Pressure Difference Across Veneer

FIGURE 4.17 CAVITY PRESSURIZATION TEST RESULTS

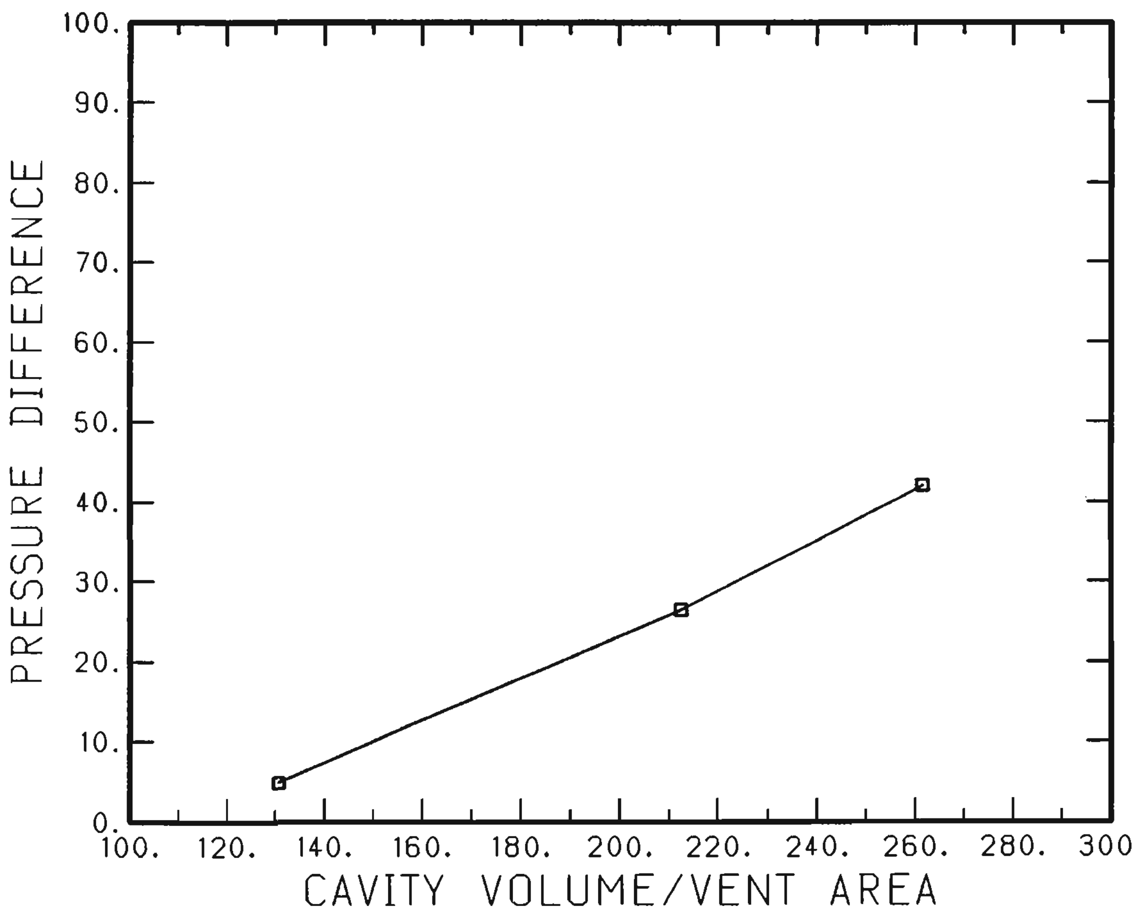


FIGURE 4.18 RELATIONSHIP BETWEEN PRESSURE DIFFERENCE AND CAVITY VOLUME TO VENT AREA RATIO

It was observed that pressurizing the cavity resulted in the greatest resistance to rain penetration compared to a depressurized cavity. A cracked veneer was only found to have significantly increased rain penetration for the case of a depressurized cavity. These results support the claim that details to ensure pressurization of the cavity are important requirements for an open rain screen design.

The observed vulnerability of an open rain screen design to moisture penetration of the backup wall when the backup wall allowed air leakage or when the cavity was not compartmentalized were very significant findings.

CHAPTER 5

STRUCTURAL TEST RESULTS

5.1 INTRODUCTION

Structural tests were conducted on the various configurations of brick veneer wall systems described in Chapter 2. These included varied end support conditions, a large opening and different backup walls. An objective of these tests was to provide qualitative observations to compare the characteristic behaviours of individual wall components, established in other Parts [33,36] of the CMHC/McMaster research program, to their behaviour in complete wall systems. To this end the performance and failure modes of the steel stud members, steel stud to track connections, movement joints, wall ties and brick masonry were of particular interest.

From a building envelope view point, the influence of cavity pressurization, required by the rain screen, on the structural response of the wall system was also investigated. Structurally, the cracking load and effect of cracking of the veneer on the structural response of the wall system were also investigated.

5.2 STRUCTURAL TEST OBJECTIVES

5.2.1 Common Objectives of the Structural Tests

Although each test wall was designed to incorporate different features and configurations, structural test objectives common to all were defined as follows:

- **Cavity Pressurization:** It is common practice and highly recommended that the cavity be pressurized to equal external air pressure levels to enhance the rain screen performance of the wall system. The impact of this serviceability performance requirement on structural behaviour was investigated by repeating tests for both the cavity pressurized and the cavity depressurized conditions.

- **Cracking Load:** Because design criteria may address cracking as either a serviceability or ultimate state, prediction of the cracking load is important. To conform to the design criteria, the initial crack development load stage was carried out with the cavity pressurized for all wall specimens.

- **Influence of Cracking on Structural Response:** For development of the first crack, care was taken to avoid development of additional cracks in order to represent conditions likely to occur at typical design loads. Thus, following initial cracking of the veneer, the load was removed and the influence of the cavity pressure was investigated at load levels below the initial cracking load.

- **Ultimate Strength:** For the purposes of the test program, the ultimate strength was defined as the load required to develop a collapse mechanism in the masonry or flexural failure of the steel studs. Continuation of a test beyond this point was not deemed either safe or relevant. Although the ultimate loads were 4 to 8 times the typical design loads, the condition and performance of the various components were recorded to provide additional information for assessing the overall behaviour and performance of the wall system.

5.2.2 Structural Test Objectives for Individual Walls

In addition to the common test objectives, each wall was designed to include independent structural tests to provide additional insight into the behaviour of BV wall systems.

- **WALL1:** To produce one way bending behaviour, the end studs were only supported top and bottom. To verify the free end condition, the backup wall was loaded prior to constructing the veneer panel. This loading procedure provided insight into the structural response independent of the brick veneer.

- **WALL2:** This specimen was constructed with the backup wall supported on all four sides to investigate the response of the wall system to the resulting two-way bending. Although the 1.86 aspect ratio of the veneer was near the value of 2.0 typically considered as the limit for two-way bending, previous analytical work [34] indicated that some two-way bending behaviour was possible.

  Another aspect investigated was the influence of the "soft" movement joint located at the top of the veneer panel. This joint usually consists of a foam backer rod sealed in place with silicone caulking to provide a weather tight joint. Although the joint is intended to be "soft", it was believed that, while jamming the backer rod into the joint, a restrained condition could be produced.

- **WALL3:** The third specimen incorporated a double steel stud design with the SS movement joint located at the base of the wall. Aside from alleviating interior design restrictions imposed by the conventional "soft" ceiling joint, this design also allowed the veneer construction to precede installation of the insulation and sheathing.

Removal of all mortar droppings from the cavity and close inspection of the veneer were accommodated by the construction sequence.

- **WALL4:** This test wall was included to examine the serviceability performance of the wall system with a large window opening. Repeated loadings were scheduled under both cavity pressurized and depressurized conditions.

- **WALL5:** A concrete block backup wall was incorporated in the design in place of the steel stud panel used in the previous specimens. In addition to comparing the behaviour of the BV/CB wall system, the potential for cracking of the CB backup wall was of particular interest.

5.3 RESULTS FOR COMMON TESTS

5.3.1 General

As described in Chapter 2, the test procedures involved a sequence of load stages arranged to examine the influence of cavity pressurization on the structural response of the wall system at a standard load level of 500 Pa, both prior to and after veneer cracking. The data collected included displacement and pressure. To account for the effects of the repeated loading of each specimen, both a cumulative displacement history over the course of the entire load sequence and incremental displacement values over each single load stage were recorded.

It is important to understand how the residual displacements have been dealt with in the presentation of the data. When comparing the lateral displacement profiles of different walls, the data has been normalized to a pressure of 500 Pa and presented as an incremental displacement designated as "flexural displacement", independent of residual movement. This allows the data to be compared without considering the possible distortion accumulated over previous stages of loading. In order to document the residual displacement observed for each wall, load-displacement plots including all displacements have been presented as "gross displacement". This also allowed the results to be presented without considering the possible bias created by differing residual movements, where the origin is merely offset by the residual amount. From Chapter 2 it may be recalled that the flexural displacements are calculated from the gross displacements by subtracting the top and bottom translational movement.

Because the body of data is so large, only a summary of the lateral displacements at 500 Pa for each load stage are provided in Appendix 4.

5.3.2 Influence of Cavity Pressurization

5.3.2.1 BV/SS Wall System

The lateral displacements at the centre stud line for WALL1 through WALL3 and at the quarter stud line for WALL4 are shown in Figure 5.1 for 500 Pa air pressure. The WALL4 data is at the quarter panel point because of the large window opening in the centre of the wall. The displacement plots correspond to the following load stages for each wall specimen:

WALL1:	Cavity Pressurized	-	Load No. 3
	Cavity Depressurized	-	Load No. 4
WALL2:	Cavity Pressurized	-	Load No. 6
	Cavity Depressurized	-	Load No. 7
WALL3:	Cavity Pressurized	-	Load No. 6
	Cavity Depressurized	-	Load No. 2
WALL4:	Cavity Pressurized	-	Load No. 1
	Cavity Depressurized	-	Load No. 2

For all walls it was observed that, with the cavity pressurized, the stud displacements were larger than the veneer displacements. Conversely, load on the veneer (depressurized

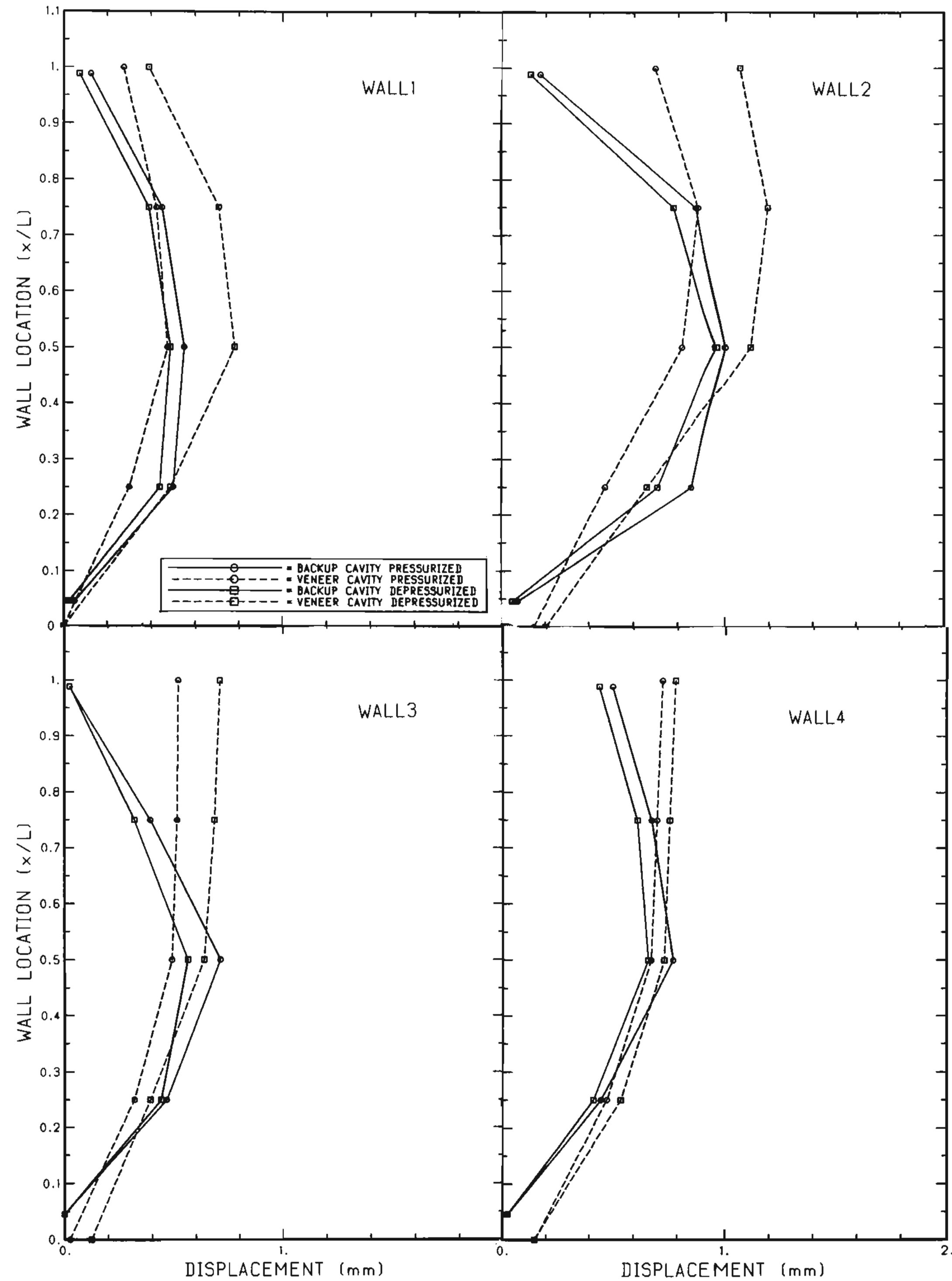


FIGURE 5.1 INFLUENCE OF CAVITY PRESSURIZATION ON DEFLECTION OF BV/SS WALL SYSTEMS AT 500 Pa AIR PRESSURE

condition) produced larger veneer displacements compared to the studs. However, for both cavity pressure conditions, the displacements of the stud walls were much more similar compared to the relative difference in displacement observed for the veneer. The pressurized cavity condition produces the largest displacement for the SS wall The converse is true for the brick veneer panels.

From the relative displacement between the veneer and the stud wall, it can be deduced whether the ties were in compression or tension. For cavity pressurization conditions, this exercise revealed compression forces in top ties and tension forces in ties located in the lower portions of the wall. For cavity depressurized cases, compressive tie forces predominated.

5.3.2.2 BV/CB Wall System

The recorded displacements at 500 Pa for the CB backup wall system in WALL5 were just over 0.5 mm, typically about half of that observed for SS backup wall systems. The displacements shown in Figure 5.2 for the cavity pressurized and depressurized conditions correspond to Load Numbers 6 and 7 respectively.

The major difference between the results for the two backup wall systems involves the cavity pressurized condition where the CB and BV wall displacements were nearly identical. Compared to the SS construction, the much stiffer CB wall and the greater tie density accounts for this behaviour. Consistent with the steel stud backup wall performance, for the cavity depressurized condition, the veneer displacements were larger than the backup wall displacements.

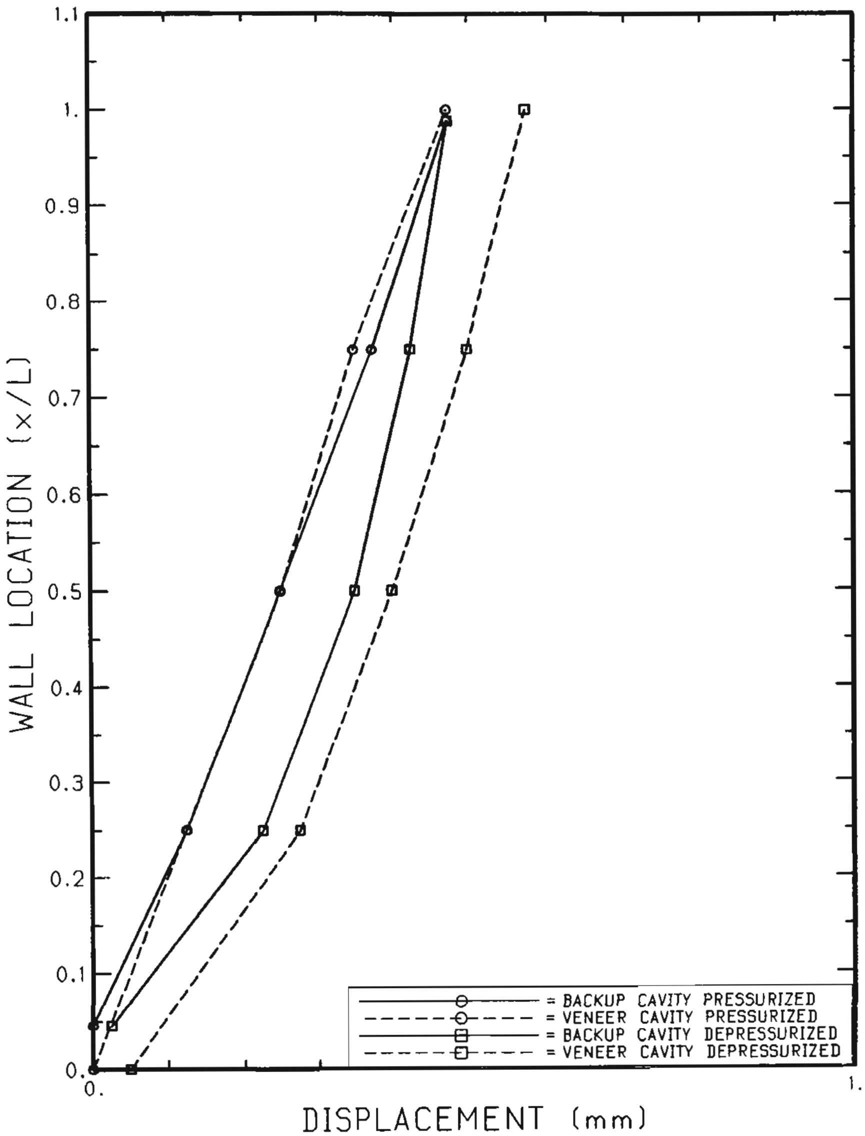


FIGURE 5.2 INFLUENCE OF CAVITY PRESSURIZATION ON DEFLECTION OF THE BV/CB WALL SYSTEM AT 500 Pa AIR PRESSURE

5.3.3 Determination of Initial Cracking Load

The tests to determine the cracking loads were conducted with the cavity pressurized up to a target air pressure of 2 kPa. If excessive flexural displacement in the veneer or noticeable damage in the air barrier was observed the test was terminated.

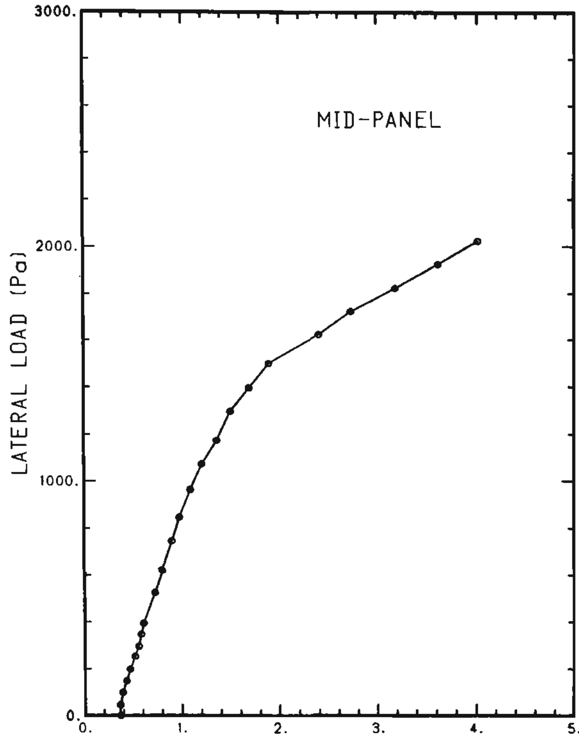
As previously described in Chapter 2, the onset of cracking involved monitoring the mid height flexural displacement of the veneer at mid length of the test specimen. For each wall, a plot of the flexural displacement vs. air pressure is provided along with the gross displacement plots of both the veneer and backup wall at top, intermediate and mid height locations. These displacements were all recorded along the vertical line at the mid length of the wall with the exception of WALL4 where the large opening in the centre of the wall required a shift to the quarter panel location.

In the cases of specimens with backup walls supported on four sides, flexural veneer displacement have been presented for both mid and quarter panel locations, in order to indicate the degree of two way bending behaviour. The displacement plots presented in this section include all residual movement and must be taken into account in the interpretation of the results.

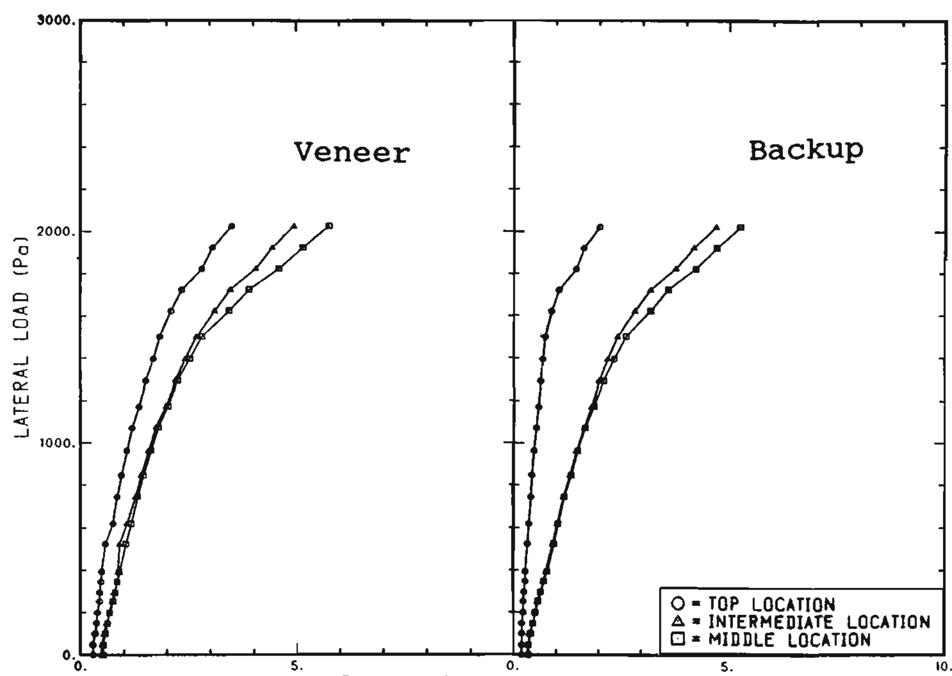
5.3.3.1 WALL1

The recorded gross displacements and calculated flexural displacement of the veneer during the cracking load stage No. 5. are shown in Figure 5.3. As can be seen in Figure 5.3(b), the top of the veneer wall deflected considerably more than the backup but the values were closer at mid height.

From Figure 5.3(a), a decrease in the slope of the mid height load-deflection curve can be seen.at around 1.4 kPa air pressure. The gradient transition indicates that the cracking



a) Flexural Veneer Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.3 DISPLACEMENTS DURING LOADING TO INITIAL CRACK STAGE FOR WALL1

was progressive and not sudden in nature. The behaviour of the steel stud backup wall, also illustrated in Figure 5.3(b), was very responsive to the cracking in the veneer. It is believed that this behaviour indicates an increased portion of lateral load being resisted by the backup, because of the loss of stiffness in the veneer due to the crack.

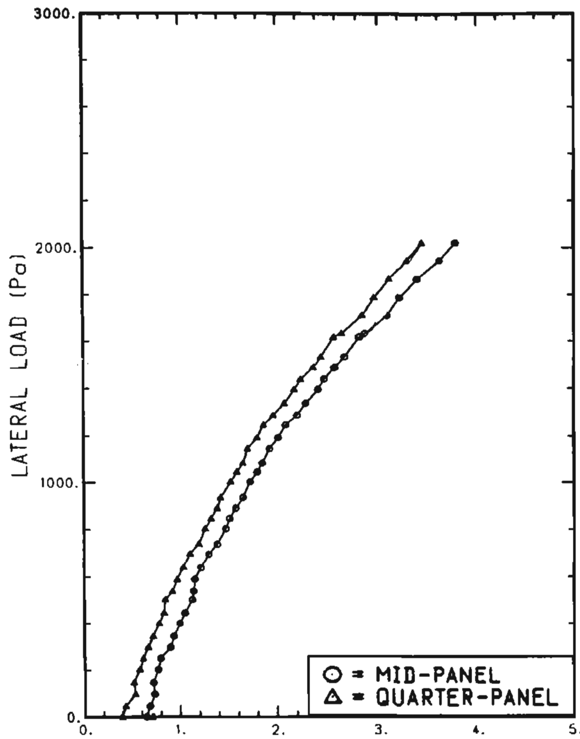
During the test, the air barrier performed adequately and transferred the pressure to the studs. However, at gypsum board screw locations, the joint compound was cracked and the gypsum board bulged and generally showed signs of distress.

5.3.3.2 WALL2

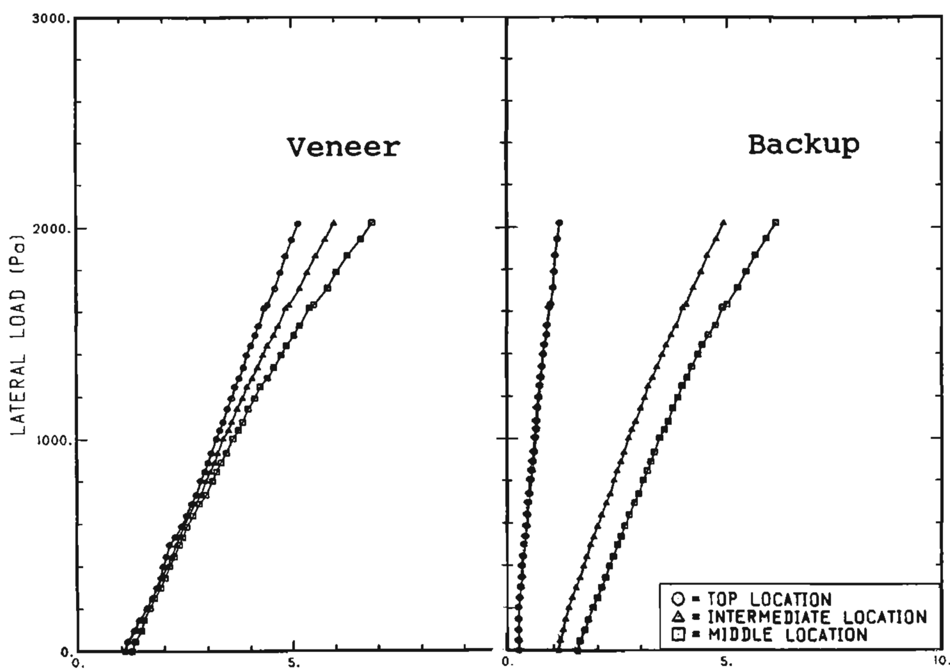
The recorded gross displacements and calculated flexural displacement of the veneer during the cracking load stage No. 7 are shown in Figure 5.4. Again, the veneer displaced considerably more than the backup wall at the top of the wall, and this is consistent with high compressive forces in the top tie locations.

The estimate of the initial cracking load for WALL2 from the flexural displacement plot shown in Figure 5.4(a) is somewhat arbitrary. The flexural behaviour of the wall system does not show either an initial linear range or any significant variation in response due to cracking. The only variation in response detected in Figure 5.4(b) was an apparent loss of stiffness between two load increments at around 1.6 kPa for both the veneer and backup wall. This is partially recovered with further load application.

The gypsum board air barrier transferred the pressure to the studs without failure but, as for WALL1, at screw locations the joint compound was cracked and the gypsum board bulged and generally showed signs of stress. Viewing ports in the backup wall allowed the rear



a) Flexural Veneer Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.4 DISPLACEMENTS DURING LOADING TO INITIAL CRACK STAGE FOR WALL2

face of the veneer to be examined and a horizontal crack near the mid height of the wall was observed.

5.3.3.3 WALL3

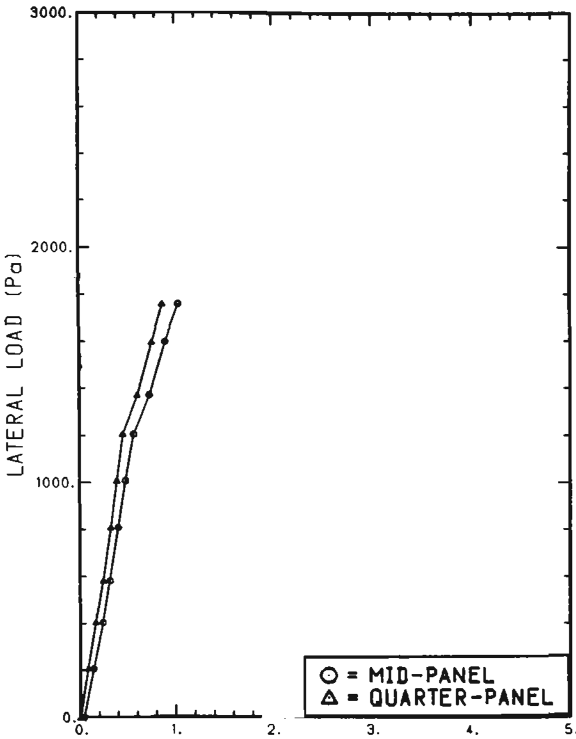
The recorded gross displacements and the calculated flexural displacements of the veneer during the cracking load stage No. 7 are shown in Figure 5.5. As shown in Figure 5.5(b), the much stiffer top connection detail resulted in almost no displacement at the top of the SS wall.

From the flexural displacement of the veneer shown in Figure 5.5(a), it is evident that cracking initiated in the veneer at a load level of approximately 1.2 kPa. The behaviour of the backup wall, shown in Figure 5.5(b), was very responsive to the initial cracking in the veneer and again indicated the increased share of the load taken by the backup afterthe veneer had cracked.

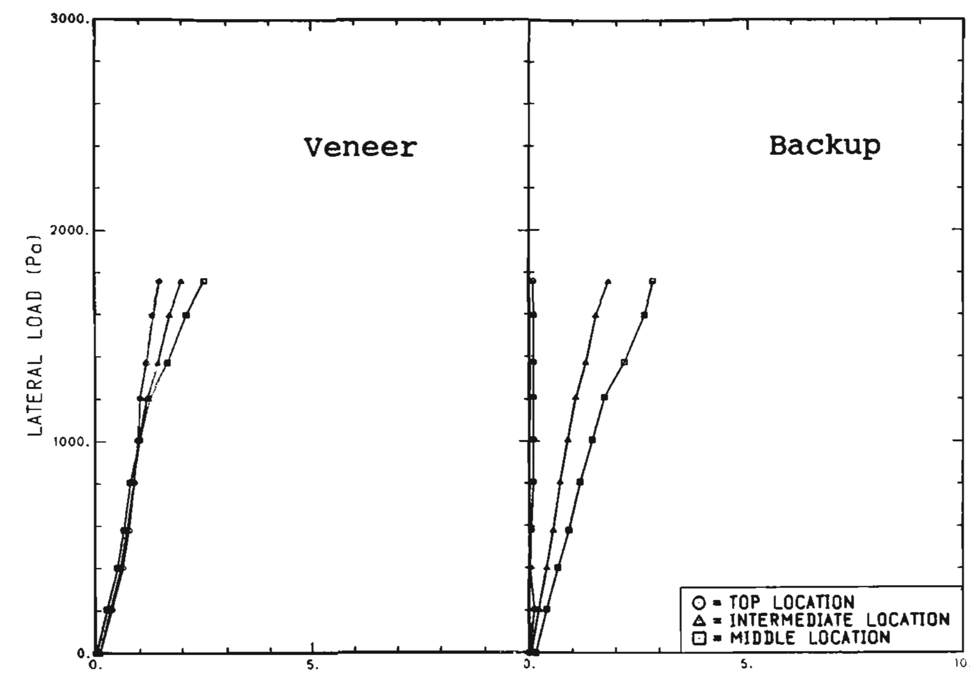
The sealed gypsum board air barrier in WALL3, did not perform satisfactorily as constructed. At a load level of approximately 1.5 kPa the gypsum board pulled away from the steel stud and gypsum board fastening screws in several places. This "screw popping" was located at the centre portion of the gypsum boards and not at the edges where more screws had been used. In order to continue the test, additional screws were installed. It should be noted that, although the vertical span for the gypsum board was 400 mm the horizontal span measured 800 mm compared to 400 mm in the other specimens.

5.3.3.4 WALL4

The recorded gross displacements and calculated flexural displacements of the veneer during the cracking load stage No. 3 are shown in Figure 5.6 for the quarter panel location.

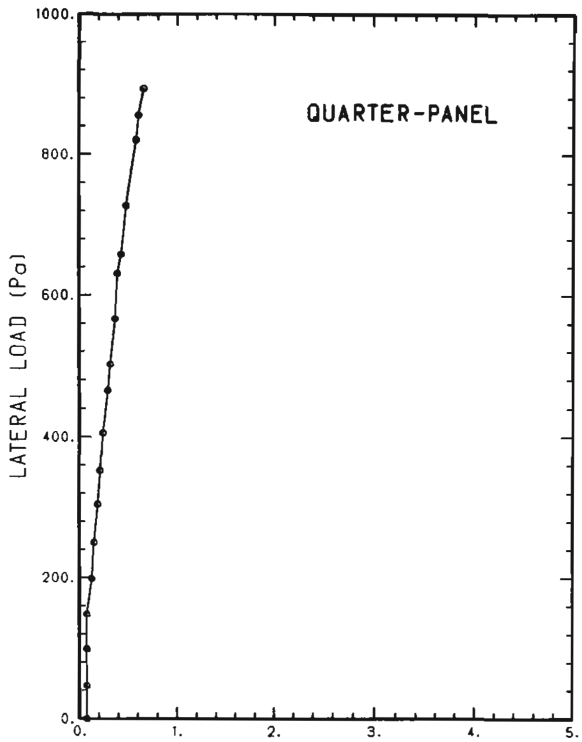


a) Flexural Veneer Displacement (mm)

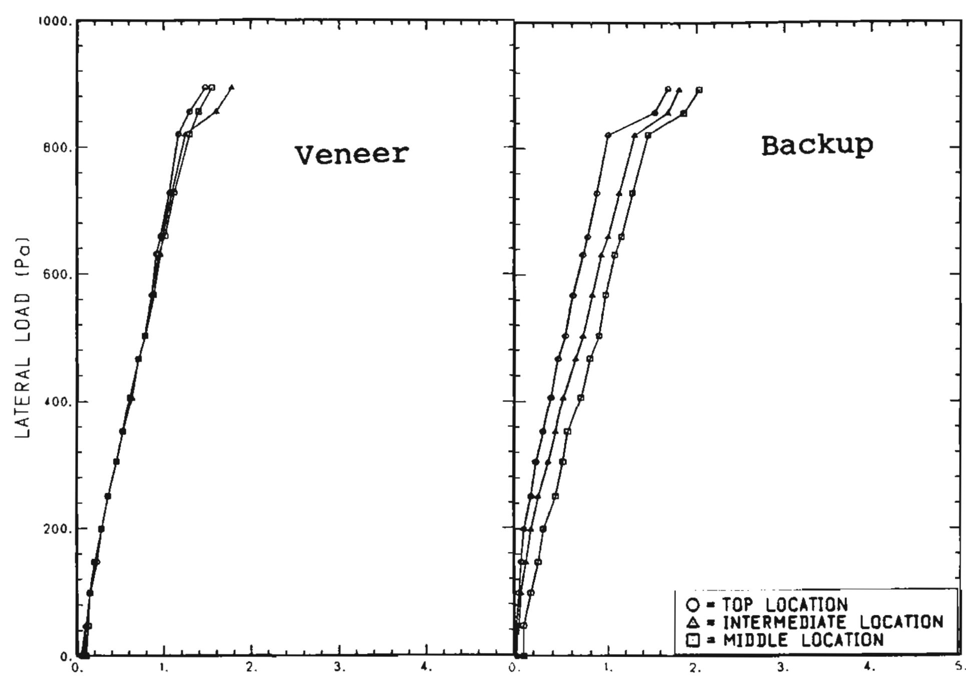


b) Gross Displacement (mm)

FIGURE 5.5 DISPLACEMENTS DURING LOADING TO INITIAL CRACK STAGE FOR WALL3



a) Flexural Veneer Displacement (mm)



b) Gross Displacement (mm)

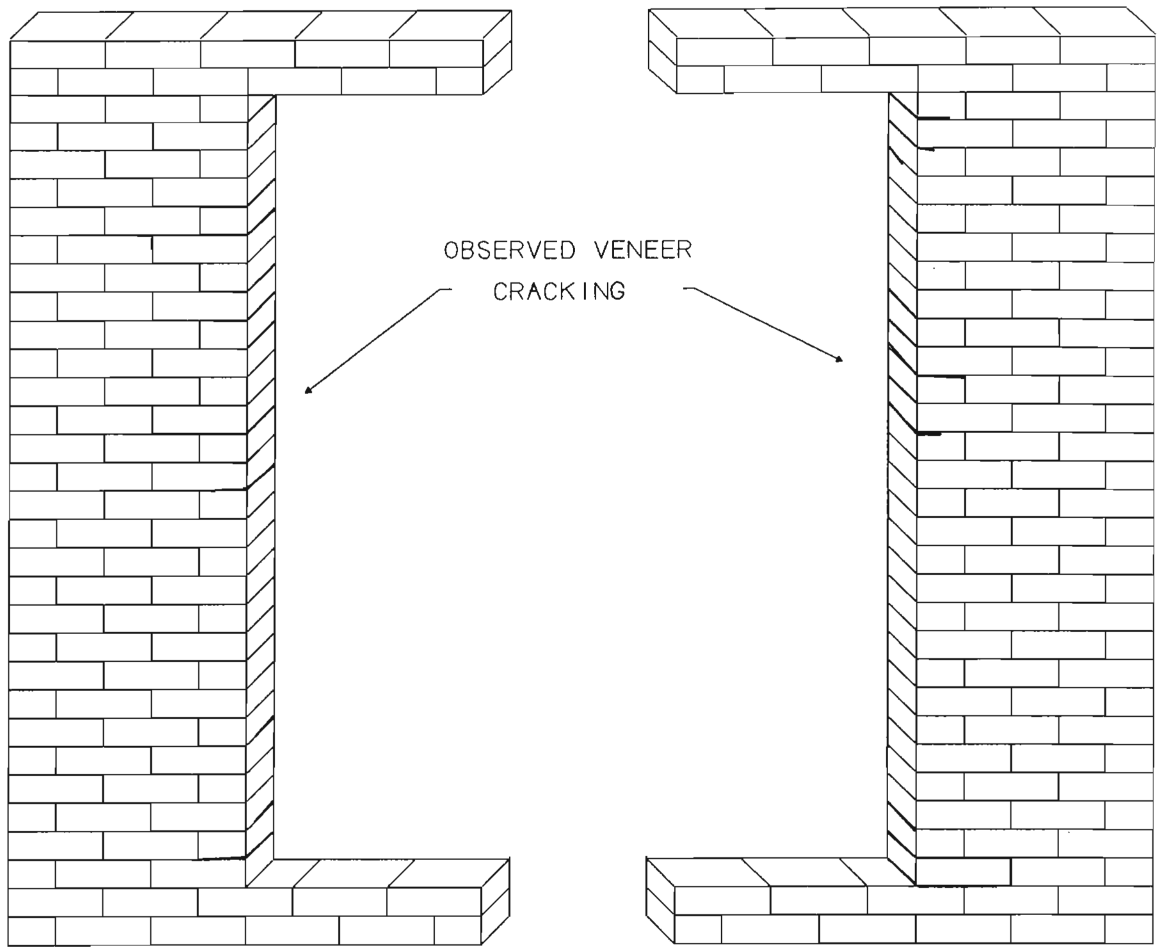
FIGURE 5.6 DISPLACEMENTS DURING LOADING TO INITIAL CRACK STAGE FOR WALL4

The top of the backup panel displaced nearly the same amount as the top of the veneer panel. This difference in behaviour can be attributed to the increased number of wall ties at the top of the backup panel as a result of the window opening.

The window was directly exposed to the applied air pressure and the load was transferred from the window to the SS backup. Because of concern for the possibility of sudden failure of the window glass or plastic framing components, the air pressure was not increased to the target load level of 2 kPa. It was also thought that consistency in degree of cracking should be preserved amongst all specimens and cracking around the window opening in WALL4 was expected at lower load levels than for previous specimens. Due to the different loading and displacement conditions for WALL4, the displacement plots in Figure 5.6 are presented using larger scales than in previous figures.

Although the flexural displacement of the veneer panel shown in Figure 5.6(a) does not clearly indicate the cracking load, as shown in Figure 5.6(b) the backup panel did have a significantly increased rate of gross displacement at around a load of 0.8 kPa. It was thought that diagonal cracking at the corners of the opening or horizontal cracking initiating at the vertical edges of the opening might occur and not be immediately detectable at the quarter panel point. The gross veneer displacements in Figure 5.6(b) show a sudden increase at the intermediate height location consistent with the response of the backup wall.

After the test, the veneer was examined for signs of distress or cracking. The large opening and recessed window frame left the ends of brick units exposed around the window. The areas where cracks were observed in the form of debonding along bedjoints are indicated in Figure 5.7. At several crack locations, the brick itself appeared to have suffered some edge spalling. This chipping or slight spalling along the bricks edges is also illustrated in Figure 5.7.



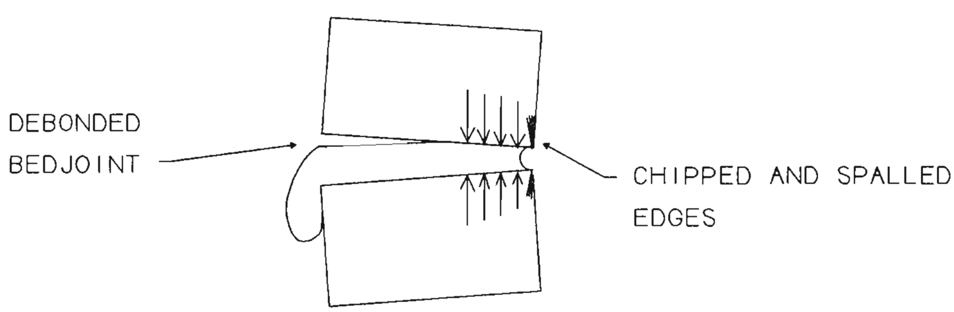


FIGURE 5.7 VISIBLE SIGNS OF CRACKING AROUND WINDOW IN WALL4

The air barrier, consisting of the exterior gypsum board covered with a bituminous membrane, transferred the pressure to the studs without failure or signs of distress. The interior gypsum board was not installed and this allowed the exterior air barrier to be visually monitored during the structural tests.

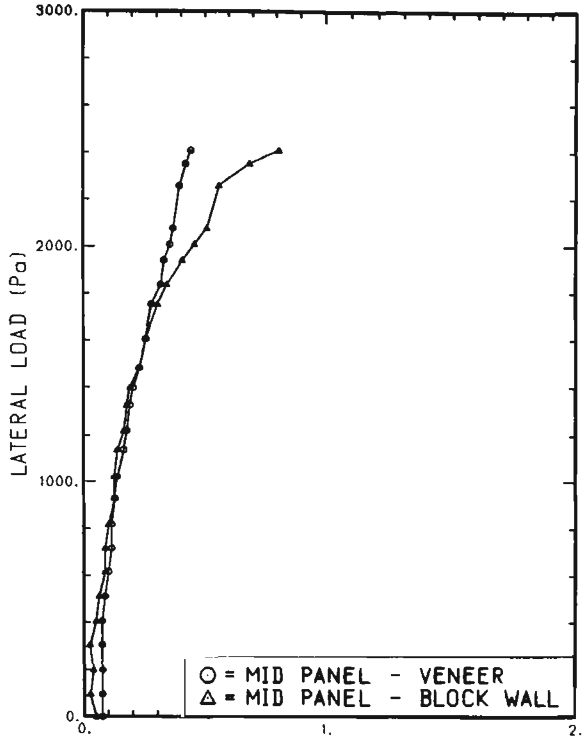
5.3.3.5 WALL5

Figure 5.8 contains the recorded gross displacements and calculated flexural displacement of the veneer during the cracking load stage No. 7. WALL5 consisted of a CB backup and, as expected, was considerable stiffer and underwent much smaller displacements than the other specimens. The displacement plots indicate that an initial softening resulted from a poor support condition at the top of the block wall. The panel was supported at the top with typical clip angles but uniform bearing was not established until some slack had been taken up. As indicated in Figure 5.8(b), after approximately 1 mm of movement, the support became effective and restrained further movement.

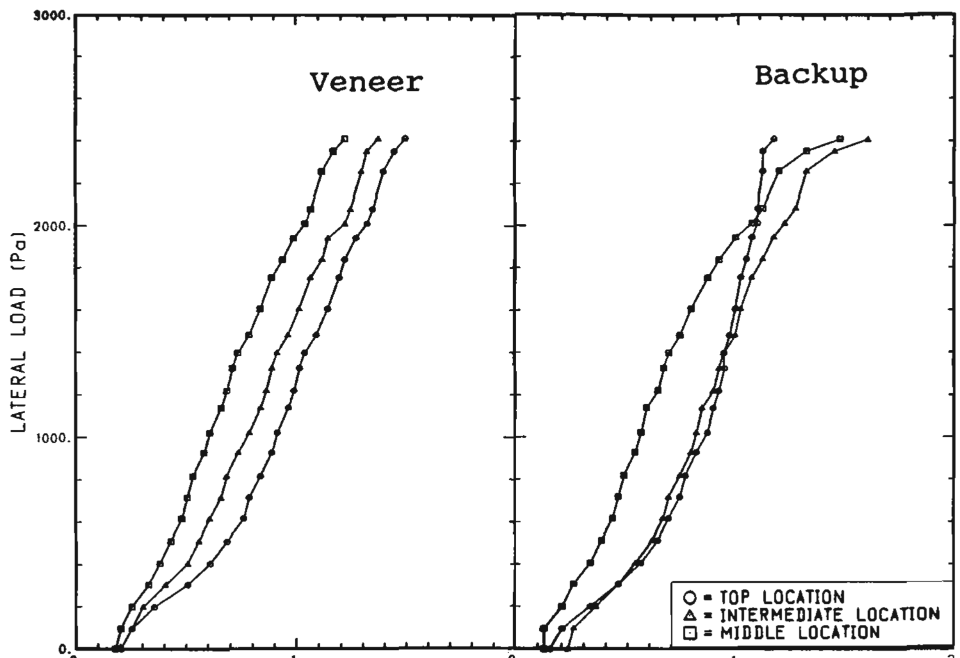
Unlike other test specimens, both the veneer and backup wall had to be monitored for potential cracking. The flexural displacements of the veneer and backup presented in Figure 5.8(a) show that the concrete backup wall cracked first at a pressure level of approximately 1.8 kPa.

5.3.4 Influence of Cracking on Response of the Veneer

It has been recommended[35] that the design procedure for BV wall system should contain limits on backup wall deflections to either prevent or control veneer cracking. For design of steel stud backup walls where cracking is to be limited to an acceptable level, the behaviour of the wall system with a cracked veneer must be considered.



a) Flexural Veneer/Backup Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.8 DISPLACEMENTS DURING LOADING TO INITIAL CRACK STAGE FOR WALL5

Of particular interest were the changes in the distribution of compressive or tensile tie loads and the overall out-of-plane displacements of the wall system as a result of cracking of the veneer. The tests were conducted in a manner identical to the tests on the uncracked veneer, and the results were normalized in a similar manner to a common load of 500 Pa from an actual pressures close to this value.

The displacements correspond to the following load stages for each BV/SS wall specimen where the information at the uncracked stage is repeated for comparison purposes.

				UNCRACKED	CRACKED
WALL1:	Cavity Pressurized	–	Load	No. 4	No. 7
	Cavity Depressurized	–	Load	No. 3	No. 6
WALL2:	Cavity Pressurized	–	Load	No. 6	No. 9
	Cavity Depressurized	–	Load	No. 7	No. 8
WALL3:	Cavity Pressurized	–	Load	No. 6	No. 8
	Cavity Depressurized	–	Load	No. 2	No. 11
WALL4:	Cavity Pressurized	–	Load	No. 2	No. 3
	Cavity Depressurized	–	Load	No. 1	No. 4

For each wall, displacement plots are provided for both the cavity pressurized and the depressurized conditions and, as before,the solid and dashed lines indicate backup and veneer displacement, respectively. Also round and square point identifers are used to distinguish between the uncracked and crackedstages, respectively.

When comparing different test results for the same specimen, the influence of previous load stages must be considered. Fortunately, as will be shown later, results of cyclic load tests indicate that at low loads there is little influence of repeated loading on the response of cracked wall panels.

5.3.4.1 WALL1

For both the pressurized and depressurized cases, the general distributions of compression and tension tie loads, as indicated by the relative displacement between the veneer and backup, were not influenced by the formation of the initial crack. However, overall displacements did increase significantly as shown in Figure 5.9(a).

Also, although the displacement at the top of the veneer increased after cracking, the veneer panel still exhibited considerable bending. This behaviour was attributed to the unintentional top support of the veneer created by the "soft" movement joint.

5.3.4.2 WALL2

The general distributions of tie loads, indicated by the relative displacement of the veneer and backup shown in Figure 5.9(b), were not influenced by development of the crack in the veneer. For WALL2, the displacements for the backup increased marginally for the cavity pressurized condition whereas significantly larger veneer displacements were recorded for the depressurized case.

It should be noted that for WALL2 the top joint was considerably softer than for WALL1. This was believed to partially contributed to the increased displacement at the top of the veneer after cracking. The top of the veneer panel was displaced approximately twice as much in WALL2 as in WALL1.

5.3.4.3 WALL3

No influence of cracking was observed aside from increased overall displacements. As was the case for WALL2, the increased displacements were most noticeable in the veneer for the cavity depressurized case and in the backup wall for the cavity pressurized case, as shown in Figure 5.9(c).

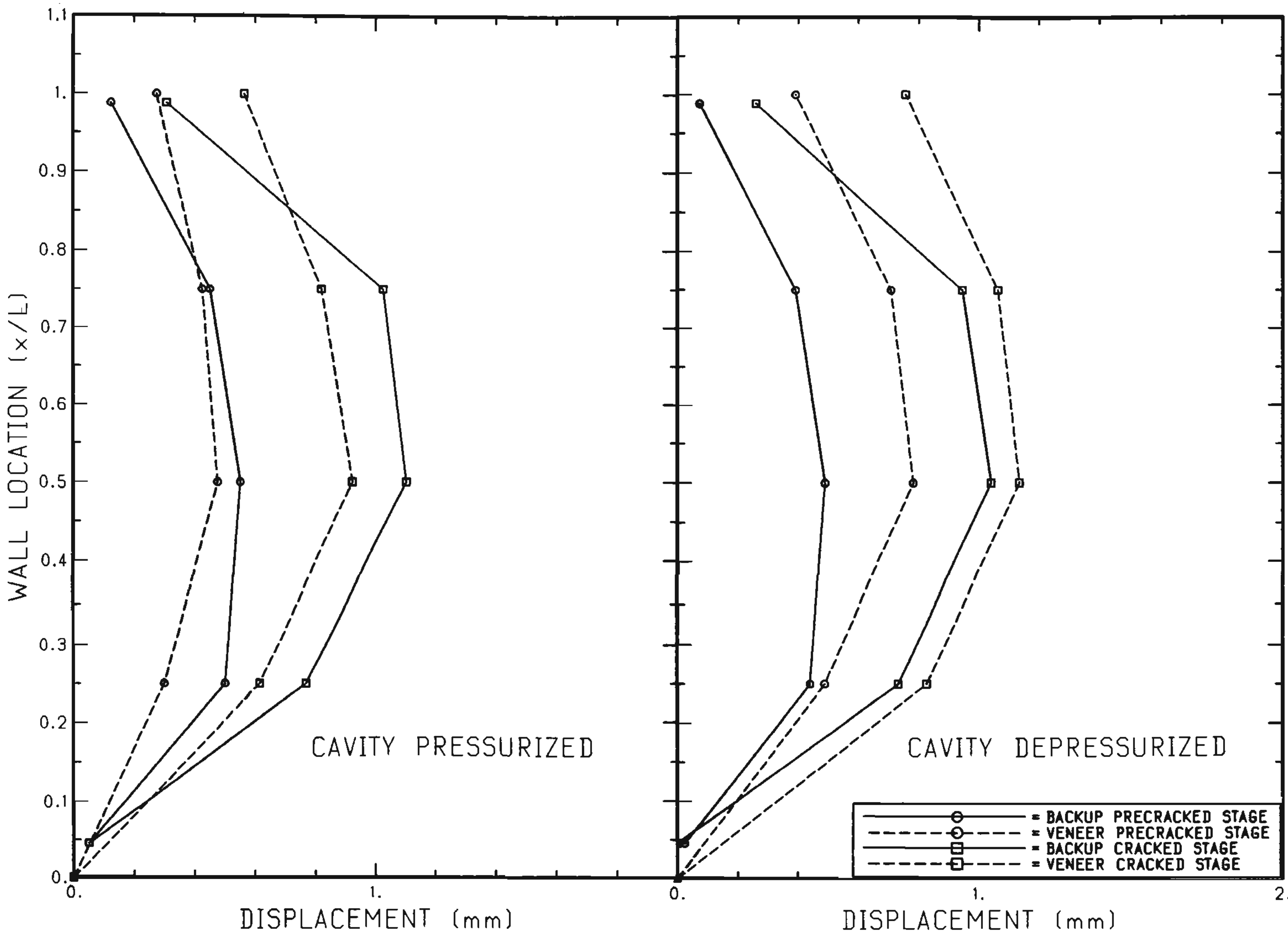


FIGURE 5.9 (a) DISPLACEMENTS FOR WALL1 BEFORE AND AFTER CRACKING OF THE BRICK VENEER

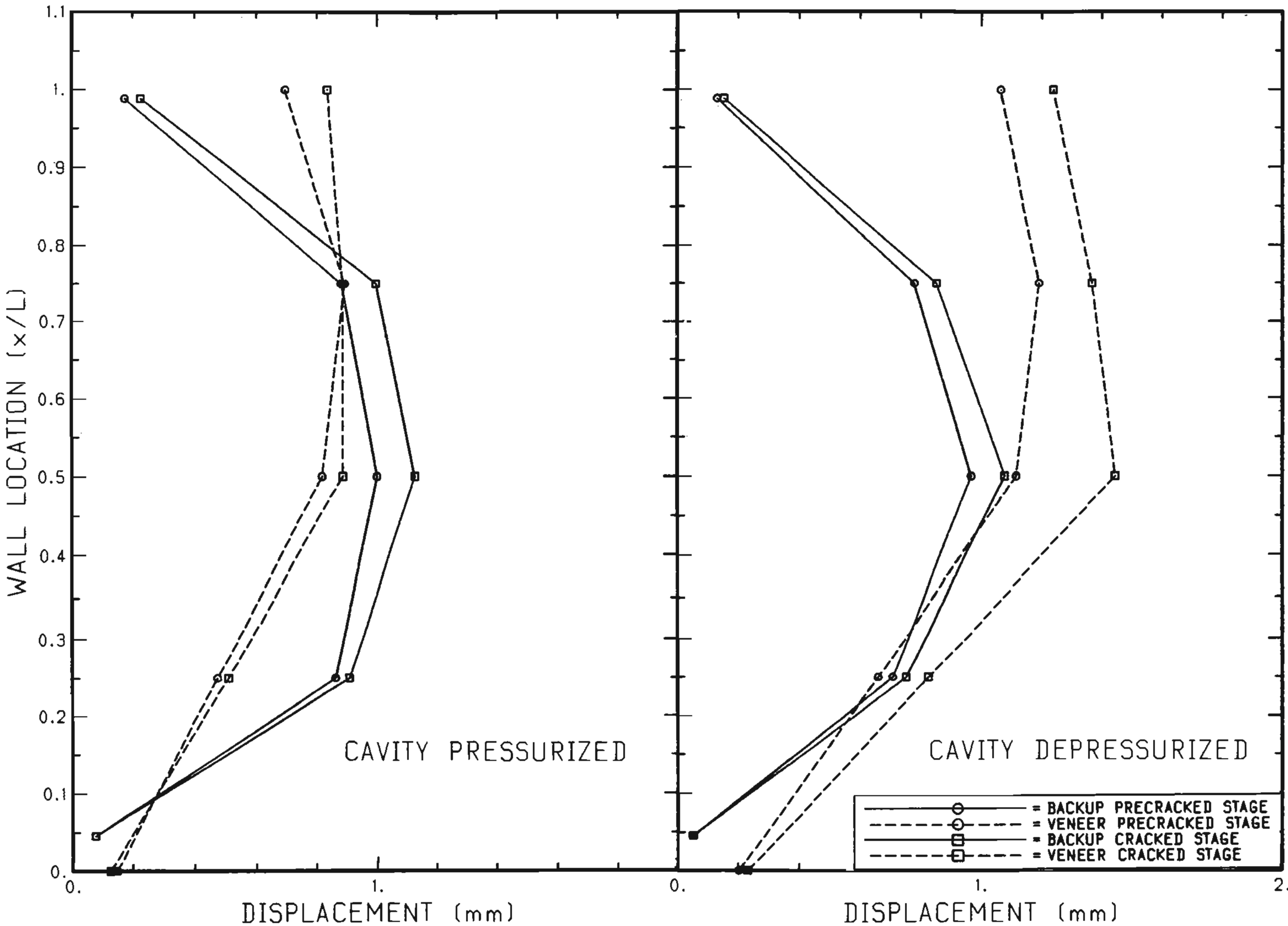


FIGURE 5.9 (b) DISPLACEMENTS FOR WALL2 BEFORE AND AFTER CRACKING OF THE BRICK VENEER

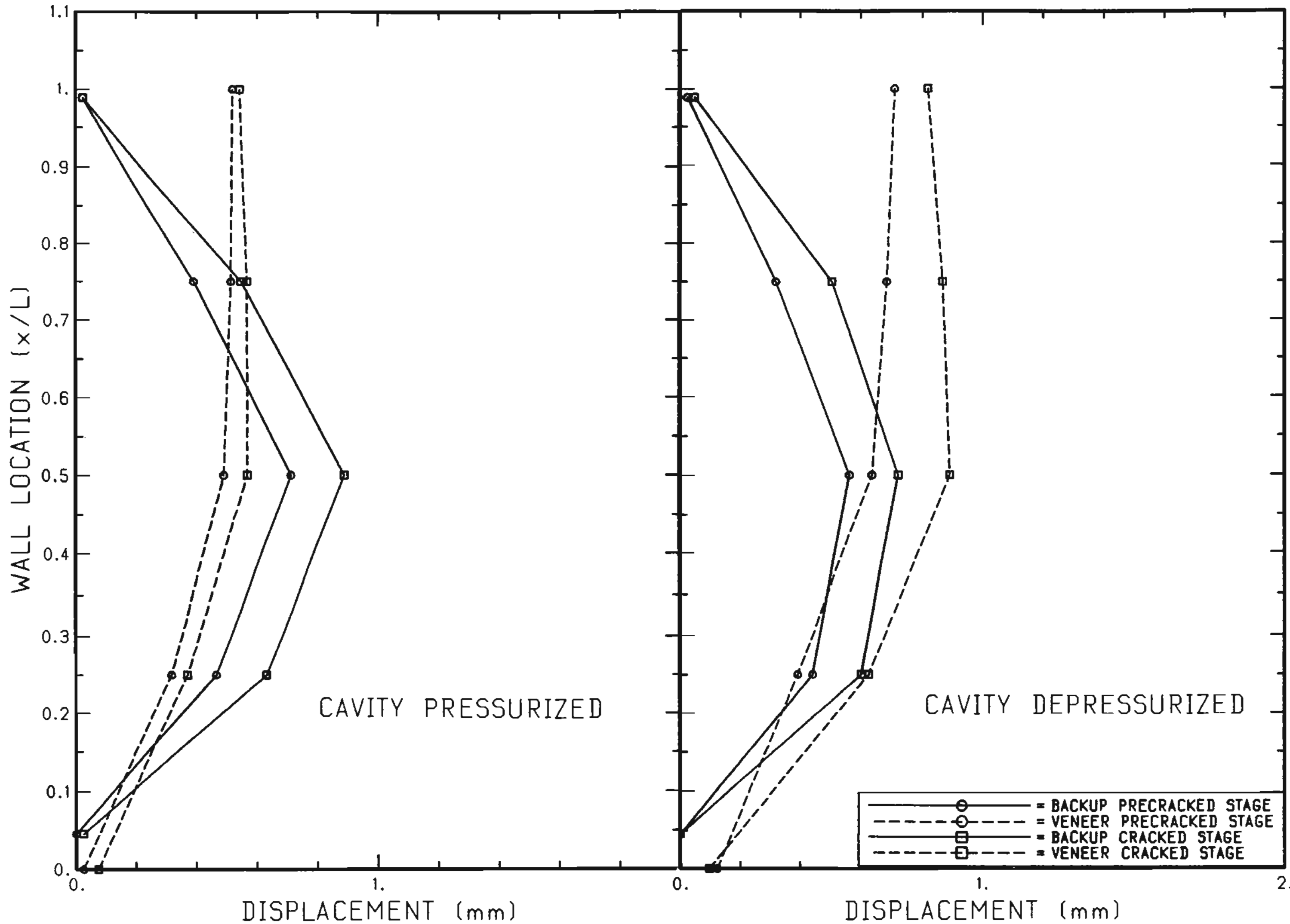


FIGURE 5.9 (c) DISPLACEMENTS FOR WALL3 BEFORE AND AFTER CRACKING OF THE BRICK VENEER

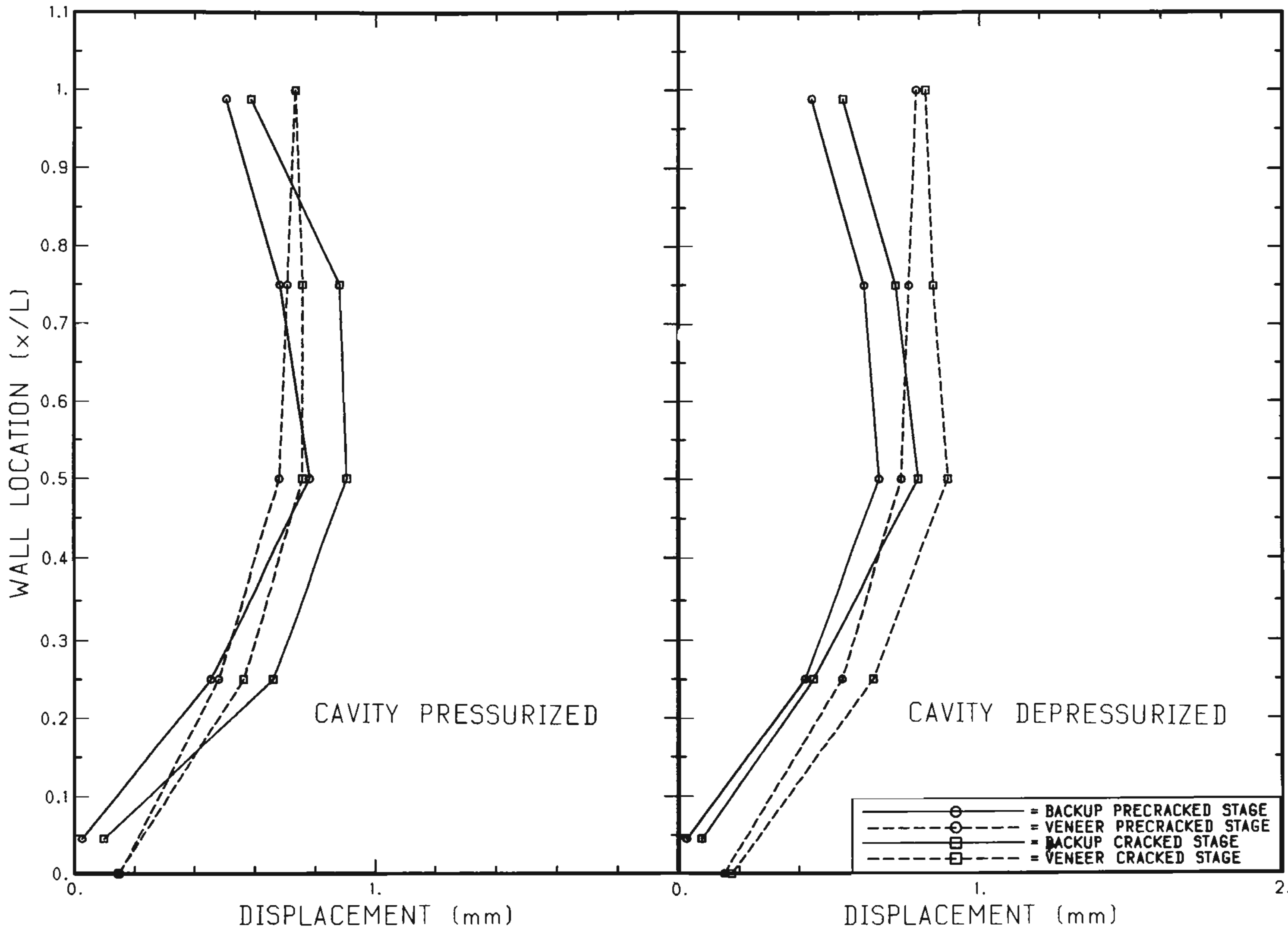


FIGURE 5.9 (d) DISPLACEMENTS FOR WALL4 BEFORE AND AFTER CRACKING OF THE BRICK VENEER

5.3.4.4 WALL4

The influence of cracking on the quarter panel displacement for WALL4 was not expected to be significant since the degree of cracking in that area of the wall was minimal. However, consistent with other results, overall displacements were observed to increased. In addition, the distribution of tensile tie forces for the cavity pressurized case were affected. Where compressive forces existed near the bottom and top of the wall before cracking, as shown in Figure 5.9(d), tensile forces were indicated after cracking.

5.3.4.5 WALL5

The main difference between the BV/SS and BV/CB investigations was that the CB backup panel, not the veneer, cracked first. The displacement profiles for WALL5 are shown in Figure 5.10. However the relatively small displacements must be considered when interpreting the graphs. As a result, it is difficult to draw any conclusions about tie load distributions. Generally greater displacements were experienced after cracking and again the impact was greatest in the veneer for depressurized conditions and in the backup for pressurized conditions.

5.3.5 Determination of Ultimate Strength

For the determination of ultimate strength, the tests were conducted with the cavity depressurized. To ensure air tightness after excessive cracking, a plastic sheet was draped over the veneer. Displacement readings were recorded until it was judged that unstable conditions were imminent. Presentation of the test results includes load-displacement data, failure loads, crack patterns, wall tie performances and steel stud failures.

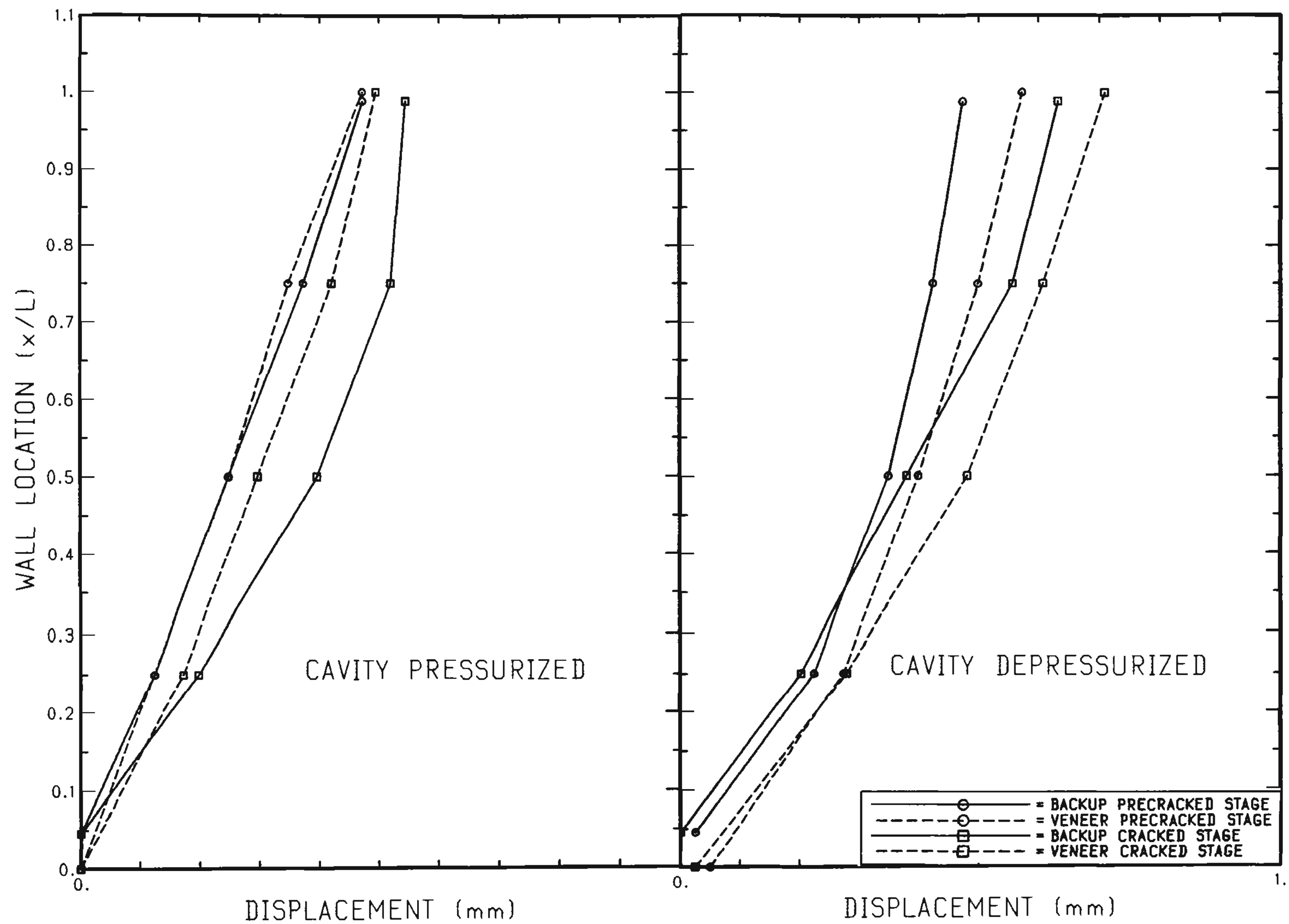
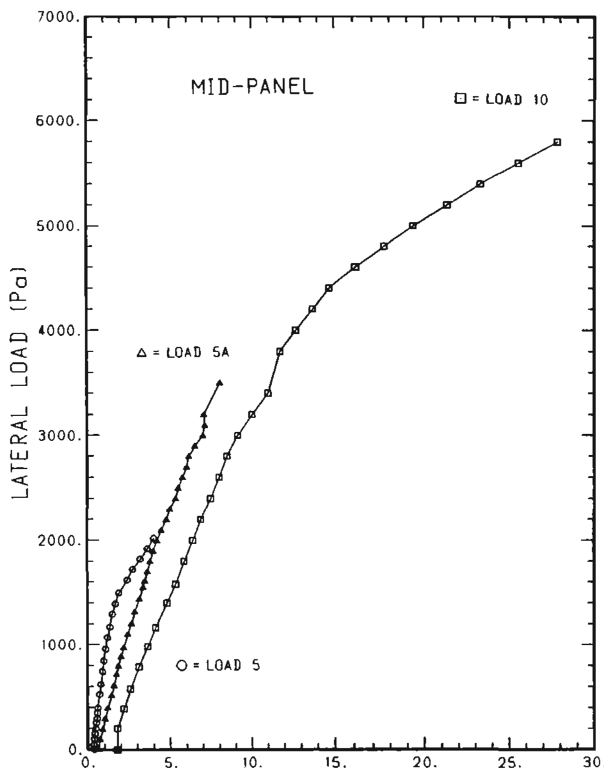
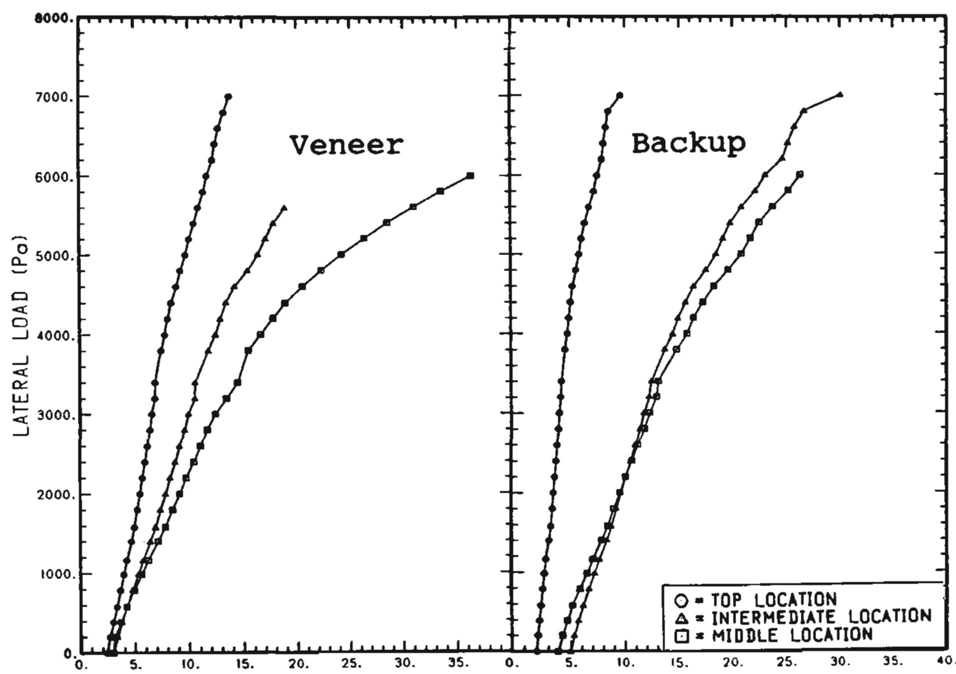


FIGURE 5.10 DISPLACEMENTS FOR WALL5 BEFORE AND AFTER CRACKING OF THE BLOCK BACKUP WALL



a) Flexural Veneer Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.11 DISPLACEMENTS DURING ULTIMATE TEST STAGE FOR WALL1 (LOAD No. 10)

5.3.5.1 WALL1

The final loading for WALL1 corresponds to Load No. 10. The results showing flexural displacement of the veneer and the gross displacements of the wall system are shown in Figure 5.11. The tests followed initial cracking in Load No. 5, extended loading to fully develop the crack in Load 5A and included additional testing at 0.5 kPa air pressure. It is interesting to note that the slope of the load-displacement plot for Load No. 10 was very similar to Load No. 5A. This indicates that the stiffness did not decrease until a second crack formed.

1) Secondary Cracking and Failure Load

The flexural displacements shown in Figure 5.11(a) were linear up to approximately 3.8 kPa at which point a second horizontal crack developed above the first. The gross backup wall displacements shown in Figure 5.11(b) also reveals marked change in response at 3.8 kPa. The failure load, recorded as 7.2 kPa, represented extreme wall displacement, formation of a collapse mechanism in the veneer and sudden flexural failure in the steel studs.

2) Cracking Pattern at Failure

The final horizontal crack pattern marked on the veneer after failure is shown in the photograph in Figure 5.12. This crack pattern correlates very closely with that predictable for the top and bottom support conditions of WALL1. The initial horizontal crack appeared near mid height with additional horizontal cracks forming above and below this crack at higher loads.

3) Performance of Wall Ties

Because the final test load stage was conducted with the cavity depressurized, this allowed openings to be made in the gypsum board to inspect wall ties at several locations along

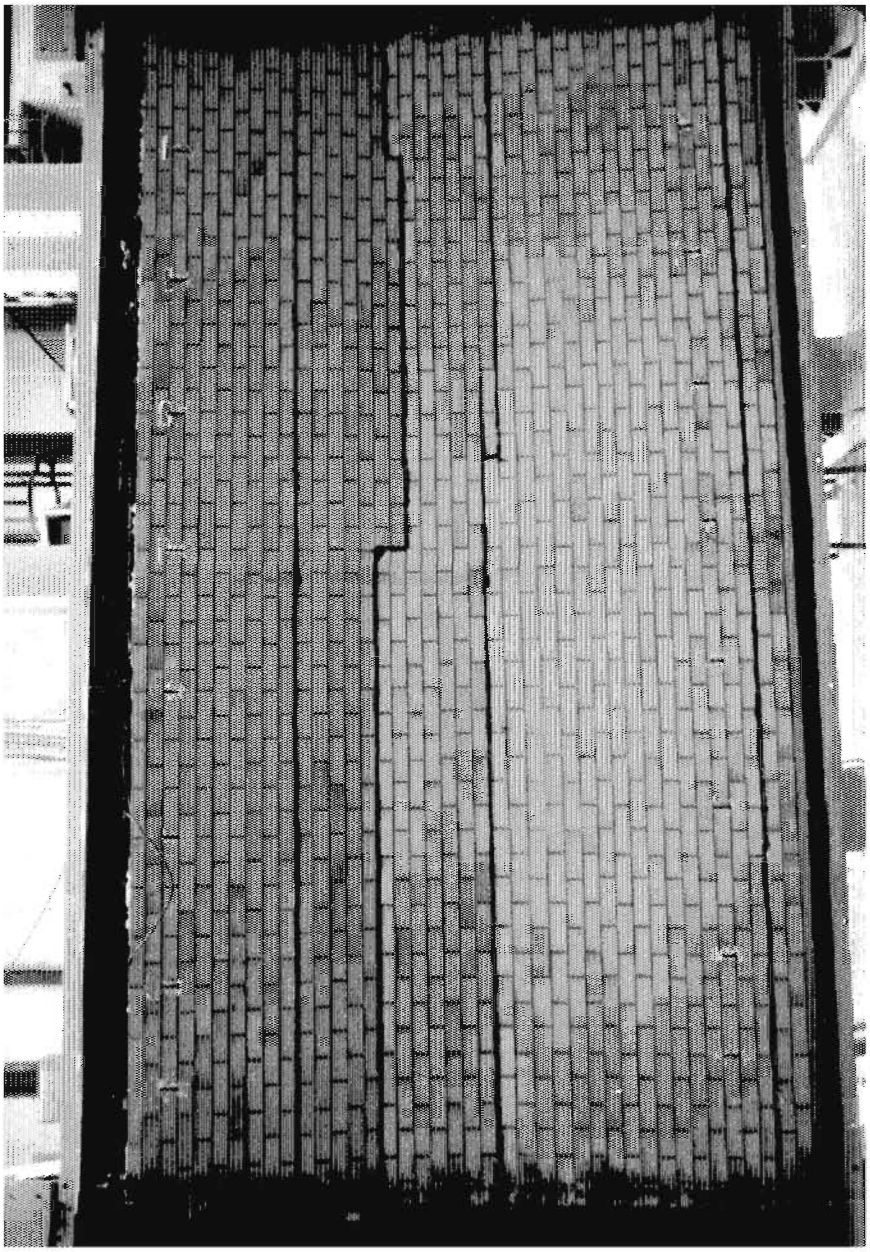


FIGURE 5.12 CRACK PATTERN AT FAILURE – WALL1

the height of the wall. No wall ties failed during any part of the test. Figure 5.13 is a photograph of a wall tie at the failure location of the steel stud adjacent to the first horizontal crack which corresponds to the position of a large localized load on the stud. From the figure, it can be observed that although the tie support stand suffered considerable damage, the wire portion of the tie was apparently undamaged.

4) Failure of Steel Stud Members

As a result of the large tie loads near the mid height of the wall, the backup panel failed in flexure with localized flange damage. The uniform failures of three studs near one end of the wall are shown in the photograph in Figure 5.14, taken after the interior gypsum board had been removed. There was no indication of twisting in the studs and the bridging performed satisfactory.

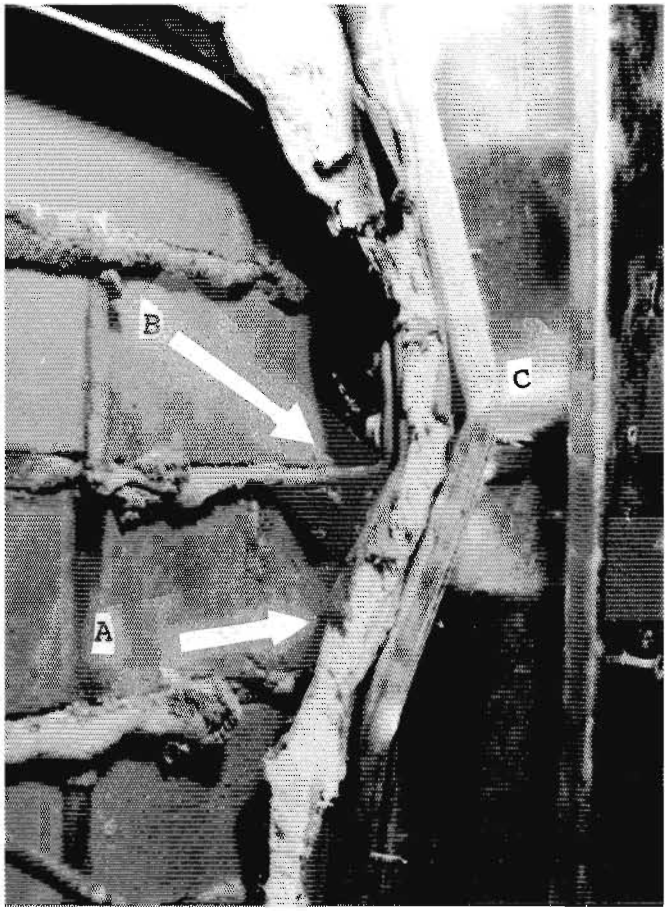
5.3.5.2 WALL2

WALL2 was loaded to failure at Load No. 15. The flexural displacements of the veneer and the gross displacements of the wall system are shown in Figure 5.15. This test followed initial cracking in Load No. 7 and additional tests at air pressures below 1.5 kPa.

1) Secondary Cracking and Failure Load

Similar to WALL1, linear load-displacement responses were recorded for reloading after initial cracking. Also shown in Figure 5.15(a), the linear flexural response continued up to a level of approximately 4.0 kPa. During the test, an initial horizontal crack became visible near mid height and appeared to extend the length of the specimen.

After the air pressure exceeded approximately 4.0 kPa, secondary diagonal cracks developed at the lower corners and extended to the centre of the horizontal crack. Also vertical



A - Tie Support

B - Wire Tie

C - Flexural Stud Failure

FIGURE 5.13 CONDITION OF WALL TIE AFTER FAILURE – WALL1

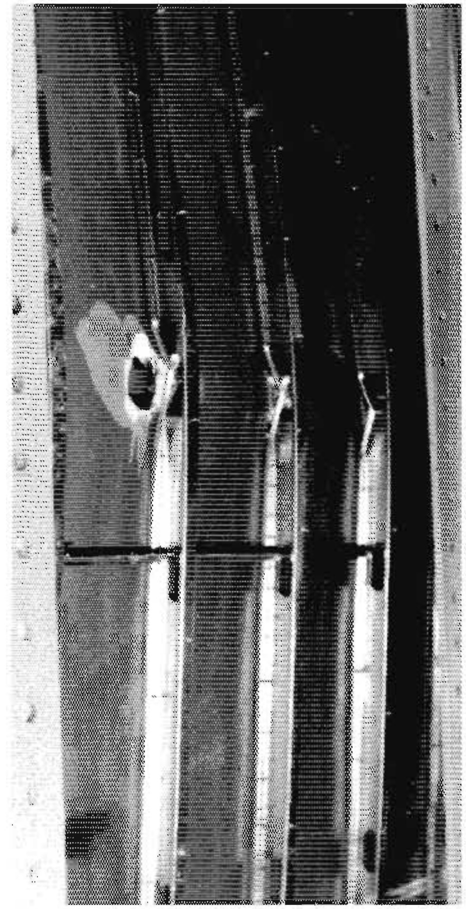
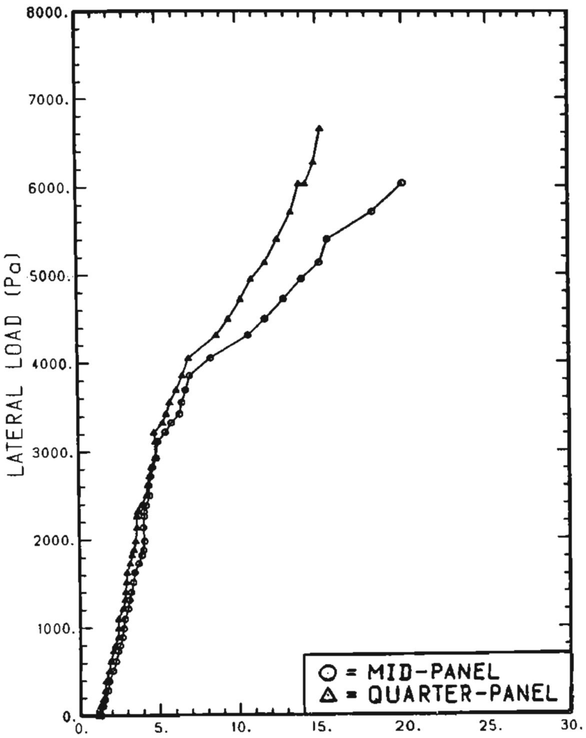
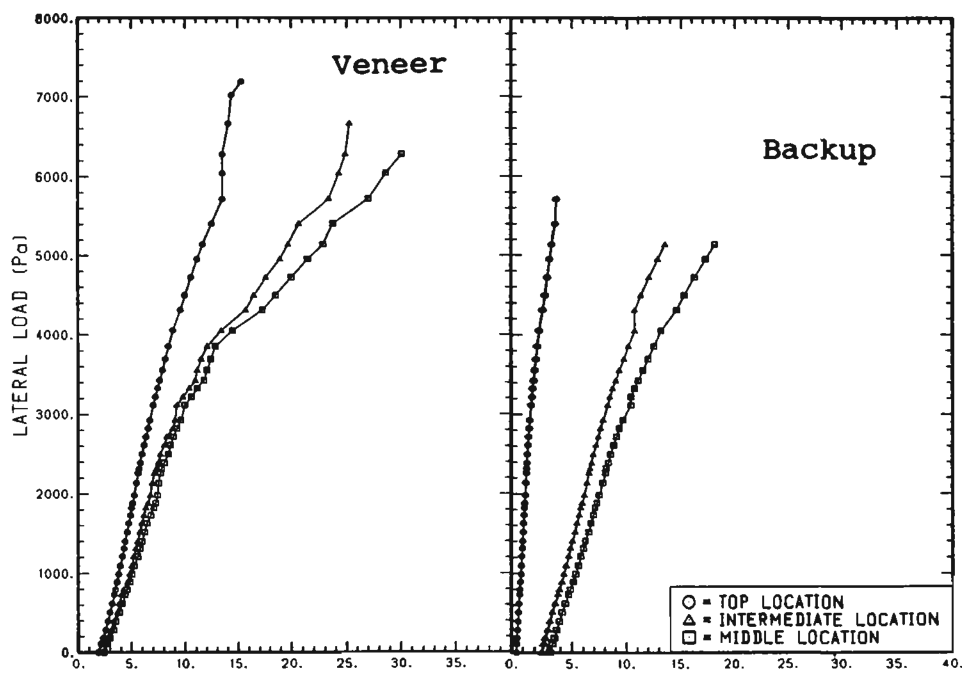


FIGURE 5.14 STEEL STUD FLEXURAL FAILURE – WALL1



a) Flexural Veneer Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.15 DISPLACEMENTS DURING ULTIMATE TEST STAGE FOR WALL2 (LOAD No. 14)

cracks developed at the centre of the isolated panel above the initial horizontal crack. This crack pattern is shown in the photograph in Figure 5.16 where the crack location were marked on the veneer after failure. Restricted visibility of the cavity side of the veneer prevented the sequence of crack formation from being established.

The test was terminated and the specimen was judged to have failed a load level of 7.2 kPa. At this stage, a collapse mechanism existed in the veneer and the studs had suddenly failed.

2) Performance of Wall Ties

At the wall ends where the backup was restrained in order to provide two way bending support for the veneer, failured of a wall tie was observed. As shown in the photograph in Figure 5.17, the shear off head portion of the tie was placed on a protruding mortar fin. No other wall tie failures were observed.

3) Failure of Steel Stud Members

Large tie loads at mid height locations resulted in localized flexural failures at these locations. Except for the restrained end members, all of the steel studs failed in a manner identical to the type of damage shown in Figure 5.18, along two elevations near mid height. The photograph was taken after the interior gypsum board had been removed to expose the failed condition of the steel studs.

An additional failure in the backup panel was observed in the nested top track detail for WALL2. The inner long leg track had displaced outward from its original position after the flange of the outer, shallow legged track had failed. The failure location coincided with a discontinuity in the inner track and was localized in that area. The inner track was placed in three segments covering the middle and end portions of the wall's length, while the outer

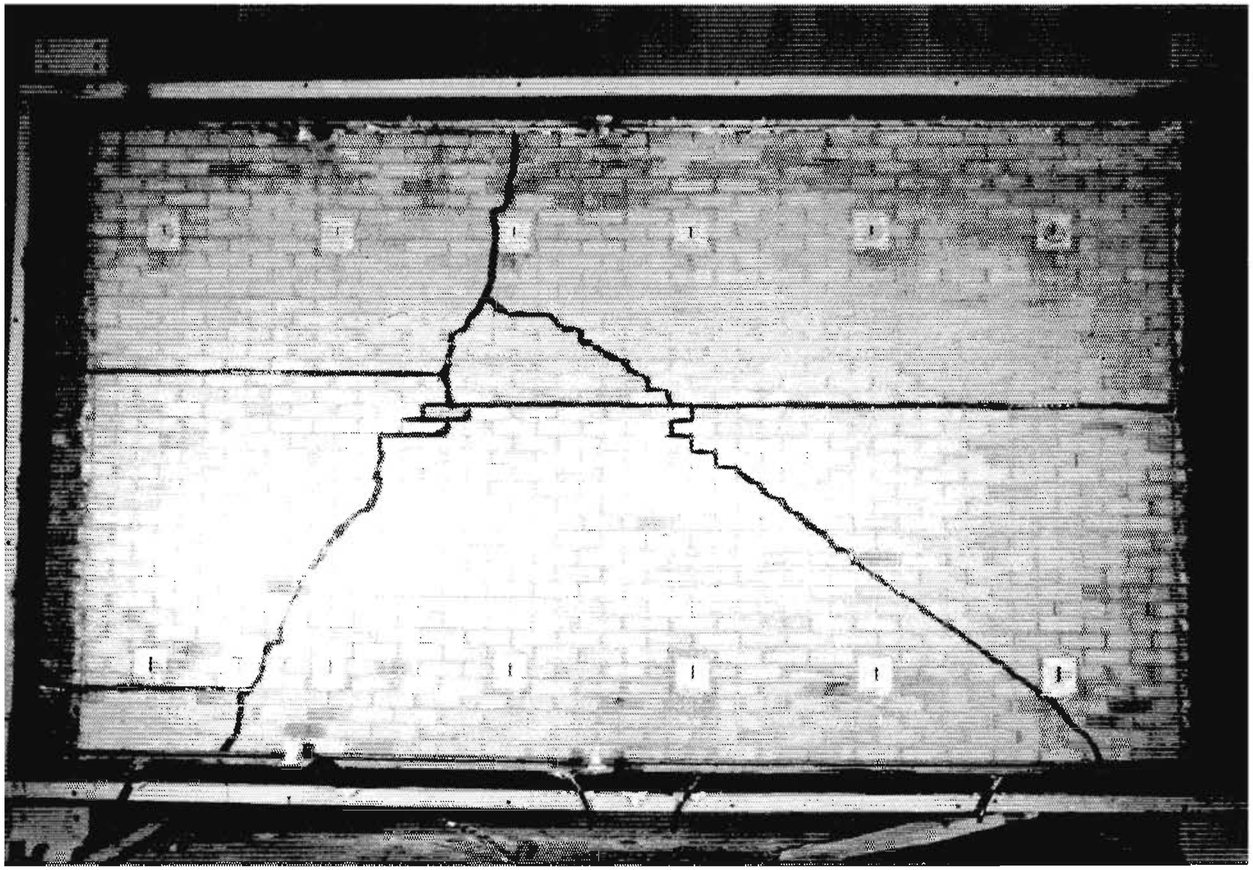


FIGURE 5.16 CRACK PATTERN AT FAILURE – WALL2

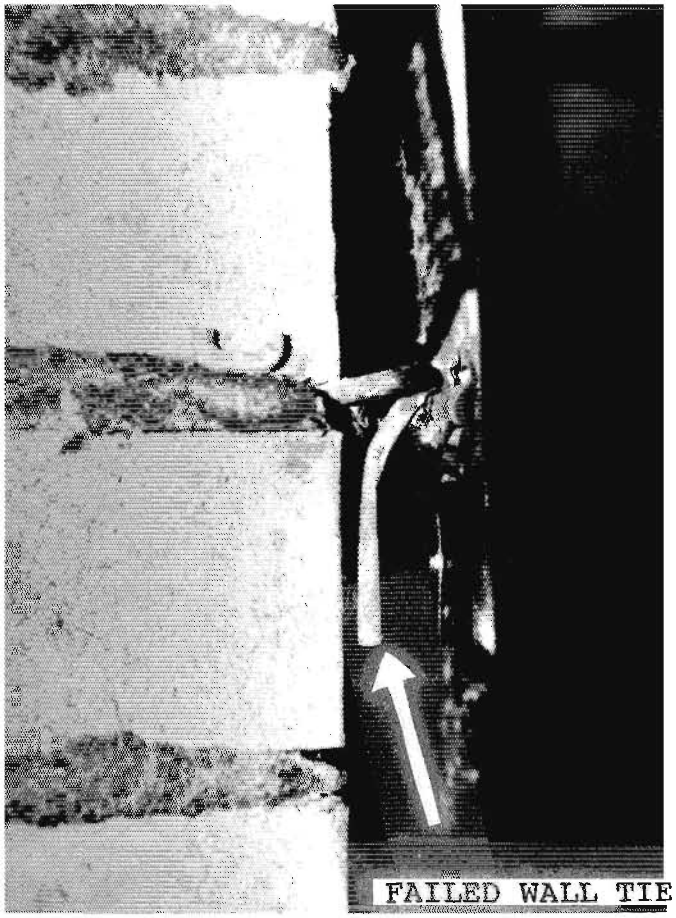


FIGURE 5.17 CONDITION OF WALL TIE AFTER FAILURE – WALL2

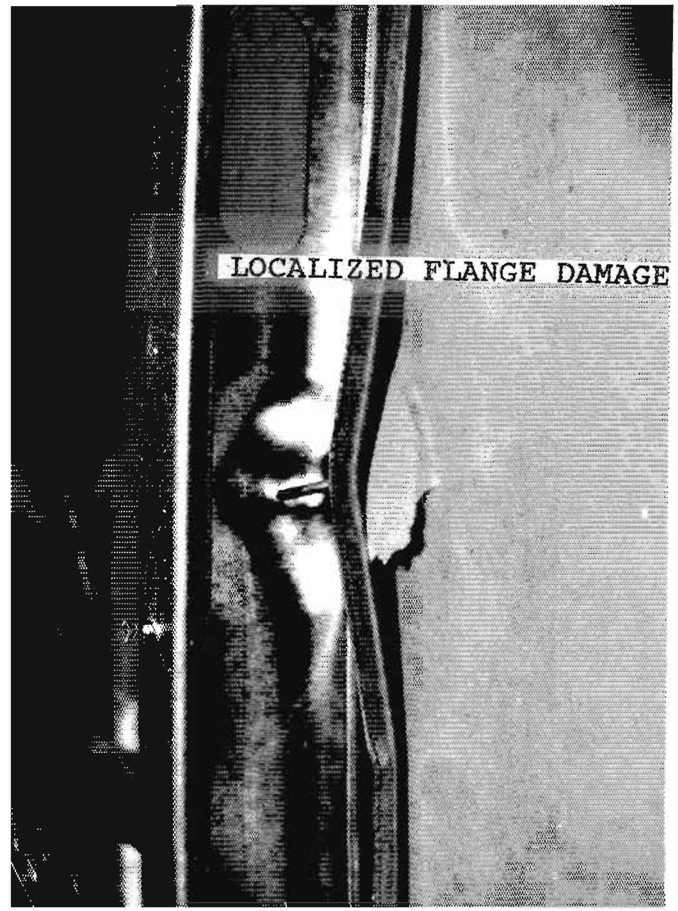


FIGURE 5.18 STEEL STUD FLEXURAL FAILURE – WALL2

shallow track was placed in two segments each covering half the length of the wall. This procedure was followed to stagger the joints in the tracks. The position of the tracks and the failed condition of the nested track assembly are shown in Figure 5.19.

5.3.5.3 WALL3

WALL3 was loaded to failure during Load No. 14. The flexural displacements of the veneer and the gross displacements of the wall system are shown in Figure 5.20. The test followed development of the initial crack in Load No. 7, cyclic tests at loads up to 1.5 kPa and additional testing at loads not greater than 0.5 kPa.

1) Secondary Cracking and Failure Load

As experienced in the other tests, for reloading following development of the initial crack, which was observed to extend across the middle portion the veneer panel, a fairly linear load-displacement response was recorded as shown in Figure 5.20(a).

Secondary cracking, in the form of diagonal cracks extending from the corners of the wall panel to the centre, developed as the air pressure was increased above approximately 4.6 kPa. Failure for WALL3 was defined after a collapse mechanism existed in the veneer and the steel studs had suddenly failed in flexure. In Figure 5.20(b), the change in response of the backup wall following development of the secondary cracks at 4.6 kPa is clearly evident. For this test wall, the stiff top support resulted in a dramatically reduced top displacement of the backup wall.

The diagonal crack pattern marked on the wall after failure is shown in the photograph in Figure 5.21. This pattern conforms with known behaviour of plates subject to two-way bending produced by a simple rigid supports on all sides.

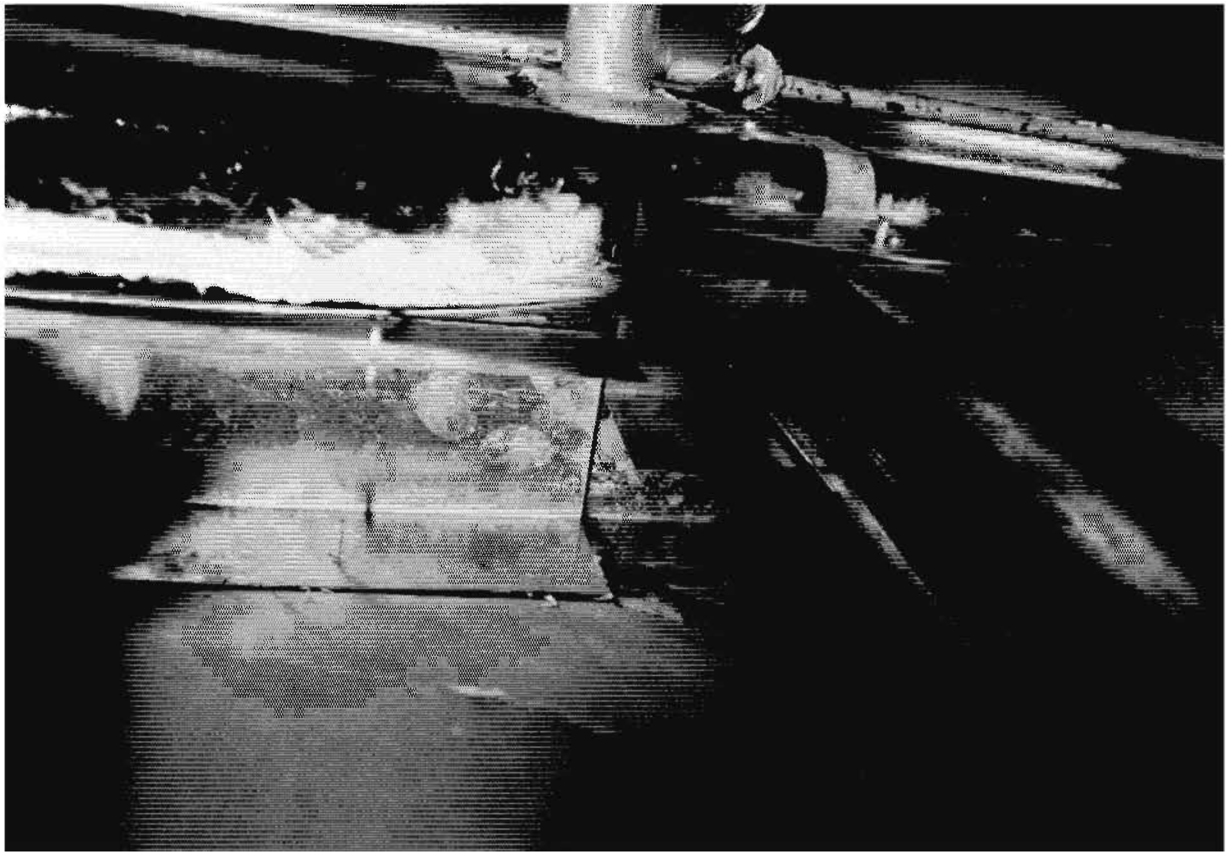
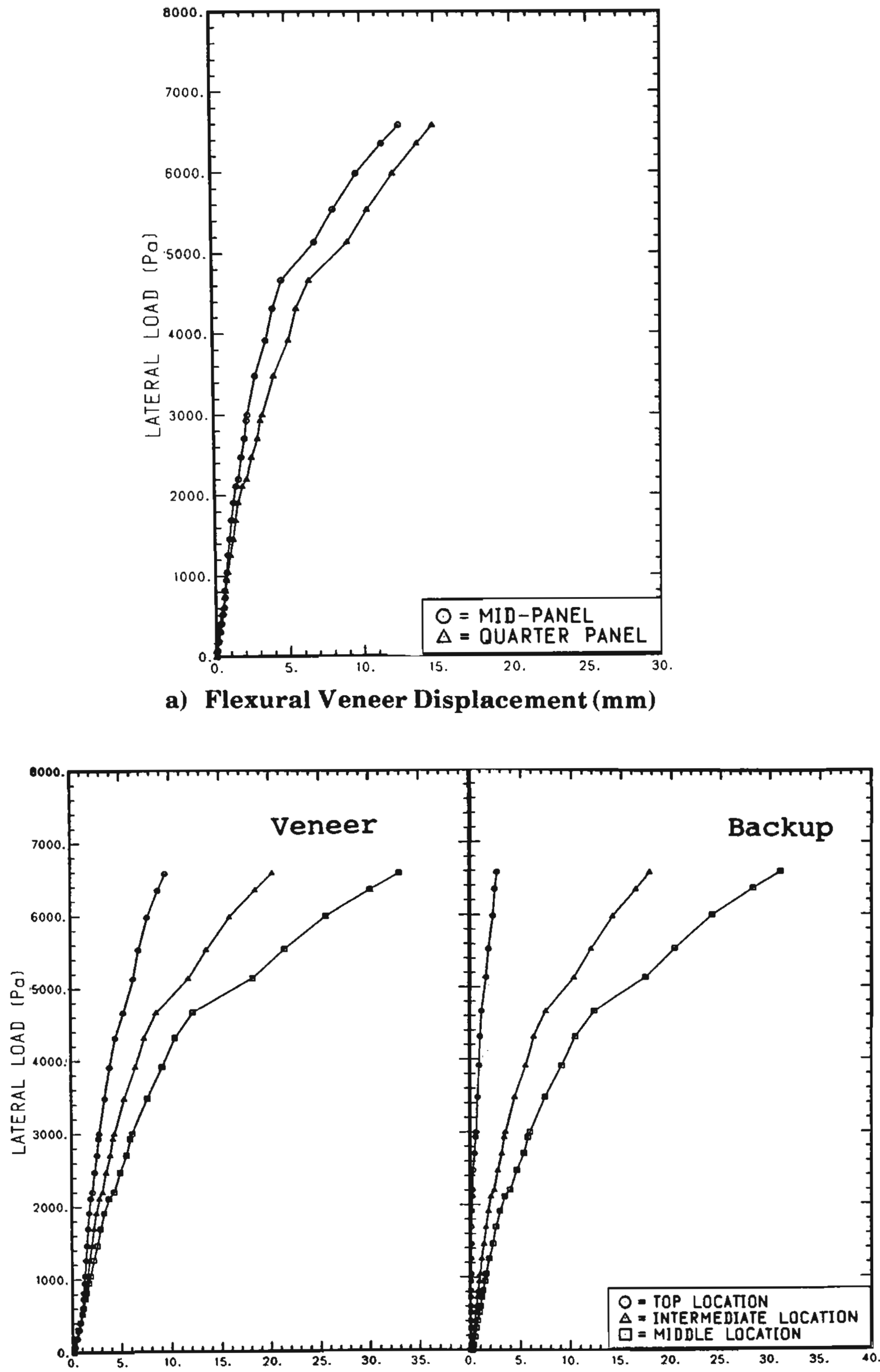


FIGURE 5.19 FAILURE OF NESTED TRACK DETAIL – WALL2



a) **Flexural Veneer Displacement (mm)**

b) **Gross Displacement (mm)**

FIGURE 5.20 DISPLACEMENT DURING ULTIMATE TEST STAGE FOR WALL3 (LOAD No. 14)

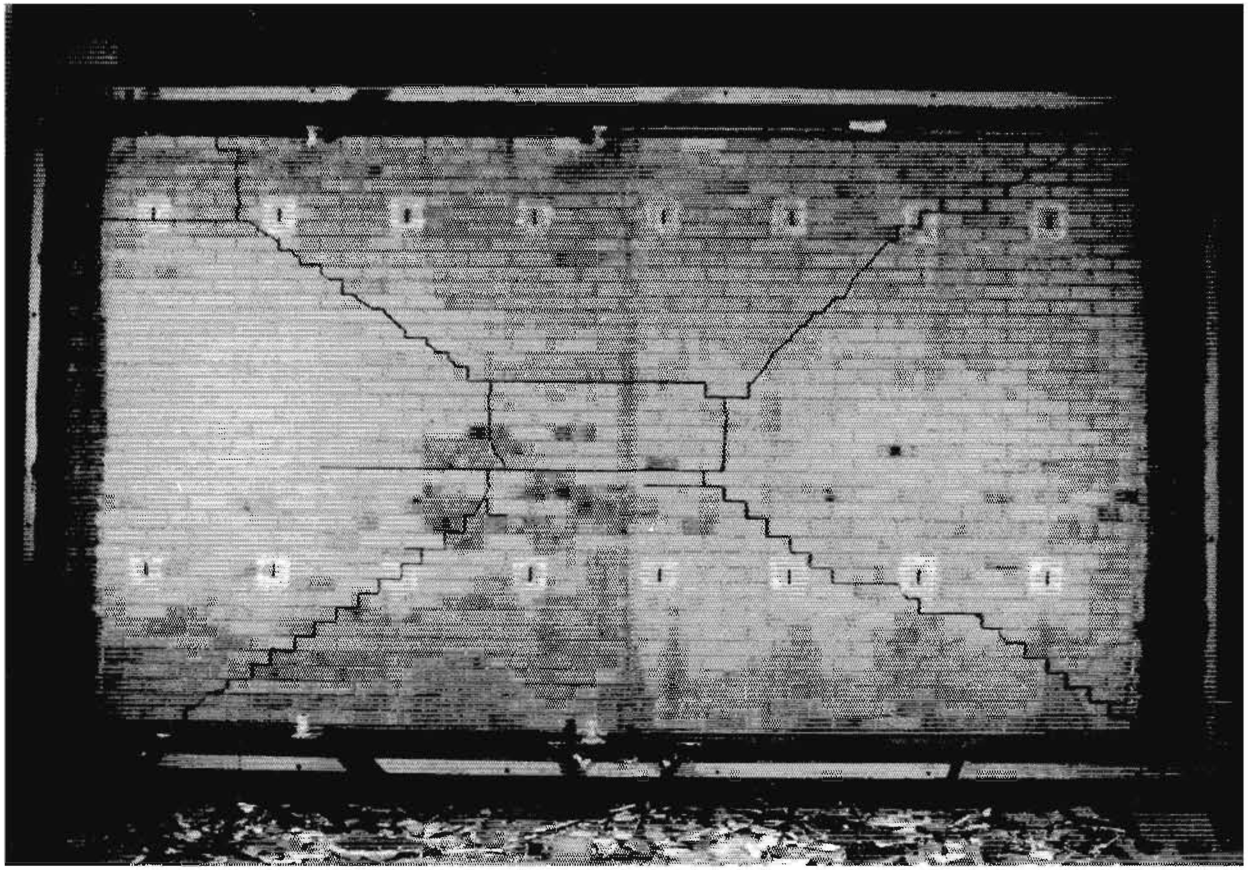


FIGURE 5.21 CRACK PATTERN AT FAILURE – WALL3

2) Performance of Wall Ties

The wall ties for WALL3 were fastened directly to the webs of the steel studs. This feature eliminated localized flange damage and, as shown in Figure 5.22, the condition of the failure zone differed from previous tests.

Inspection near failure of the wall revealed that the wire portions of some top ties had failed. Because the final test was conducted with the cavity depressurized, it was possible to remove some gypsum board sections. Thus it was confirmed that damage to the top ties occurred only at loads in excess of 6.0 kPa.

4) Failure of Steel Stud Members

The steel studs failed in flexure along one elevation in all studs except those immediately next to the restrained end studs. As shown in Figure 5.23, the flexural failures were observed in both back to back studs. It should be noted that all stud failures were observed at mid height at the knock out hole location between two levels of wall ties. This corresponds to the critical location of lowest strength and the highest bending moment.

The large tie loads were not accompanied by localized flange damage as observed in the previous wall tests.

5.3.5.4 WALL4

The flexural displacement of the veneer and the gross displacements of the wall system are shown in Figure 5.24 for the final load stage for WALL4. This Load No. 10 followed development of the initial crack during Load No. 7, cyclic test up to 0.8 kPa and additional test at 0.5 kPa air pressure.

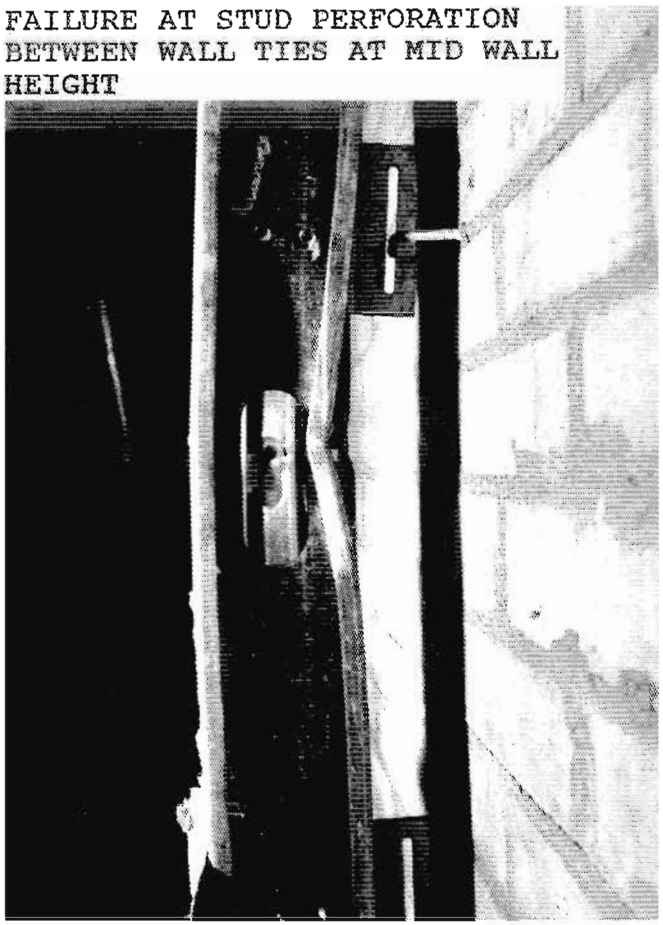


FIGURE 5.22 CONDITION OF WALL TIE AFTER FAILURE – WALL3

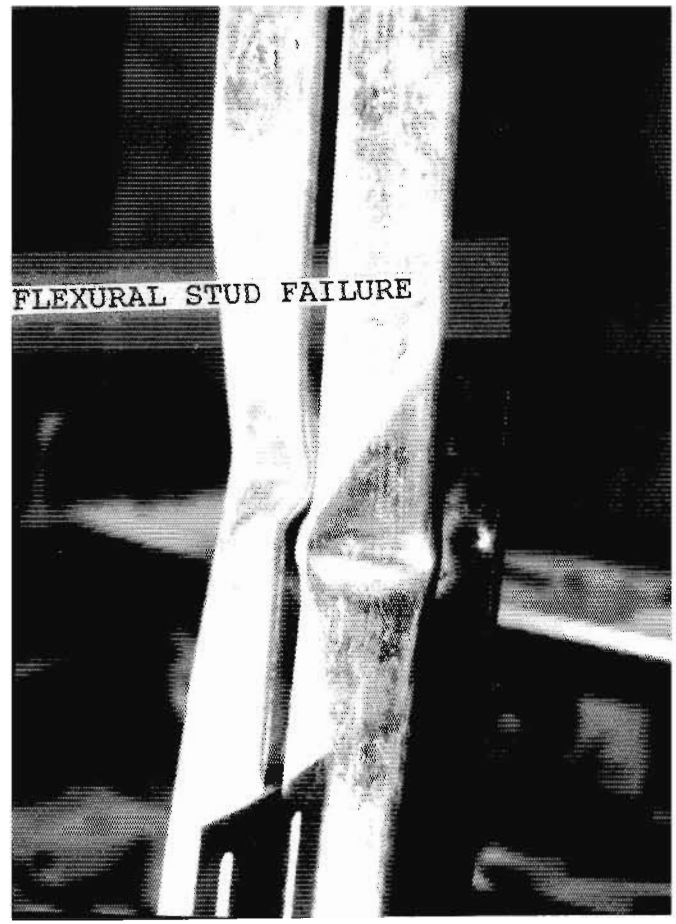
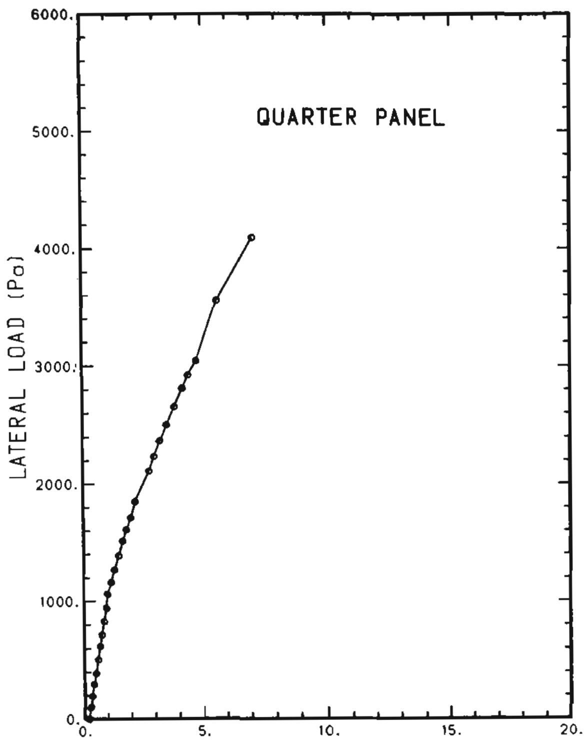
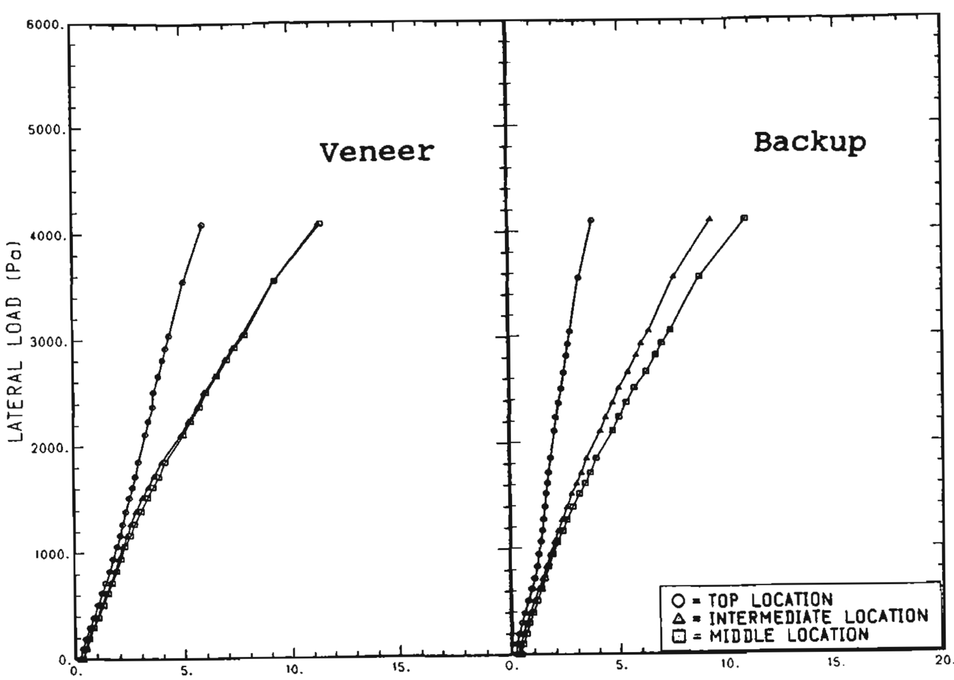


FIGURE 5.23 STEEL STUD FLEXURAL FAILURE – WALL3



a) Flexural Veneer Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.24 DISPLACEMENT DURING ULTIMATE TEST STAGE FOR WALL4 (LOAD No. 10)

To test this "window wall" to failure, a covered wooden frame was fitted over the window and supported by the edges of the veneer opening. This precaution was taken to guard against the possibility of an explosive failure of the glass in the window.

1) <u>Secondary Cracking and Failure Load</u>

Because of failure of the backup wall, no secondary cracks were developed in the brick veneer. As shown in Figure 5.24(a), a fairly linear response at the quarter stud location was recorded up to 4.0 kPa. Failure of the wall was identified by excessive displacement of the steel stud sections above the window opening. The test was terminated for safety reasons.

2) <u>Crack Pattern at Failure</u>

Cracking in the veneer amounted to a number of horizontal cracks located around the window opening. The horizontal cracks in the veneer around the window had developed by the end of the test to the extent shown in the photograph in Figure 5.25

3) <u>Performance of Wall Ties</u>

Although most wall ties were observed to be undamaged after the test, a few ties located along the edge of the window opening at mid height showed signs of overloading. The wire pintle legs used to connect the veneer to the anchor portion of the tie were bent slightly inward which would be consistent with the expected compressive forces.

4) <u>Backup Wall Failure</u>

The failure observed in the backup wall involved the displacement of the steel stud panel above the window opening. As shown in Figure 5.26, the sides of the window opening were formed with double studs welded together to produce a box section. A track section was

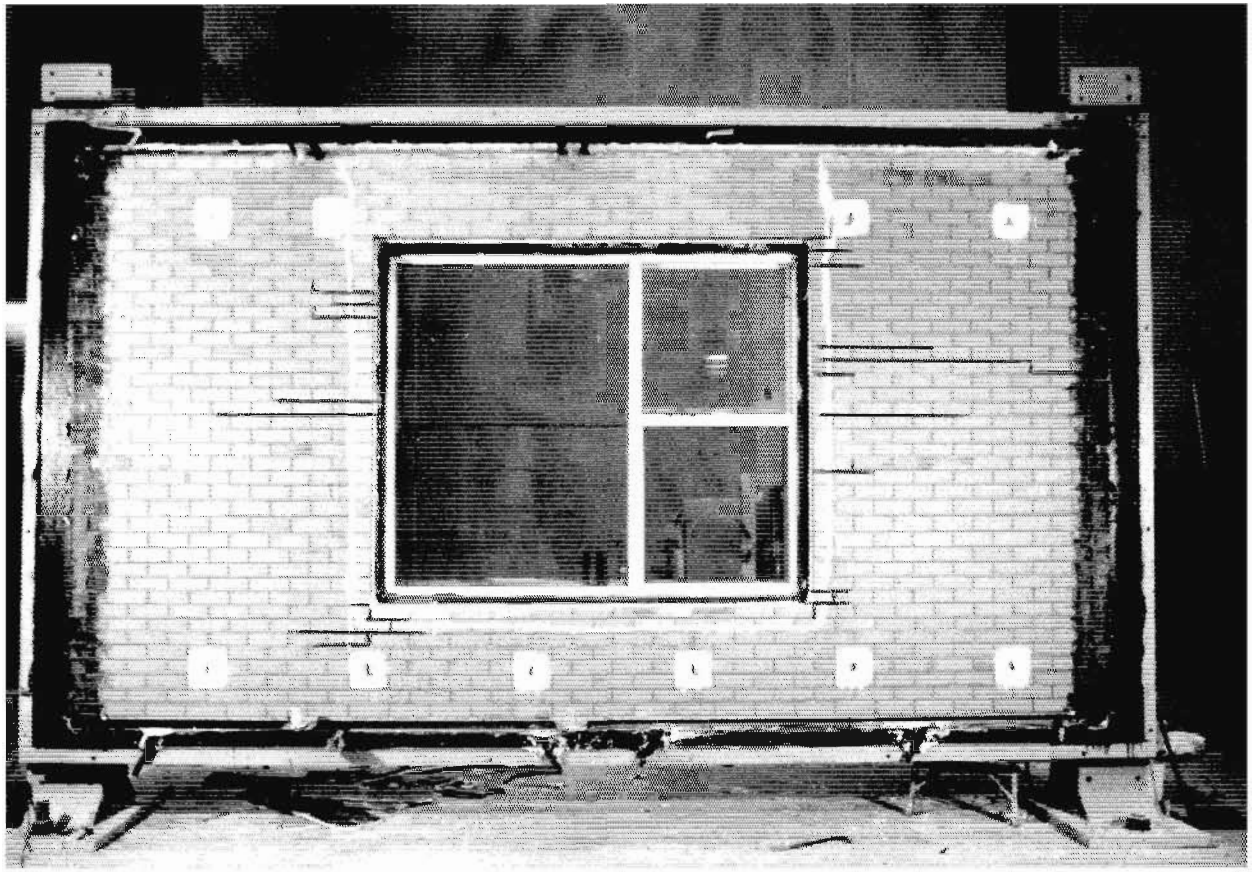


FIGURE 5.25 CRACK PATTERN AT FAILURE – WALL4

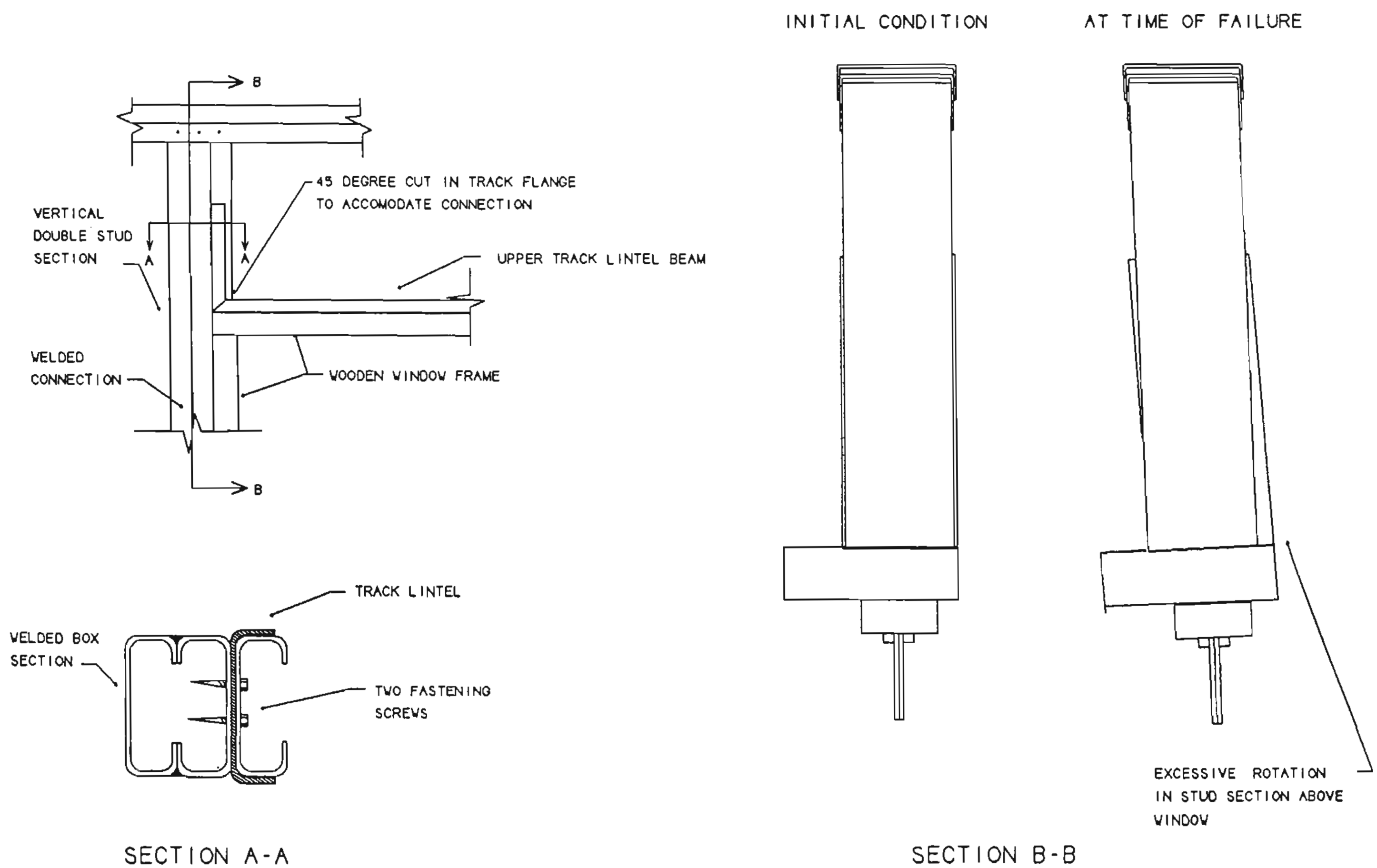


FIGURE 5.26 FAILURE OF BACKUP PANEL AT WINDOW OPENING

used to form the top lintel beam, framing the opening. Attachment of the top track lintel was accomplished by cutting the flanges and bending this section at a 90 degree angle to fit over the vertical box section.

During testing the top of the window frame was observed to be displaced away from the veneer and the connection of the top track lintel section to the double steel stud showed signs of failure. The test was stopped before complete structural failure had occurred but certainly after serviceability failure was evident. The observed failure in the track lintel detail over the window is illustrated in Figure 5.26.

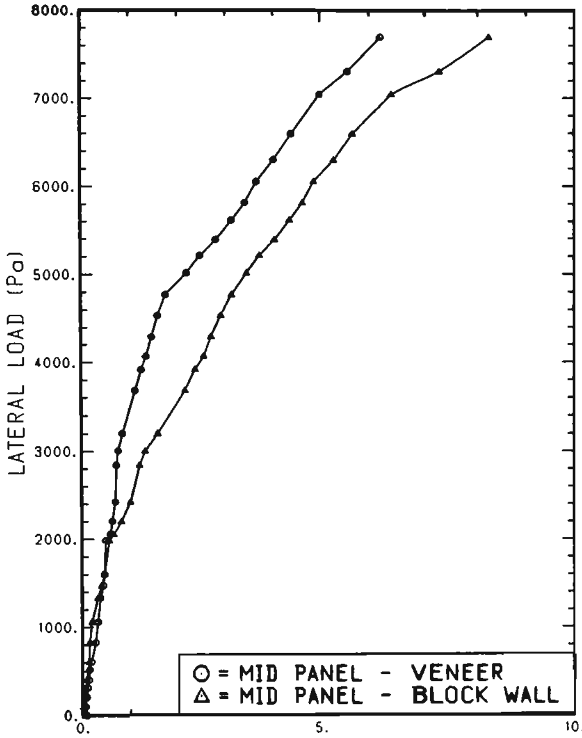
5.3.5.5 WALL5

The flexural displacement of the veneer and the gross displacements of the wall system are shown in Figure 5.27 for the final load sequence for WALL5, Load No. 10. This test followed development of the initial crack during Load No. 7 and additional tests at 0.5 kPa air pressure.

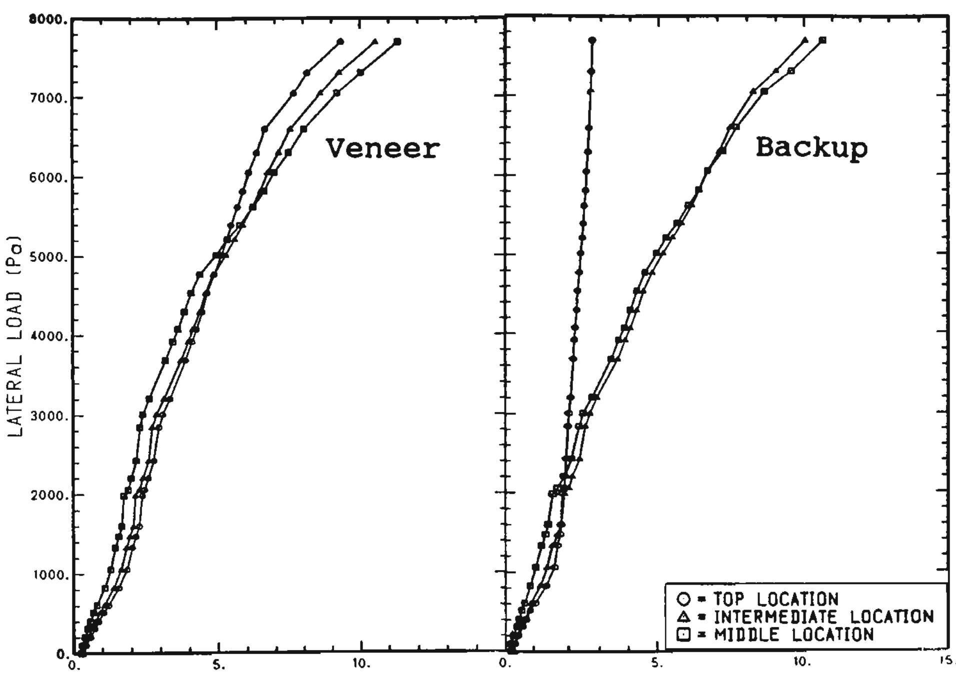
1) <u>Secondary Cracking and Failure Loads</u>

The flexural response recorded during the final load stage for WALL5, shown in Figure 5.27(a), closely resembled the initial cracking stage presented in Figure 5.8. The deflections were nearly identical for the veneer and the concrete block backup up to a load of approximately 2.0 kPa for both load stages

At loads above the initial crack level, cracking in the CB backup wall was both detectable from the flexural response and visible at horizontally debonded bed joints at mid height. As can be seen in Figure 5.27(b), at a load of around 1.0 kPa, the initial gap or mechanical play at the top support had been closed and the more uniform bearing did not allow much additional displacement at this location.



a) Flexural Veneer/Backup Displacement (mm)



b) Gross Displacement (mm)

FIGURE 5.27 DISPLACEMENT DURING ULTIMATE TEST STAGE FOR WALL5 (LOAD No. 10)

The brick veneer was not observed to be cracked or damaged in any way. Comparisons with the flexural displacement plots at failure for the veneers in other wall specimens showed that, bending in the veneer was relatively small for WALL5.

An initial horizontal crack did develop in the CB backup and was followed by secondary diagonal cracks before the test was terminated. The final air pressure recorded was near the failure loads previous recorded for the other walls. The test was stopped prior to failure because of the possibility of a sudden collapse.

2) Crack Pattern at Failure

The crack pattern marked on the CB backup wall after failure is shown in the photograph in Figure 5.28. The initial horizontal crack was traced across most of the length of the wall but was not visible all the way to the ends.

The secondary diagonal cracking in the backup wall was consistent with the two-way bending behaviour introduced by simply supporting the wall on all edges. The diagonal cracks initiated at the corners of the wall and had progressed towards the centre when the test was terminated. The diagonal cracks followed the mortar joints in a stepped pattern.

5.4 RESULTS OF INDEPENDENT STRUCTURAL TESTS

5.4.1 Influence of Veneer on Response of SS Backup

Before constructing the brick veneer for WALL1, a preliminary test was conducted to try out the test apparatus, to check for one way bending behaviour and to document the separate response of the steel stud backup wall. Because the steel studs were designed for a deflection of L/720 at 0.96 kPa, at 0.5 kPa the calculated displacement was 1.88 mm. The observed gross mid height deflection of 1.7 mm shown in Figure 5.29 is in excellent agreement considering that the gypsum board sheathing provided some initial composite action. During

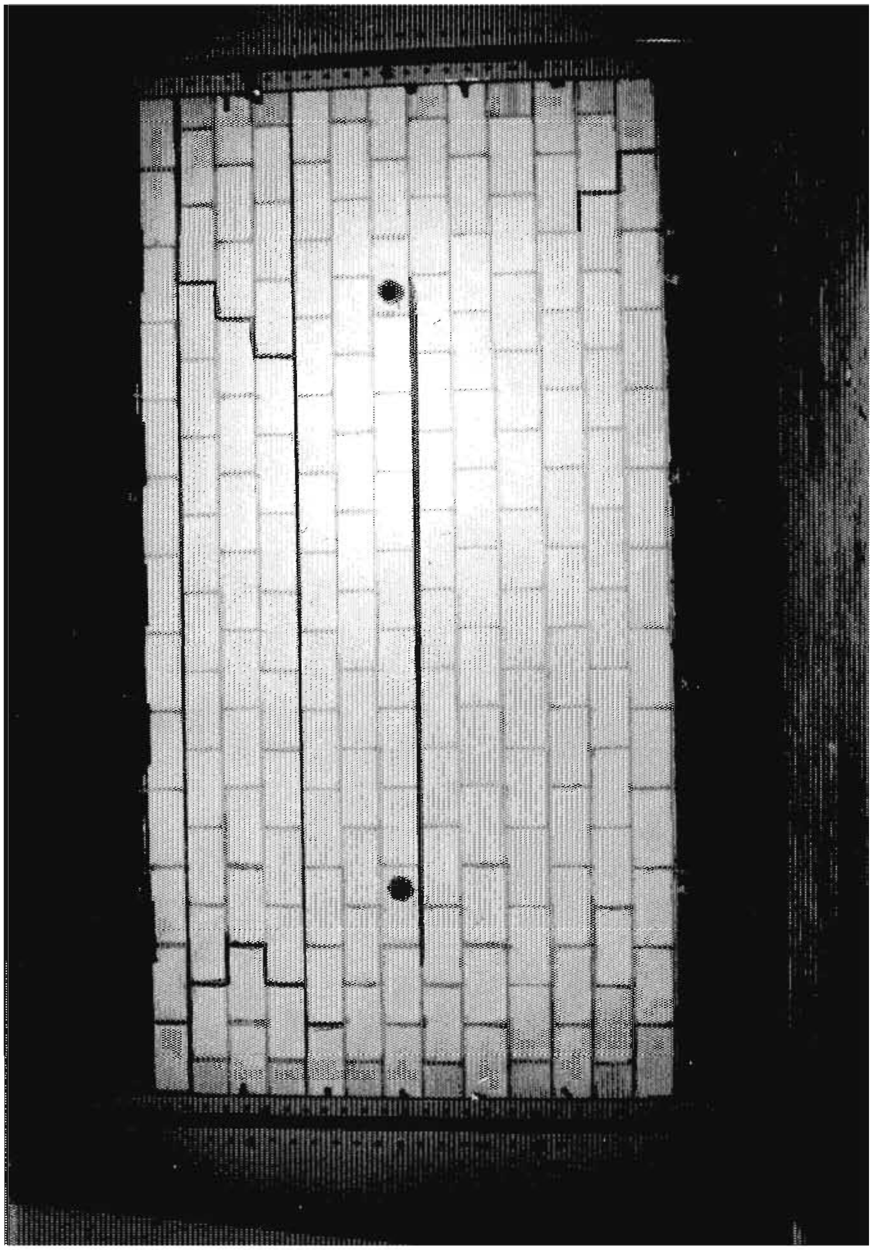


FIGURE 5.28 CRACK PATTERN AT FAILURE – WALL5

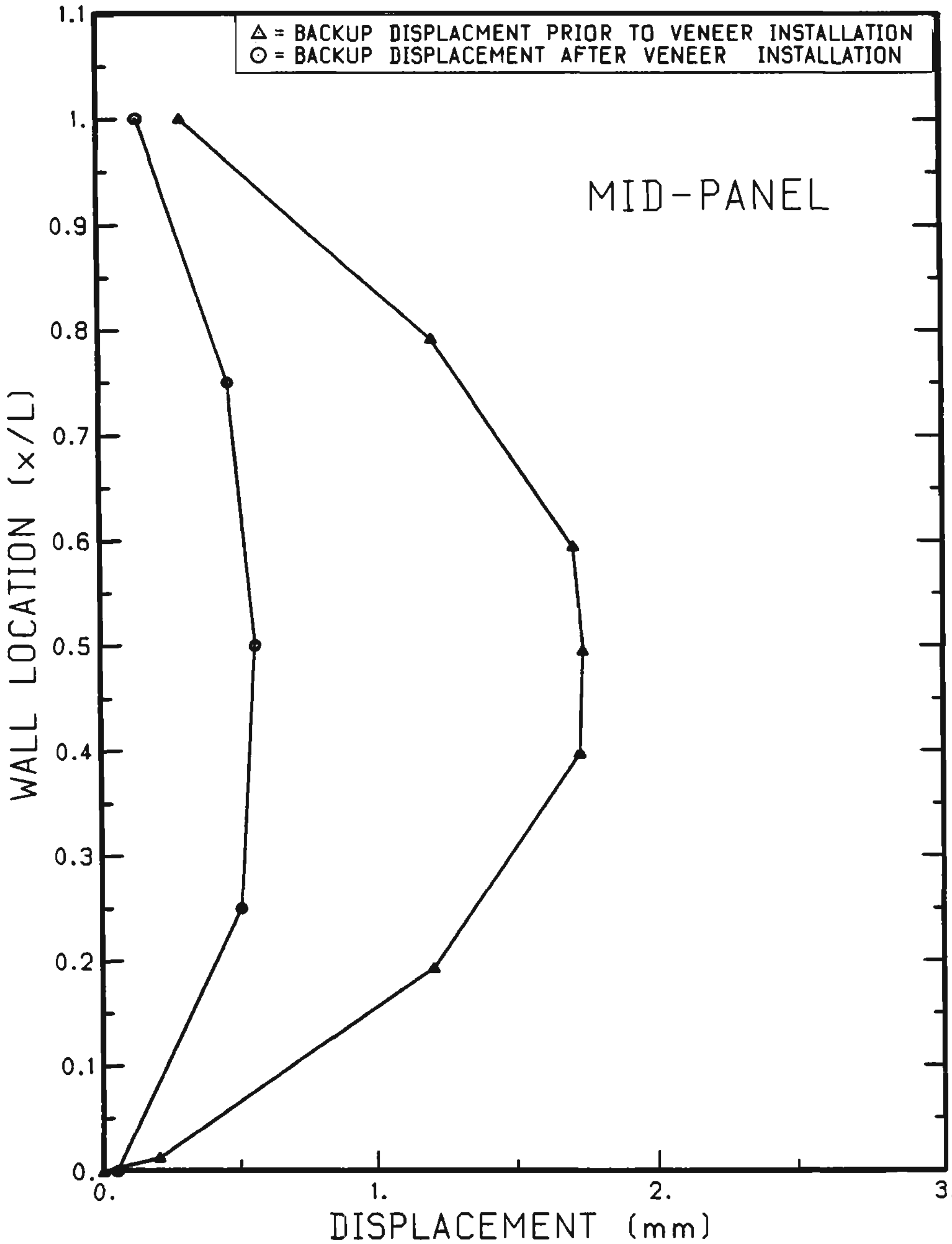


FIGURE 5.29 DISPLACEMENT OF SS BACKUP WALL BEFORE AND AFTER VENEER CONSTRUCTION – WALL1

the test, all of the studs were observed to displace in a similar manner indicating one way bending behaviour.

It should be noted that displacements of the ends of the stud due to translation in the upper and lower tracks were not accounted for in the stud deflection design limits. With this effect subtracted, the deflection due to bending of the studs was about 1.6 mm. For comparison purposes, the corresponding displacement profile of the steel stud wall with the uncracked veneer panel in place is also shown in Figure 5.29.

5.4.2 Influence of Filler Material in the Veneer Movement Joint

From the results for WALL1, it appeared that forcing of a large backer rod into the movement joint between the veneer and the shelf angle created a fairly rigid support condition at the top of the veneer. The restraint observed is indicated in the photograph in Figure 5.30. Therefore, this was identified as a test variable for WALL2. WALL2 was initially loaded without any backer rod in the movement joint followed by reloading after the correct size backer rod along with proper caulking were installed. This procedure also provided an opportunity to study the distribution of tie loads, as calculated from relative displacements and the average tie stiffness.

The 12.7 mm diameter backer rod used in the movement joint for WALL2 was much smaller than that used for WALL1 and much less force was required to place it in the 10 mm gap. As shown in Figure 5.31, despite this relatively "soft" joint, the displacement plots over the height of the veneer at the mid length of the wall indicate that significant top restraint was introduced. The tests with and without the backup rod in the joint were both done with the cavity pressurized. This condition places the least force on the veneer and thus results in the smallest reactions.

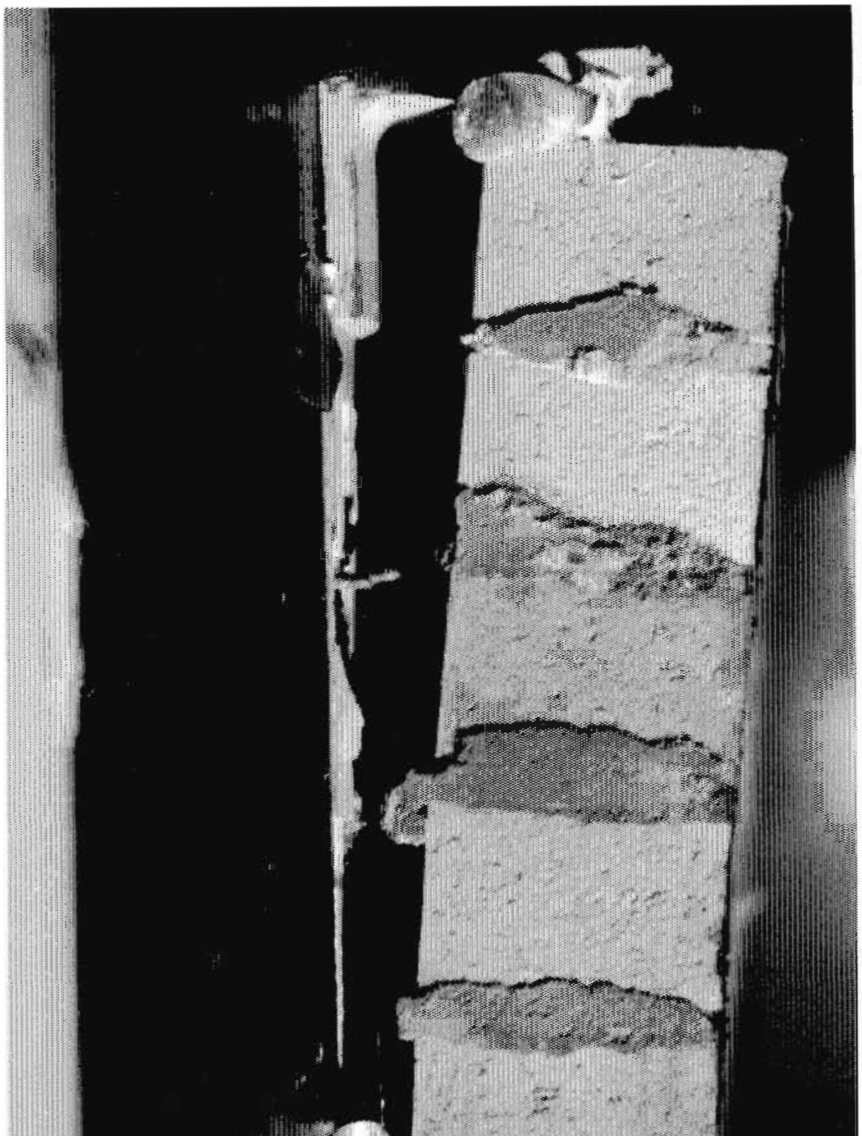


FIGURE 5.30 PHOTOGRAPH OF TOP RESTRAINT CAUSED BY TIGHTLY PACKED FILLER MATERIAL IN MOVEMENT JOINT OF WALL1

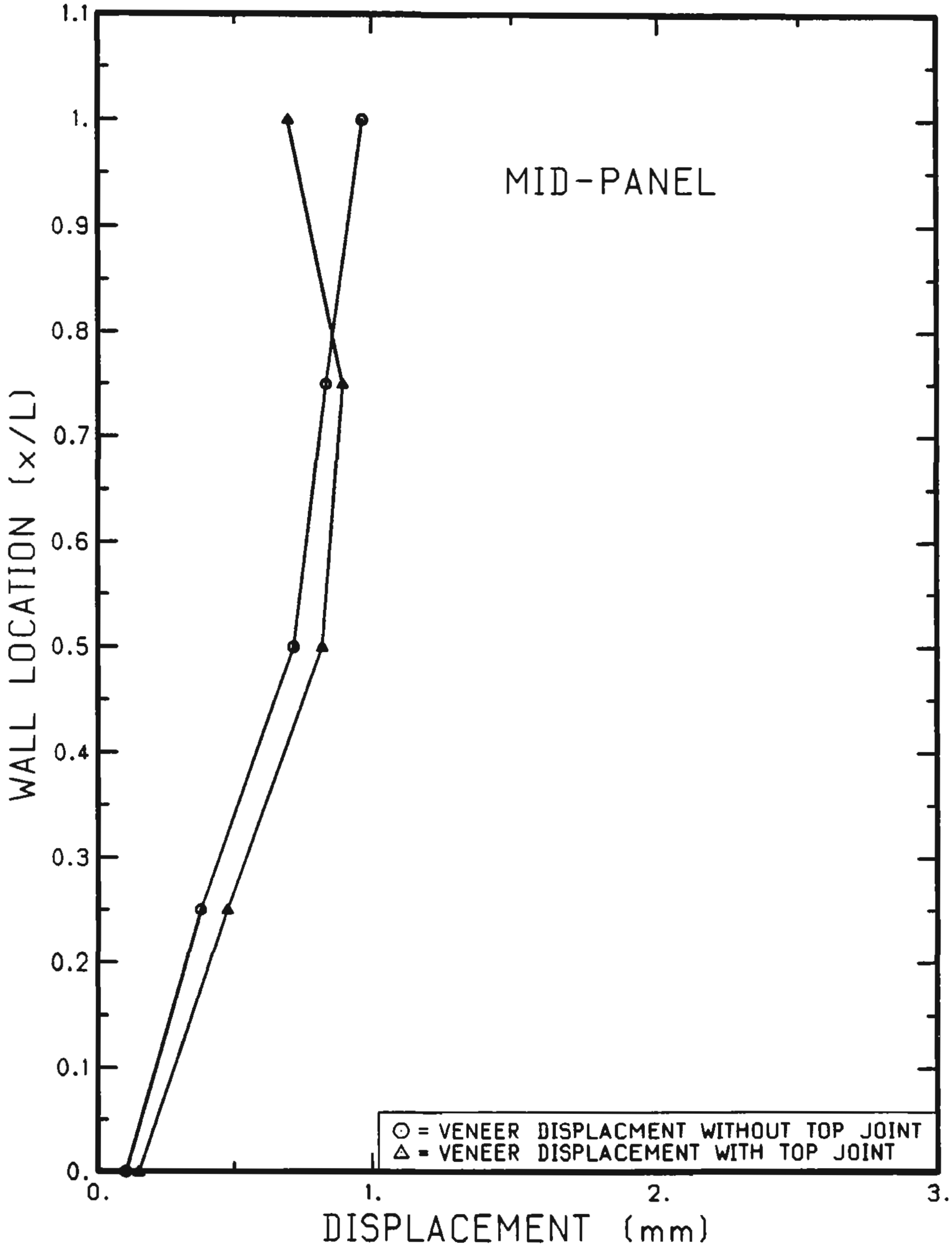


FIGURE 5.31 INFLUENCE OF FILLER IN VENEER MOVEMENT JOINT – WALL2

5.4.3 Response to repeated Loading

The load sequence designed for some wall specimens contained a repeated load stage at standard pressure levels after initial cracking of the veneer so that any influence of repeated loading would be most noticeable. Repeated loading stages were carried out with the cavity both pressurized and depressurized.

WALL3 was loaded to pressure levels of 1 kPa and 1.5 kPa, 50 times each for both the cavity pressurized and depressurized conditions. The results in Figure 5.32 indicate that even after 200 cycles of loading and unloading, very little evidence of structural softening, as shown by increased displacements, was observed.

WALL4 was loaded 50 times to a pressure of 0.8 kPa for both the cavity pressurization and depressurization conditions. The results presented in Figure 5.33 again indicate that, like WALL3, no significant damage or softening occurred during the load cycles.

5.4.4 Measurement of Crack Width

An attempt was made to measure actual crack widths during the test of WALL3. For WALL3, six horizontal mortar joints were gauged with LPDT's in a manner that allowed the displacement across the joints to be recorded. The gauged joints were located at mid height of the wall between successive wall ties.Because of the low tensile bond between the mortar and brick, all recorded displacement was assumed to represent crack width.

At the peak load of 1.8 kPa during initial cracking, the sum of the displacements over the 6 joints amounted to 0.23 mm with a maximum of 0.1 mm for a single joint.

The gross displacement of the veneer can be used to conservatively estimate the maximum crack width. A simple geometric relationship has been proposed[35] for which it is assumed that the veneer sections above and below the crack remain straight. This

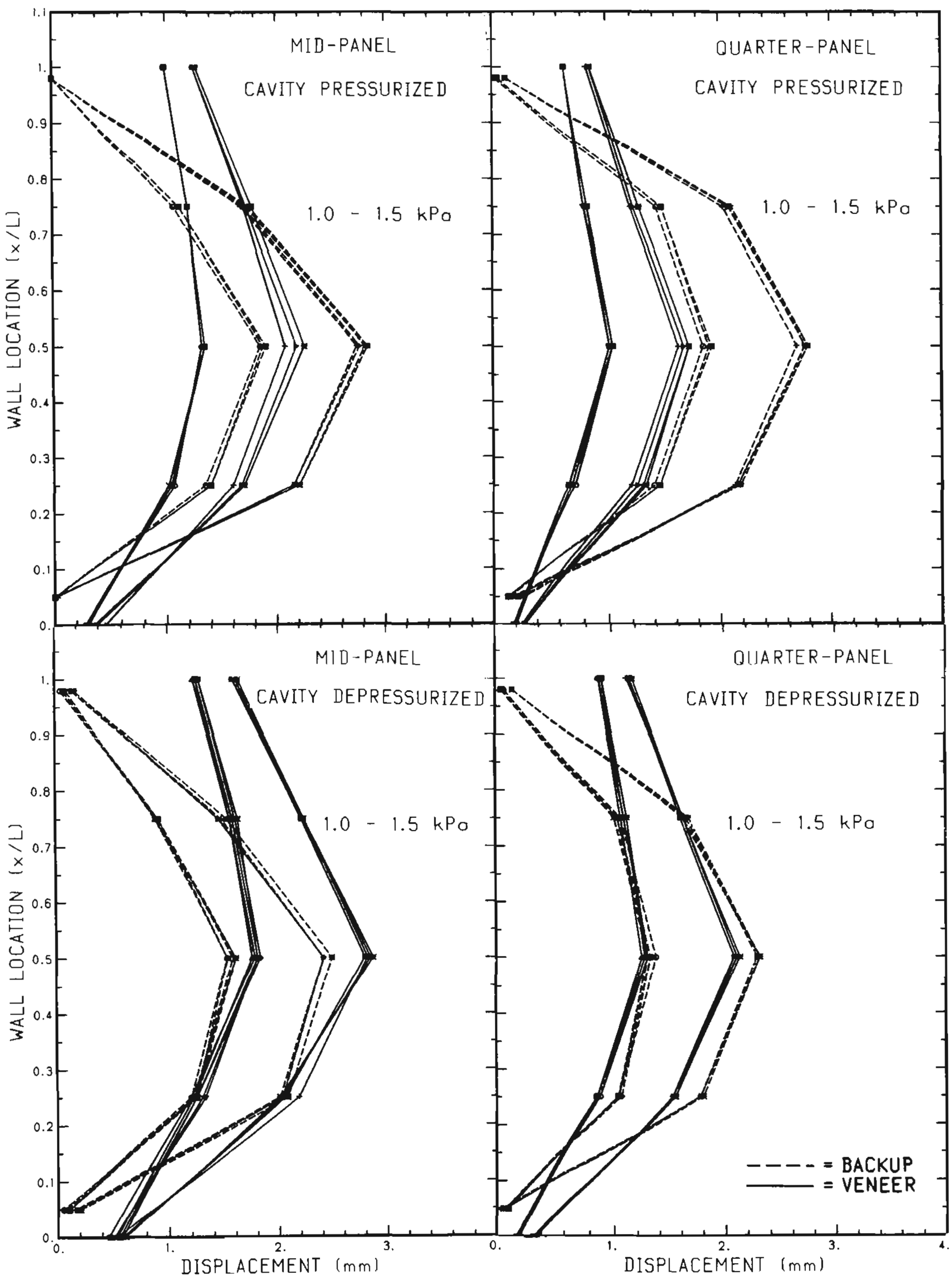


FIGURE 5.32 DISPLACEMENTS FOR CYCLIC LOADING OF WALL3

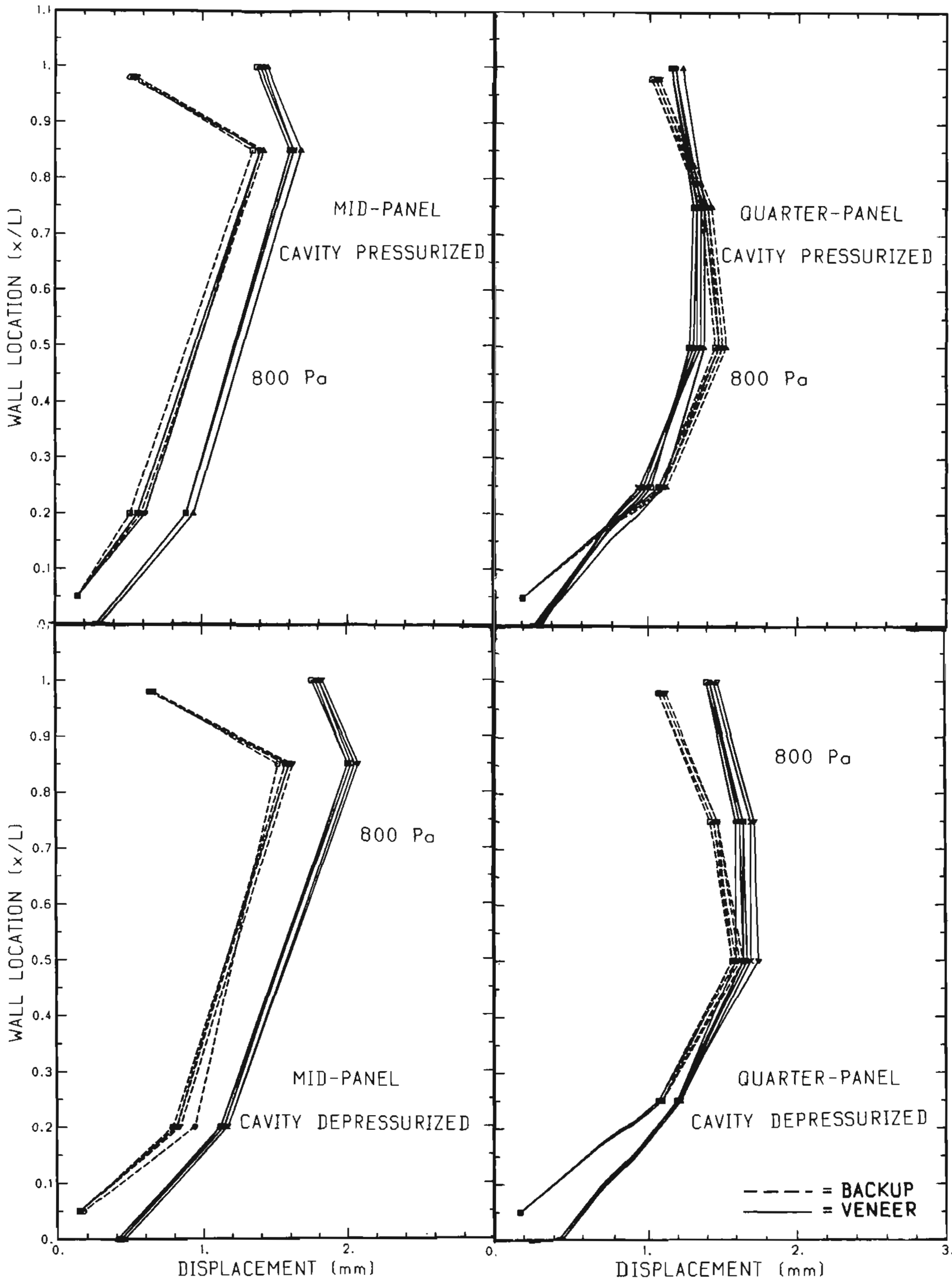


FIGURE 5.33 DISPLACEMENTS FOR CYCLIC LOADING OF WALL4

approximation appears to be justified considering the small displacements and angles involved. The relationship is as follows:

$$d_c = 4d_v t/L$$

where, d_c = maximum crack width

d_v = mid height veneer deflection

t = thickness of the brick

L = height of the veneer

Using this relationship, the crack width at the peak load was predicted to be 0.21 mm. Although this correlated very closely with the measured value of 0.23, such close agreement would not normally be expected.

5.4.5 Two Way Bending Behaviour

The support conditions for the BV/SS test walls were varied in the program. WALL1 was constructed with top and bottom support and demonstrated one way behaviour by developing both initial and secondary horizontal cracks in the veneer. Also simultaneous mid height flexural failures in all steel stud members were observed. WALL2 and WALL3 were constructed with the end studs fixed to the specimen frame in an effort to produce two way bending in the veneer. These two tests demonstrated varying degrees of two way behaviour.

WALL2 exhibited limited two way behaviour and, because the nested top track connection in the backup wall was flexible and eventually failed, the veneer was basically supported on three sides. This conclusion was confirmed by the crack pattern observed at failure. This observation is important because it emphasises the role that the backup support conditions play in the flexural behaviour of the veneer.

The relative flexural displacements of the veneer at the mid vs. quarter panel points shown in 5.20(a) and the final diagonal cracking in the veneer are evidence of two-way bending in WALL3. WALL1 and WALL3 initially cracked at loads of 1.4 and 1.2 kPa and secondary cracks developed at loads of 3.8 and 4.6 kPa, respectively. Because of support on four sides, the veneer panel of WALL3 was stiffer and resisted a greater share of the load compared to WALL1. As a result it would be expected to crack at a lower overall load than WALL1. However, in assessing the effects of two way bending of the veneer, the overall displacements of the wall system should not be overlooked. The flexural displacements of the veneer for WALL1 and WALL3 at the time of initial cracking were approximately 1.1 and 0.6 mm and at secondary cracking were approximately 12.0 and 6.0 mm, respectively. Therefore, although two way bending had a seemly negative affect on the cracking strength, the overall wall displacements were considerably reduced.

5.5 COMPARISON WITH PREVIOUS WALL COMPONENT TESTS

As stated early, an objective of the research was to provide qualitative data to accommodate a comparison between characteristics previously established from individual component test programs with the full scale behaviour of the complete wall system. The comparison includes the performance of wall ties, flexural behaviour of steel studs, nested top track behaviour and bridging performance.

5.5.1 Wall Ties

The initial stiffness of various BV/SS wall tie systems were documented as Part 4 of the CMHC/McMaster research program[36]. The system stiffness included the steel stud connection and was defined over a performance range of 4 mm of displacement. It was observed, from the full scale test results that 4 mm was representative of the tie system displacement in top ties at an air pressure of approximately 4 kPa.

Few wall ties were observed to fail in the test program. Where wall ties were observed to have failed, they were located at the top of the veneer.

An observation reported in the tie test program[36], which was confirmed in the full scale investigation, was the importance of the wall tie connection detail. The connection of the wall tie to the steel stud had been shown to have a major influence on both stiffness and strength. In the full scale test program, it was observed that wall ties mounted on the flanges of studs contributed to localized damage and it was thought that this may have initiated flexural failure of the studs by weakening the section. This observation was substantiated by the results from WALL3 where the wall tie was attached directly between the webs of two studs. In this case the flexural failure did not occur at a tie location, as others had, but instead coincided with the weakest section at a web knock out hole.

5.5.2 Steel Studs

5.5.2.1 Flexural Behaviour

For WALL1 and WALL2, sudden flexural failures occurred at loads around 7.2 kPa. At an air pressure of 7.2 kPa, the load resisted by a single stud from the tributary width of veneer is approximately 8 kN producing a maximum moment of 2.5 kNm for an assumed uniform loading. In Part 1[13,33] of the CMHC/McMaster research program it was established that a single 18 gauge stud could be expected to resist a moment of 1.825 kNm before failuring in flexure. Part of this difference will be due to the fact that uniform loading of the steel studs did not occur and the veneer continued to contribute to the flexural resistance of the wall system even after extensive cracking. It is suggested that part of the load carried by the veneer could be attributed to some in-plane arching caused by the tight fitting movement joints.

In WALL3, the full flexural strength of two back to back steel studs was obtained. The failure occurred suddenly at 6.6 kPa, providing a maximum bending moment per stud of 2.3 kNm for an assumed uniformly distributed load. Again this indicates that, even after extensive cracking, the veneer contributed to the load resistance up to failure.

5.5.2.2 Stud/Track Connections

At no time in the study were there any signs of distress in the bottom tracks. However, the connections between the tracks and the test frame must be considered. Although it is difficult to determine the actual loads resisted by the nested top track connections during the tests, the failure of this detail in WALL2 is consistent with observations from the component test program[13,33].

5.5.2.3 Bridging

The recommended spacing of bridging to achieve the full flexural capacity of the steel studs is 1.2 m[13,33]. The results from the full scale tests of steel stud walls spanning 2.59 m with one line of bridging indicate that this recommendation may be conservative depending on the additional bracing contribution of the wall tie system. However, because the exterior gypsum board was not eliminated as a source of bracing, no change from the 1.2 m spacing is recommended.

5.6 CLOSURE

Additional discussion of the significance of the structural test results will be included in Chapter 6. The test walls were all observed to crack at loads between 1.2 to 1.8 kPa. Because these loads are comparable to the design loads based on either an L/360 or L/720 defection criteria an evaluation of the design requirements is warranted and will be included.

The wall displacements were observed to be sensitive to the cracked condition of the veneer and the condition of cavity pressure. The cavity depressurization condition with load directly on the veneer was found to be critical for individual tie loads and veneer displacement. After cracking, the reduced stiffness of the veneer allowed the SS backup walls to resist a greater share of the lateral load which in turn resulted in increased overall wall displacements.

The ultimate strengths of the wall specimens were found to be much greater than their required design strength. It was also observed that creation of two way bending served to increase the load necessary for secondary cracking and also limited overall wall displacements. Development of two way bending behaviour was also found to lower the load required to crack the veneer panel. This was attributed to the increased share of the load resisted by the veneer resulting from the increased veneer stiffness due to two way bending behaviour.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL OVERVIEW

This study was focused on the overall structural behaviour and rain screen performance of BV/SS and BV/CB wall systems. A review of the literature revealed the lack of adequate test procedures for measurement of structural and rain penetration performances of wall systems. Therefore apparatus and test procedures were developed and used to assess the performance of five full scale wall specimens.

The test walls were designed and constructed in accordance with typical current practices in order to evaluate the adequacy of present day standards. A complete record of the specimen details including material tests were presented to fully describe the test walls. Tests were not repeated but instead the different specimens were designed to include a wide range of wall configurations and construction features. The experimental study involved both rain penetration tests and air pressure structural tests. The two experimental programs, presented separately in this report, were conducted together in the laboratory.

Contributions to understanding the behaviour of BV wall systems were made in the following areas:

- Assessment of the likelihood of cracking in the veneer under wind loading and of the vulnerability of the wall system to rain penetration and moisture deterioration in pre- and post- cracked conditions were unique areas of study.
- Documentation of overall full scale structural behaviour and rain screen performance of present day standard design and construction practices were essential for judging the adequacy of these practices.

The major observations and conclusions are summarized in the following sections, and design recommendations aimed at better wall performance are provided.

6.2 SUMMARY OF OBSERVATIONS

The major observations discussed in detail elsewhere in the report are summarized below. Where applicable, separate observations are made with regard to rain penetration and structural performance.

6.2.1 Influence of Cavity Pressure

Rain Penetration: For the open rain screen design to function properly, the cavity must be pressurized to external air pressure levels. When pressures on both sides of the veneer were not equal, rain penetration was found to be roughly proportional to the pressure difference across the veneer.

Structural Behaviour: Cavity pressure influenced the structural behaviour of the wall system. Pressurizing the cavity led to increased backup displacements and depressurizing the cavity led to increased veneer displacements. Throughout the investigation, the displacement of the veneer was found to be more sensitive to the condition of cavity pressure than was the displacement of the backup wall. For positive pressure prior to cracking of the veneer, the pressurized cavity condition resulted in top tie compression forces and tension forces in the other ties. Conversely, the depressurized cavity condition generally produced compressive tie forces. This behaviour was consistent with the behaviour predicted by finite element analyses[34].

6.2.2 Influence of Veneer Cracking

Rain Penetration: The development of a crack in the veneer introduced another leakage path for rain penetration. The significance of this additional leakage path varied with the condition of cavity pressure. For large pressure differences across the veneer, the rain penetration increased several fold whereas for equal pressures on both sides of the veneer the increased leakage was much less and only fractionally more than for the uncracked condition.

Structural Behaviour: A cracking in the veneer led to increased lateral displacement of the wall system. The type of tie forces (compression or tension) and the influence of cavity pressurization were not affected by cracking.

6.2.3 Influence of Compartmentalization

Rain Penetration: Compartmentalization was observed to be necessary for cavity pressurization and the effective performance of the rain screen. Increased leakage was observed when the cavity was not comparted. When the cavity was not comparted, in addition to the pressure differential across the veneer, large air movements into the cavity caused increased rain penetration. A backup wall with significant air leakage resulted in the same type of performance.

6.2.4 Influence of Top Veneer Movement Joint

Rain Penetration: When the top veneer movement joint was not fully sealed, a very large leakage path for rain penetration existed. Rain penetrated this joint and, travelling on the underside of the overhead shelf angle, gained access to the backup wall.

Structural Behaviour: Tightly packing the top joint with an oversized backer rod created a top support condition for the veneer. This behaviour was confirmed by analysis with a finite element program[34].

6.2.5 Leakage Paths for Rain Penetration

Rain Penetration: The major leakage paths for rain penetration were observed to be through the mortar joints at the intersection of the head and bed joints. Head joints were observed as allowing significantly more leakage than the bed joints. Other leakage paths identified included the interface between the veneer and the steel shelf angle and the top movement joint in the veneer.

6.2.6 Two Way Bending Behaviour

Structural Behaviour: Two way bending behaviour was observed in walls where the backup was supported on all four sides. This behaviour led to decreased wall displacements and increased secondary cracking loads.

6.3 EVALUATION OF DESIGN REQUIREMENTS

The steel stud deflection criteria of L/720, for a design load of 0.96 kPa, corresponded to a 3.6 mm displacement for the 2.59 m high backup walls tested. This displacement was viewed as a flexural displacement and did not account for translational movement at either the top or bottom track connections. Evaluation of the design criteria based on the first three wall specimens follows.

For WALL1, WALL2 and WALL3, the 3.6 mm flexural displacement in the backup wall was recorded at 1.9 kPa, 1.8 kPa and 2.2 kPa air pressures respectively. At these pressures, the top translational displacements of the backup wall were recorded as 1.5 mm, 0.8 mm and 0.3 mm respectively.

Cracking in the veneers was judged to occur at approximately 1.2 - 1.6 kPa in all three walls at which point the flexural mid height veneer displacements were recorded as 1.1 mm, 1.5 mm and 0.6 mm respectively. These flexural mid height veneer displacements can be expressed as relate deflection ratios of L/2500, L/1800 and L/4470 where L refers to the height of the veneer wall. Thus cracking in the veneer occurred before the backup deflection reached the L/720 limit and near the design load of 0.96 kPa. It can easily be shown that the deflection limit of L/720 had little effect on the cracking load.

The design load of 0.96 kPa can be considered in terms of the capacity of the veneer alone. For brick veneer spanning 2.747 m use of simple bending theory indicates that cracking at the 0.96 kPa design load would occur for a flexural tensile strength of 0.67 MPa. Neglecting to account for the load shared by the steel stud backup and simply analyzing the veneer to carry the entire wind load over a span between the shelf angle and the top tie provides an only slightly conservative basis for estimating cracking loads.

It is not practical to limit the deflection of the studs to prevent cracking in the veneer. For higher design loads or larger spans than those considered in this study, use of closer stud spacing or larger stud sections to prevent cracking is generally not practical. Therefore the potential for cracking does exist and must be considered in the design. Thus, the use of a deflection limit should not be interpreted as an attempt to avoid cracking but rather to control the crack width to some acceptable limit. As such, it is the deflection of the veneer that should be controlled.

In other areas of interest, wall performance was judged to be adequate. No tie failures were observed prior to failure of the specimen. In post failure examination, lack of twisting and evidence of flexural failure in the studs for all walls led to the conclusion that one line of bridging was adequate for the storey height used.

6.4 CONCLUSIONS

From the laboratory observations the following main conclusions can be drawn:

For BV/SS Walls,

- Cavity pressurization reduces rain penetration.
- Compartmentalization of cavity is required for cavity pressurization.
- Standard weep hole and vent spacings are sufficient for cavity pressurization.
- Veneer cracking has a relatively small impact on rain screen performance provided the cavity is comparted and the backup is constructed with an adequate air barrier.
- With respect to the permeance of brick masonry,the effects of poor workmanship can outweigh most other influences.
- Very large tie forces occur at the top ties prior to cracking of the veneer and at the ties nearest the crack after cracking of the veneer.
- The depressurized condition (load on the veneer) represented the critical load condition for the veneer and for individual tie forces.
- Prior to cracking, the much stiffer brick veneer limits the bending of steel stud backup walls.
- The air pressure required to cause cracking in the veneer is most influenced by the flexural strength of the masonry.
- Tight packing of the movement joint provides a top support condition for the veneer.
- Supporting the end studs of the backup wall introduces two way bending behaviour in the veneer.
- Two way bending behaviour reduces out of plane displacements of the wall system and increases secondary cracking strength.
- For storey height veneer construction, development of secondary cracks may not be of much interest because of the high wind pressures required.
- Air flow resulting from inadequate perimeter sealing of the air barrier or other deficiencies can result in "through-wall" rain penetration and damage to interior gypsum board in addition to wetting of materials in the stud cavity.
- Because most water penetration of the veneer occurs through head joints, complete filling and compaction of these is necessary.
- Poorly sealed top veneer movement joints or interfaces between veneer and shelf angles can lead to large volumes of rain penetration.

For BV/CB Walls,

- In the design of BV/CB wall systems cracking in the veneer is not of great concern. However cracking in the concrete block backup can mean failure of the wall system and must be evaluated.

- The conclusions regarding rain penetration of BV/SS walls are generally applicable to BV/CB walls.

6.5 RECOMMENDATIONS

Using an assessment of the reported test results as background, additional general recommendations have been prepared. The recommendations are divided into good practice recommendations, related primarily to the BV/SS wall system, and more general recommendations applicable to wall systems employing open rain screen design features.

It should be noted that the successful performance of the wall system will depend on the detailing and the quality of construction as well was the completeness of the design for structural and rain screen requirements.

6.5.1 Good Practice Recommendations

The following recommendations are classified with respect to wall system components or feature:

CAVITY:	•Provide a 50 mm clear air space. •Clean wall cavity of mortar droppings. •Compart cavity.
MORTAR:	•Tool mortar joints. •Provide full head joints. •Minimize furrowing of bed joint. •Minimize mortar fins.
BACKUP:	•Properly attach tracks to the structure. •Keep knockout hole away from mid height. •Use four screws for bridging connections. •Provide splice joints in bridging. •Use two screws for stud/track joints. •Provide vertical movement joint. •Provide at least double studs at openings.
WALL TIES:	•Minimize adjustability to achieve acceptable performance characteristics. •Place line of action of tie force as close to stud web as possible.

	•Do not locate near knockout holes. •Use proper size screws. •Use hot dipped galvanized or stainless steel components. •Provide additional ties at openings.
AIR BARRIER:	•Air barrier must transfer air pressure to the supporting members. •Seal perimeter of air barrier. •Provide continuity around openings.
BRICK VENEER:	•Fully seal top movement joint. •Use proper sized backer rod in joint. •Keep weep holes and vents clear.
FLASHING:	•Must be continuous and installed with proper lap joints. •Should be integrated with backup wall to protection against water infiltrating behind flashing material.

6.5.2 General Recommendations

The following recommendations developed for BV wall systems can generally be applied to most masonry cladding systems.

- BV wall design should anticipate and account for stresses in the veneer and include measures to control the cracking. The allowable crack size should reflect the performance requirement for the wall system. In situations where proper open rain screen performance is doubtful excessive veneer cracking should be avoided.

- Limiting the deflection of the veneer to L/720 restricts possible average crack width to a maximum average width of 0.25 mm, which is comparable to reinforced concrete standards. However, if this approach is to be taken in the design of the steel stud members, the flexible track connections and non-uniform tie stiffness must be considered. Although design by limited stud displacement is convenient for designers, it does not reflect the behaviour of the wall system.

- For an open rain screen wall, the cavity must be pressurized and comparted or large amounts of rain penetration can occur. An open rain screen wall does not guard against incidental water leakage. It relies on cavity pressurization to retard moisture migration into the wall system and on adequate drainage to remove incidental leakage through veneer openings.

- The sensitivity of open rain screen wall systems to construction deficiencies which leave the system vulnerable to moisture damage must be addressed in the design. Choice of type and location of materials should reflect this vulnerability assessment [35]. Quality of skilled labour, type and frequency of inspection and use of the structure are aspects that should be taken into account.

6.6 CONCLUDING REMARKS

For the use of BV/SS wall systems with acceptable levels of performance, owners, designers and contractors require guidance in order to avoid repeating incorrect or ineffective practices. The results of this study indicate some of the vulnerabilities of the BV/SS wall system regarding rain penetration and potential moisture damage. The recommendations from this study must be integrated with other design requirements for air and vapour barriers, insulation, structural features, and practical construction considerations

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APPENDIX 1

TABLE A1.1 WALL1 MORTAR TEST RESULTS

	Batch No.	Flow Measurement Initial (%)	Flow Measurement 20 min (%)	Air Content (%)	Cube Strength (MPa)	Aver. (MPa)	C.O.V. (%)
DAY 1	1	120.0			8.10		
					11.70	8.9	27.7%
					6.98		
	2	117.5	98.0	11.5	9.73		
					12.36	11.3	12.4%
					11.86		
	3	119.0			9.54		
					10.29	10.6	11.9%
					12.01		
	4	118.5			7.39		
					9.03	8.2	10.0%
					8.19		
DAY 2	5	121.0			9.79		
					9.94	9.8	1.8%
					9.59		
	6	118.0	99.0		10.70		
					10.15	10.2	5.3%
					9.61		
	7	119.0		12.5	10.42		
					10.58	10.5	0.8%
					10.54		
	8	120.5			9.03		
					9.07	8.9	2.1%
					8.72		
	9	123.0			9.69		
					9.65	9.5	4.0%
					9.02		
DAY 3	10	120.0		13.0	7.25		
					8.28	7.7	6.7%
					7.71		
	11	122.0	101.0		9.26		
					9.53	8.8	10.9%
					7.75		
	12	122.0			9.60		
					9.99	9.5	6.1%
					8.85		
	13	120.0			9.53		
					9.89	9.4	5.4%
					8.88		
	14	121.0			7.17		
					8.88	8.2	11.2%
					8.62		
NUMBER		14	3	3	42		
AVERAGE		120.3	99.3	12.3	9.4		
COV		1.4%	1.5%	6.2%	13.6%		

TABLE A1.2 WALL2 MORTAR TEST RESULTS

	Batch No.	Flow Measurement Initial (%)	20 min (%)	Air Content (%)	Cube Strength (MPa)	Aver. (MPa)	C.O.V. (%)
DAY 1	1						
	2						
	3				23.68		
					24.86	24.2	2.4%
					24.16		
	4				24.66		
					23.17	23.9	3.1%
					23.93		
DAY 2	5	128.0			21.78		
					22.44	22.1	1.5%
					22.20		
	6	124.5			22.75		
					22.13	22.7	2.7%
					23.35		
	7	125.0			19.88		
					19.38	20.0	3.7%
					20.85		
	8	125.0	109.0	6.5	20.40		
					21.45	21.5	5.5%
					22.75		
	9	126.0			22.01		
					21.70	21.4	3.7%
					20.50		
DAY 3	10	127.0			19.07		
					19.49	19.2	1.6%
					18.89		
	11	125.5			18.46		
					20.69	20.5	9.4%
					22.28		
	12	126.0			23.37		
					22.44	22.9	2.0%
					23.00		
	13	125.5			24.68		
					23.33	23.7	3.5%
					23.17		
	14	125.0			24.14		
					23.13	23.8	2.4%
					24.14		
NUMBER		13.0	1.0	1.0	36.0		
AVERAGE		96.7	109.0	6.5	22.2		
COV		57.0%			8.0%		

TABLE A1.3 WALL3 MORTAR TEST RESULTS

Batch No.	Flow Measurement Initial (%)	Flow Measurement 20 min (%)	Air Co'nt (%)	air cured Cube St'gth (MPa)	air cured Aver. (MPa)	air cured C.O.V. (%)	moist cured Cube St'gth (MPa)	moist cured Aver. (MPa)	moist cured C.O.V. (%)
1	110.0	97.0	11	15.04			15.77		
				14.73	15.0	2.1%	14.96	15.8	5.2%
				15.35			16.59		
2	114.0			13.95			16.31		
				14.45	14.1	2.0%	16.00	15.9	2.7%
				13.99			15.46		
3	119.0	95.0	7.5	12.48			13.87		
				13.41	13.2	4.8%	14.42	14.1	2.0%
				13.68			13.99		
4	120.0			16.35			10.54		
				16.04	16.2	1.0%	12.83	11.6	9.9%
				16.08			11.51		
5	121.0	95.0	8	13.95			12.79		
				14.03	13.9	0.7%	13.76	13.1	4.0%
				13.83			12.90		
6	120.0			14.88			15.42		
				14.84	15.0	1.1%	15.66	15.6	1.0%
				15.15			15.73		
7	119.0	99.0	9	15.35			16.00		
				15.50	14.9	5.9%	15.54	15.7	2.0%
				13.91			15.42		
8	122.0			14.34			15.19		
				14.11	14.2	0.9%	15.69	15.6	2.0%
				14.14			15.77		
9	122.0	101.0	8.5	12.05			12.75		
				12.71	12.3	3.2%	13.49	13.4	4.8%
				12.01			14.03		
10	122.0			17.17			17.55		
				17.13	16.7	4.2%	15.81	16.5	5.8%
				15.93			16.00		
11	122.0	98.0	6	15.42			16.62		
				16.43			15.73		
				16.59			16.39		
12	121.0			12.98			15.11		
				12.52			15.58		
				12.59			15.19		
13	122.0	100.0	8	14.45			15.38		
				14.14			15.46		
				14.65			15.23		
14	121.0			15.54			17.90		
				15.27			18.45		
				14.73			17.86		
NUMBER	14	7	7	42			42		
AVERAG	119.6	97.9	8.3	14.6			15.2		
COV	2.9%	2.4%	18.4%	9.1%			10.8%		

TABLE A1.4 WALL4 MORTAR TEST RESULTS

Batch No.	Flow Measurement Initial (%)	20 min (%)	Air Co'nt (%)	air cured Cube St'gth (MPa)	Aver. (MPa)	C.O.V. (%)	moist cured Cube St'gth (MPa)	Aver. MPa)	C.O.V. (%)
1	117.0			13.33			11.70		
				13.06	13.2	1.11%	11.59	11.7	0.51%
				13.10			11.66		
2	118.0	89.0		13.68			11.35		
				15.00	14.3	4.61%	11.66	11.6	1.65%
				14.26			11.70		
3	123.0			14.88			12.40		
				15.31	14.9	3.00%	11.82	12.1	2.45%
				14.42			12.01		
4	125.0	93.0	15	15.00			10.04		
				13.52	14.1	5.83%	10.77	10.4	3.56%
				13.64			10.35		
5	126.0			15.81			12.48		
				16.12	16.2	2.54%	13.14	12.9	2.73%
				16.62			13.02		
6	127.0	96.0	14.5	17.01			13.49		
				16.86	16.7	2.19%	13.52	13.4	1.59%
				16.31			13.14		
7	127.0		14.5	17.40			12.75		
				17.21	17.3	0.59%	13.60	13.1	3.54%
				17.24			12.87		
8	127.0	92.0	15	16.20			10.62		
				16.39	16.0	3.62%	10.62	10.5	1.27%
				15.31			10.39		
9	128.0			18.14			12.98		
				18.87	18.4	2.15%	12.71	12.8	1.14%
				18.25			12.75		
10	127.0	90.0	15.5	16.35			12.48		
				16.39	16.3	0.49%	12.56	12.5	0.47%
				16.24			12.44		
NUMBER	10	5	5	30			30		
AVERAG	124.5	92.0	14.9	15.7			12.1		
COV	3.2%	3.0%	2.8%	10.2%			8.5%		

TABLE A1.5 WALL5 MORTAR TEST RESULTS

	Batch No.	Flow Measurement Initial (%)	20 min (%)	Air Content (%)	Cube Strength (MPa)	Aver. (MPa)	C.O.V. (%)
DAY 1	1	128.0			9.69		
					11.59	10.9	9.45%
					11.32		
	2	127.0	98.0	18	9.69		
					10.00	9.9	2.38%
					10.15		
	3	128.0		18	12.63		
					11.12	11.9	6.41%
					12.09		
	4	129.0	101.0	17	13.41		
					12.21	13.0	5.04%
					13.25		
	5	128.0			13.60		
					13.83	13.8	1.29%
					13.95		
	6	128.0	103.0				
DAY 2	7	126.0			12.83		
					12.94	12.9	0.46%
					12.87		
	8	127.0	100.0	17	10.89		
					11.32	11.0	2.60%
					10.77		
	9	127.5		16.5	10.42		
					10.62	10.5	1.19%
					10.39		
	10	127.0	102.0	17	9.73		
					9.88	9.8	0.82%
					9.77		
DAY 3	11	127.0			9.65		
					9.80	9.7	0.80%
					9.73		
	12	129.0	107.0	17.5	9.61		
					9.42	9.6	1.30%
					9.65		
	13	126.0			9.73		
					9.80	9.7	1.00%
					9.61		
	14	126.0	106.0	17	9.57		
					9.65	9.5	1.24%
					9.42		
	15	126			11.35		
					11.90	11.8	2.99%
					12.01		
	16	124	93	17	13.33		
					12.63	12.9	2.97%
					12.71		
	17	124.5			10.54		
					10.70	10.6	0.73%
					10.62		
	18	125	97	16.5	9.80		
					9.73	9.7	0.80%
					9.65		
	19	122			10.93		
					11.01	11.0	0.41%
					10.93		
	20	123			9.26		
					9.30	9.4	1.80%
					9.57		
NUMBER		20	9	10	57		
AVERAGE		126.4	100.8	17.2	10.9		
COV		1.5%	4.4%	3.1%	12.8%		

TABLE A1.6 FLEXURAL STRENGTH TEST RESULTS

	Moment Arm (mm)	Load (kN)	Moment (Nmm)	Stress (MPa)	No. Specimens	Avg.	C.O.V. (%)
WALL 1 Normal	171	2.251	192460.50	0.75			
	171	1.928	164844.00	0.64			
	171	1.501	128335.50	0.50			
	171	2.643	225976.50	0.88			
	171	1.632	139536.00	0.54	5	0.66	23.4%
WALL 2 Normal	134	4.965	332655.00	1.30			
	134	4.643	311081.00	1.21			
	134	3.786	253662.00	0.99			
	134	2.964	198588.00	0.77			
	134	3.643	244081.00	0.95	5	1.04	20.1%
WALL 2 Parallel	220	8.9	979000.00	2.81			
	220	10.5	1155000.00	3.32			
	220	6.2	682000.00	1.96			
	220	10.5	1155000.00	3.32			
	220	5.6	616000.00	1.77	5	2.63	27.9%
WALL 3 Parallel	220	9.250	1017500.00	2.92			
	220	9.450	1039500.00	2.98			
	220	11.750	1292500.00	3.71			
	220	10.250	1127500.00	3.24	4	3.21	11.2%
WALL 4 Normal	134	1.65	110550.00	0.43			
	134	1	67000.00	0.26			
	134	1.575	105525.00	0.41			
	134	1.8	120600.00	0.47			
	134	1.7	113900.00	0.44	5	0.40	20.4%
WALL 4 Parallel	220	7.800	858000.00	2.46			
	220	5.650	621500.00	1.78			
	220	7.600	836000.00	2.40			
	220	7.950	874500.00	2.51			
	220	8.575	943250.00	2.71	5	2.37	14.7%
WALL 5 Normal	134	2.875	192625.00	0.75			
	134	2.075	139025.00	0.54			
	134	3.275	219425.00	0.86			
	134	2.775	185925.00	0.72			
	134	2.725	182575.00	0.71	5	0.72	15.8%

TABLE A1.7 WALL1 BOND WRENCH TEST RESULTS

	PRISM SPECIMENS - CONSTRUCTED WITH TEST WALL						WALL SPECIMENS	
JOINT	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)
1	5	1.460		7	0.399		WALL	1.216
2		0.812			0.516			0.766
3		0.664			0.513			0.466
4		0.376			0.376			0.519
5					0.506			0.538
6		0.512			0.362			0.729
1		0.517			0.381			0.947
2		0.873			0.641			0.728
3		1.022			0.369			0.443
4		1.090			0.607			0.589
5		0.540			0.362			0.928
6		0.468			0.473			0.468
1		0.895			0.526			0.521
2		0.946			0.421			0.985
3		0.846			0.581			
4		1.072			0.522			
5		1.010			0.558			
6		0.840	0.819		0.579	0.483		
1	6	0.463		8	1.011			
2		0.614			0.813			
3		0.429			1.068			
4		0.532			0.947			
5		0.747			0.870			
6		0.668			0.690			
1		0.856			0.852			
2		0.656			0.793			
3		0.700			0.821			
4		0.945			1.314			
5		0.569			1.022			
6		0.519			0.729			
1		0.674			0.849			
2		0.659			0.910			
3		1.113			0.783			
4		1.082			0.876			
5		0.727			0.954			
6		0.729	0.704		0.806	0.895		
COMBINED AVERAGE					0.72			0.70
NUMBER OF RESULTS					71			14
COV					33.5%			34.0%

TABLE A1.8 WALL2 BOND WRENCH TEST RESULTS

	PRISM SPECIMENS - CONSTRUCTED WITH TEST WALL						WALL SPECIMENS	
JOINT	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)
1	5	0.444		7	1.128		WALL	0.420
2		0.369			1.096			0.963
3		0.445			0.896			1.223
4					1.230			0.664
5		0.935			0.467			0.591
6		1.271			1.051			
1		0.512			1.332			1.054
2		0.430			1.063			0.825
3		0.418			1.013			0.556
4		0.597			0.668			0.483
5		0.703			1.018			0.697
6		0.591			0.936			
1		0.527			0.991			0.696
2		0.772			1.175			0.632
3		0.475			0.900			0.965
4		0.746			0.968			1.208
5		0.814			0.985			1.096
6		0.877	0.623		0.802	0.979		
1	6	0.638		8	1.269			
2		0.482			1.763			
3		0.083			1.492			
4		0.629			1.076			
5					0.956			
6					1.247			
1		0.459			1.957			
2		0.794			1.176			
3		0.390			1.176			
4		0.560			1.517			
5		0.447			0.928			
6		0.663			0.922			
1		1.067			1.329			
2		0.619			1.418			
3					1.862			
4		0.629			1.563			
5		0.651			0.939			
6		0.510	0.570		0.946	1.308		
COMBINED AVERAGE					68			15
NUMBER OF RESULTS					0.89			0.80
COV					43.0%			32.7%

TABLE A1.9 WALL3 BOND WRENCH TEST RESULTS

JOINT	PRISM SPECIMENS - CONSTRUCTED WITH TEST WALL						WALL SPECIMENS	
	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)
1	5	0.573		7	0.484		WALL	0.433
2		0.705			1.334			0.731
3		0.616			1.149			0.894
4		0.605			0.911			0.545
5		0.579			1.418			0.832
6		1.026			1.607			
1		0.489			0.649			0.631
2		0.562			0.967			0.498
3		0.618			1.219			0.834
4		0.510			0.863			0.691
5		0.840			1.541			0.961
6		1.237			1.023			
1		0.353			0.556			0.771
2		0.422			0.810			0.827
3		0.732			0.936			0.934
4		0.481			0.590			0.695
5		0.541			0.541			0.624
6		0.635	0.640		0.719	0.962		0.361
1	6	0.590		8	0.853			
2		0.814			1.427			
3		0.585						
4		1.040			1.030			
5		0.654			0.969			
6		0.852			1.430			
1		0.744			0.407			
2		0.741			0.591			
3		0.597			1.561			
4		0.683			1.207			
5		0.585			0.887			
6		0.723			0.769			
1		0.400			0.714			
2		0.571			0.717			
3		0.418			0.930			
4		0.613			0.536			
5		0.563			0.395			
6		0.523	0.650		0.543	0.880		
NUMBER OF RESULTS						71		16
COMBINED AVERAGE						0.78		0.70
COV						39.8%		25.4%

TABLE A1.10 WALL4 BOND WRENCH TEST RESULTS

	PRISM SPECIMENS - CONSTRUCTED WITH TEST WALL						WALL SPECIMENS	
JOINT	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)
1	5	0.814		7	0.897		WALL	0.344
2		0.821			0.801			0.624
3		0.831			0.493			0.366
4		0.713			0.622			0.444
5		0.637			0.784			0.626
6					0.804			
1		0.577			0.661			0.494
2		0.622			0.877			0.650
3		0.857			0.767			0.691
4		0.805			0.693			0.755
5		0.684			0.911			0.861
6		0.611			0.771			
1		0.626			0.801			0.611
2		0.747			0.834			0.689
3		0.674			0.861			0.557
4		0.794			0.821			0.674
5		0.757			0.567			0.834
6		0.664	0.720		0.489	0.747		0.761
1	6	0.543		8	0.701			
2		0.624			0.489			
3		0.693			0.579			
4		0.491			0.827			
5		0.507			0.624			
6		0.591			0.677			
1		0.829			0.617			
2		0.527			0.767			
3		0.493						
4		0.487			0.507			
5		0.626			0.821			
6		0.839			0.761			
1		0.597			0.527			
2		0.671			0.647			
3		0.761			0.667			
4		0.833			0.624			
5		0.636			0.664			
6		0.650	0.633		0.314	0.636		
NUMBER OF RESULTS					70			16
COMBINED AVERAGE					0.68			0.62
COV					18.6%			24.4%

TABLE A1.11 WALL5 BOND WRENCH TEST RESULTS

JOINT	PRISM SPECIMENS - CONSTRUCTED WITH TEST WALL: PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	PRISM BATCH	BOND STRENGTH (MPa)	BATCH AVG	BLOCK FLEXURAL: PRISM BATCH	BOND STRENGTH (MPa)
1	5	0.807		7	0.821		WALL	0.316
2		0.970			0.794			0.274
3		0.489			0.514			0.258
4		0.827			0.835			0.257
5		0.521			0.577			0.293
6		0.562			0.634			0.260
								0.268
1		0.827			0.813			0.319
2		0.814			0.577			0.280
3		0.837			0.898			0.305
4		0.587			0.834			0.256
5		0.744			0.498			
6		0.694			0.901			
1		0.977			0.767			
2		0.794			0.747			
3		0.827			0.952			
4		0.565			0.694			
5		0.759			0.821			
6		0.891	0.750		0.939	0.756		
1	6	0.761		8	0.565			
2		0.827			0.834			
3		0.827			0.977			
4		0.694			0.674			
5		0.694			0.827			
6		0.654			0.627			
1		0.827			0.961			
2		1.114			0.894			
3		0.762			0.627			
4		1.127			0.794			
5		1.007			0.561			
6		0.944			0.861			
1		0.506			0.767			
2		0.565			0.565			
3		0.681			0.867			
4		0.961			0.893			
5		0.427			0.825			
6		0.827	0.789		0.363	0.749		
COMBINED AVERAGE					72			11
NUMBER OF RESULTS					0.76			0.28
COV					21.2%			8.5%

TABLE A1.12 WALL1 COMPRESSION PRISM TEST RESULTS

(PRISMS SIX COURSES HIGH H/W RATIO OF 4.36)

SPECIMEN	Pmax (kN)	Area (mm^2)	MAXIMUM STRESS (MPa)	25% OF MAXIMUN STRESS (MPa)	STRAIN AT 25% MAX STRESS	E (MPa)
1	700.06	17100	40.94	10.23	0.000616	16614
2	733.39	17100	42.89	10.72	0.000905	11847
3	688.94	17100	40.29	10.07	0.000847	11891
4	722.28	17100	42.24	10.56	0.000679	15551
5	733.39	17100	42.89	10.72	0.000830	12917

NUMBER OF SAMPLES	5	NUMBER OF SAMPLES	5
AVERAGE	41.85	AVERAGE	13763.78
COV	2.8%	COV	15.9%

TABLE A1.13 WALL2 COMPRESSION PRISM TEST RESULTS

(PRISMS SIX COURSES HIGH H/W RATIO OF 4.36)

SPECIMEN	Pmax (kN)	Area (mm^2)	MAXIMUM STRESS (MPa)	25% OF MAXIMUN STRESS (MPa)	STRAIN AT 25% MAX STRESS	E (MPa)
1	726.72	17100	42.50	10.62	0.000650	16346
2	676.10	17100	39.54	9.88	0.000800	12356
3	777.84	17100	45.49	11.37	0.000710	16017
4	784.51	17100	45.88	11.47	0.000680	16867
5	685.39	17100	40.08	10.02	0.000620	16162

NUMBER OF SAMPLES	5	NUMBER OF SAMPLES	5
AVERAGE	42.70	AVERAGE	15549.30
COV	6.9%	COV	11.7%

TABLE A1.14 WALL3 COMPRESSION PRISM TEST RESULTS

(PRISMS SIX COURSES HIGH H/W RATIO OF 4.36)

SPECIMEN	Pmax (kN)	Area (mm^2)	MAXIMUM STRESS (MPa)	25% OF MAXIMUN STRESS (MPa)	STRAIN AT 25% MAX STRESS	E (MPa)
1	582.2268	17100	34.05	8.51	0.000538	15822
2	517.7819	17100	30.28	7.57	0.000509	14872
3	555.56	17100	32.49	8.12	0.00065	12496
4						
5						

NUMBER OF SAMPLES	3	NUMBER OF SAMPLES	3
AVERAGE	32.27	AVERAGE	14396.53
COV	5.9%	COV	11.9%

TABLE A1.15 WALL4 COMPRESSION PRISM TEST RESULTS

(PRISMS SIX COURSES HIGH H/W RATIO OF 4.36)

SPECIMEN	Pmax (kN)	Area (mm^2)	MAXIMUM STRESS (MPa)	25% OF MAXIMUN STRESS (MPa)	STRAIN AT 25% MAX STRESS	E (MPa)
1	542.2226	17100	31.71	7.93	0.000513	15453
2	566.6671	17100	33.14	8.28	0.000552	14997
3	513.3337	17100	30.02	7.50	0.000488	15379
4	522.2226	17100	30.54	7.63	0.000474	16107
5	551.1115	17100	32.23	8.06	0.000496	16244

NUMBER OF SAMPLES	5	NUMBER OF SAMPLES	5
AVERAGE	31.53	AVERAGE	15636.12
COV	4.0%	COV	3.4%

TABLE A1.16 WALL5 COMPRESSION PRISM TEST RESULTS

(PRISMS SIX COURSES HIGH H/W RATIO OF 4.36)

SPECIMEN	Pmax (kN)	Area (mm^2)	MAXIMUM STRESS (MPa)	25% OF MAXIMUN STRESS (MPa)	STRAIN AT 25% MAX STRESS	E (MPa)
1	651.12	17100	38.08	9.52	0.000812	11723
2	613.34	17100	35.87	8.97	0.000709	12647
3	551.12	17100	32.23	8.06	0.000850	9479
4	604.45	17100	35.35	8.84	0.000769	11492
5	586.67	17100	34.31	8.58	0.000708	12115

NUMBER OF SAMPLES	5	NUMBER OF SAMPLES	5
AVERAGE	35.17	AVERAGE	11491.13
COV	6.1%	COV	10.5%

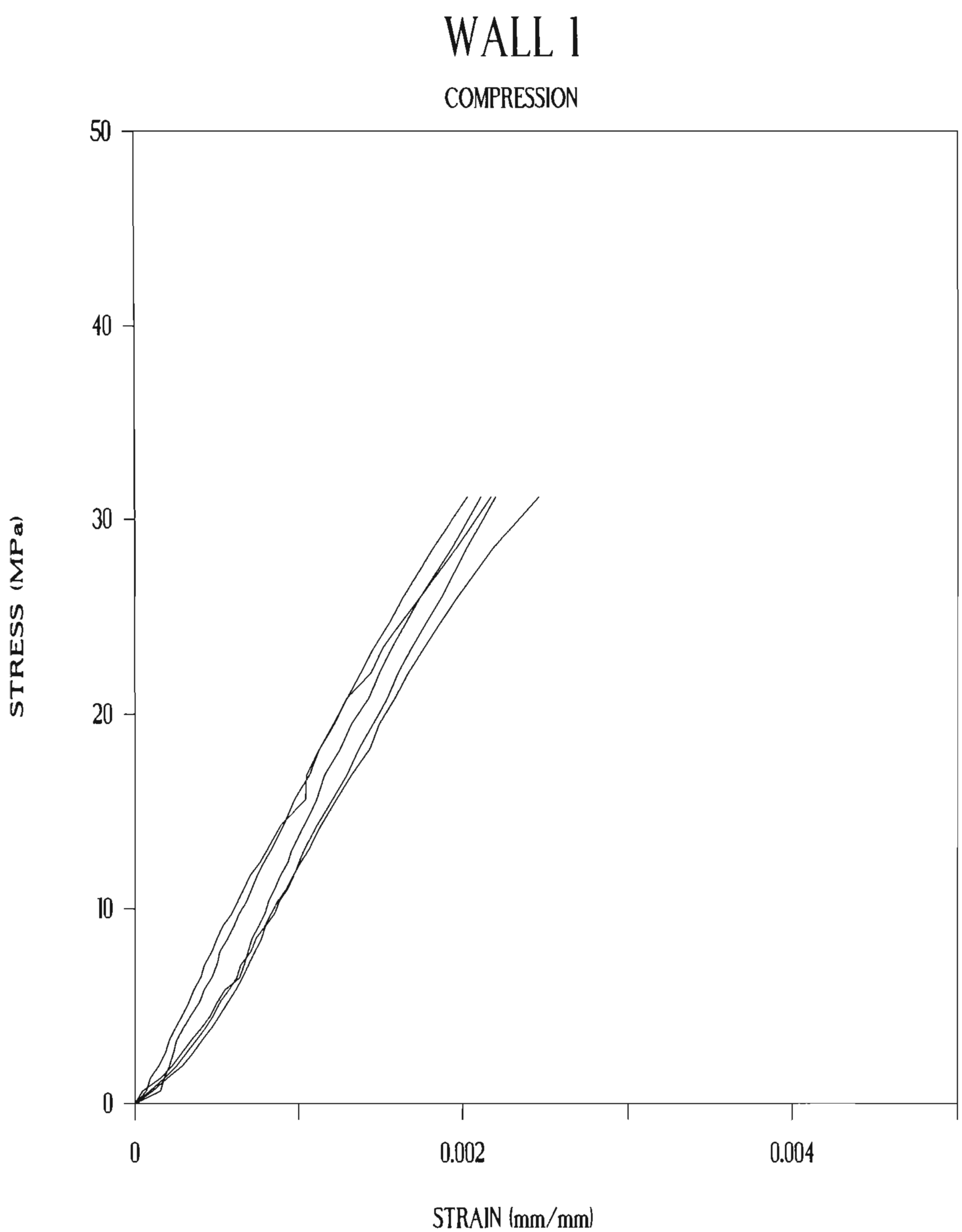


FIGURE A1.1 STRESS STRAIN CURVES - WALL1 PRISMS

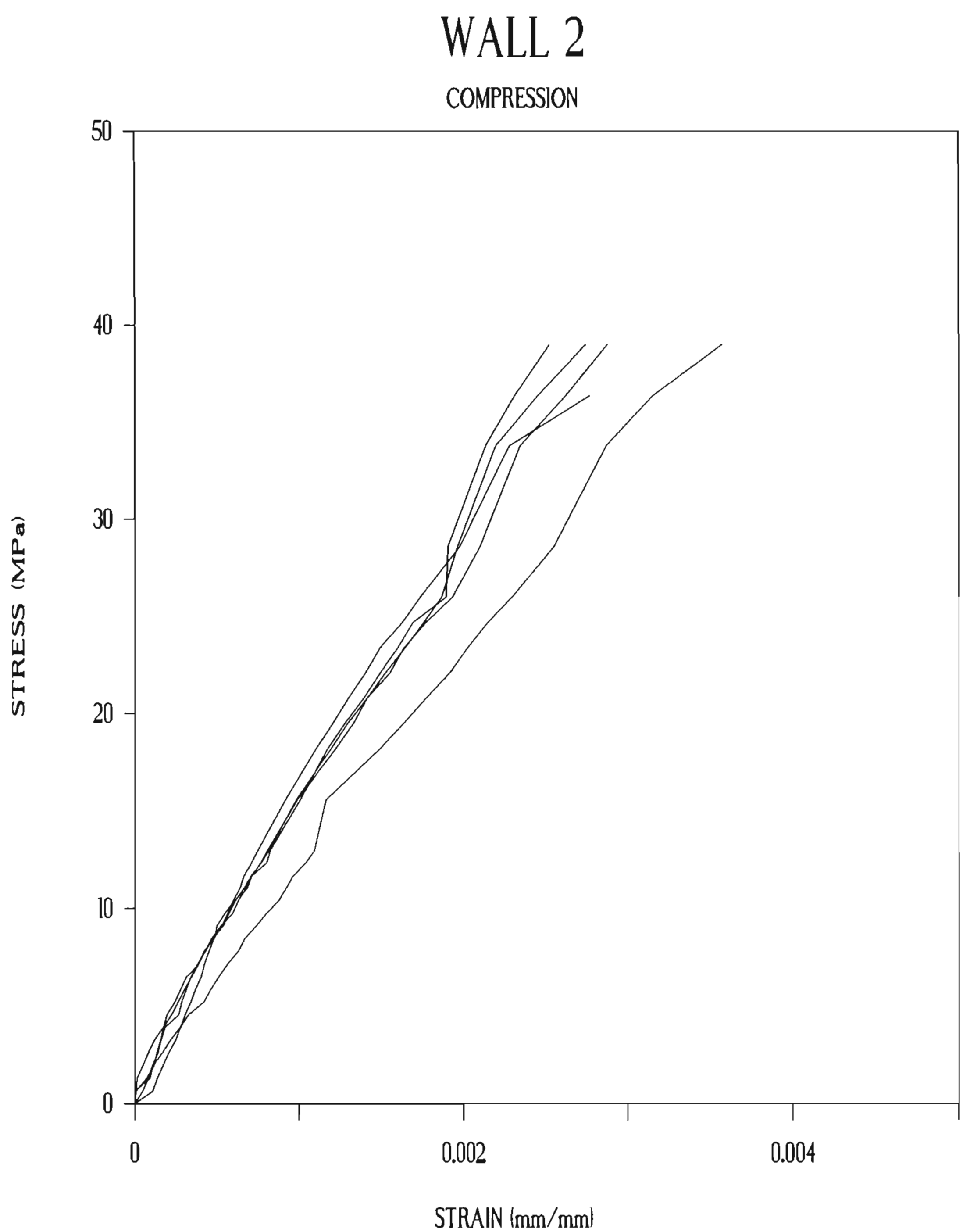


FIGURE A1.2   STRESS STRAIN CURVES - WALL2 PRISMS

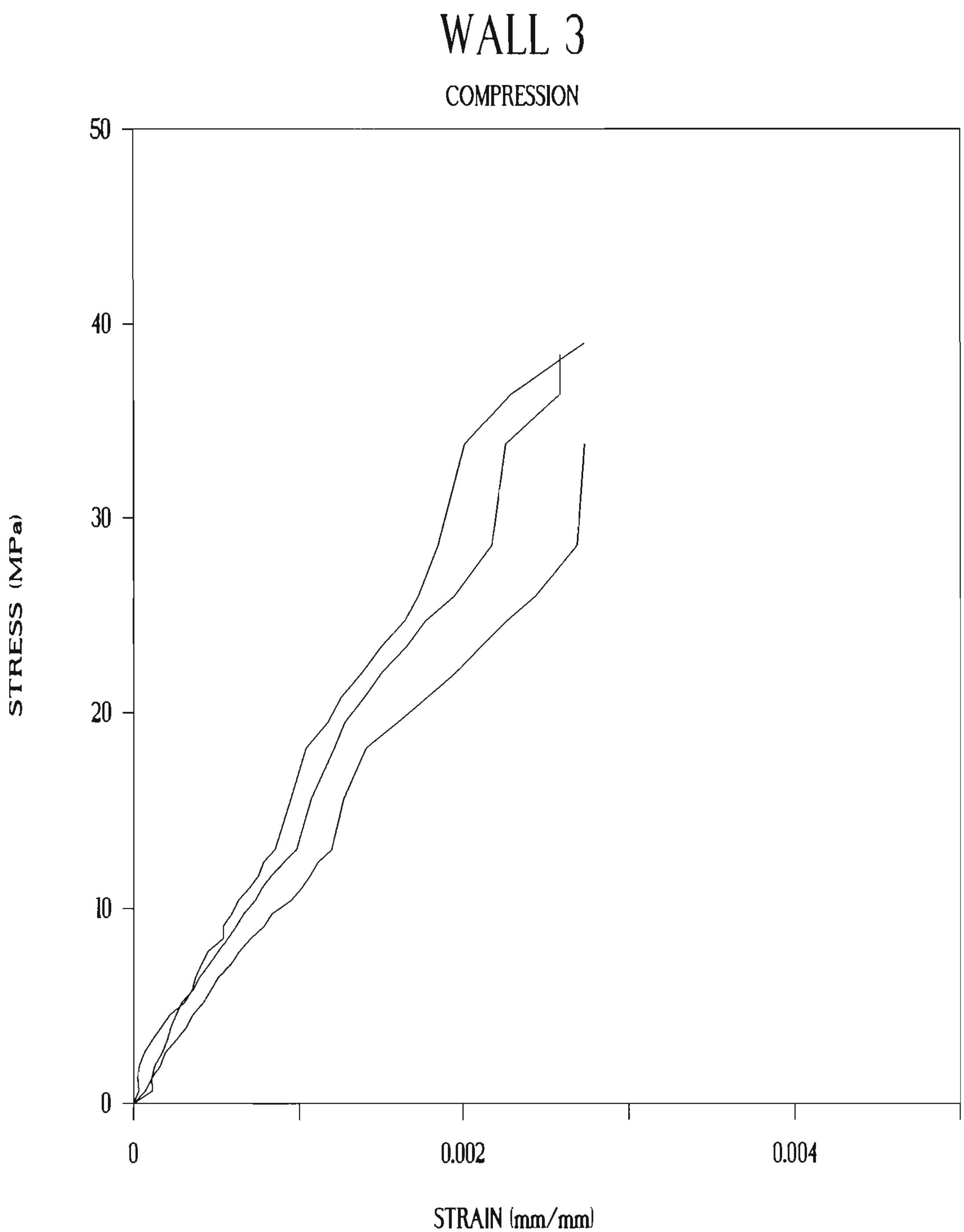


FIGURE A1.3 STRESS STRAIN CURVES - WALL3 PRISMS

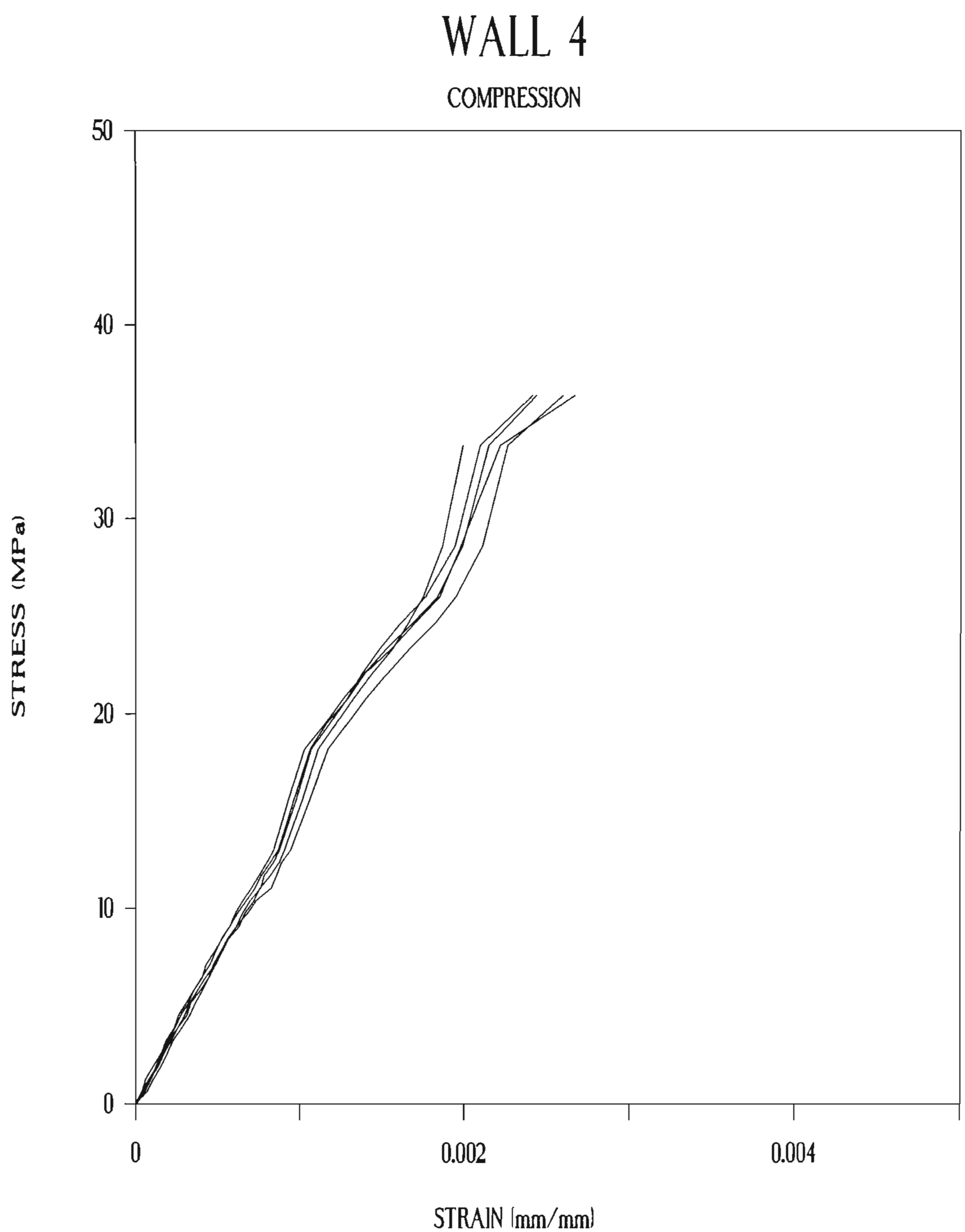


FIGURE A1.4 STRESS STRAIN CURVES - WALL4 PRISMS

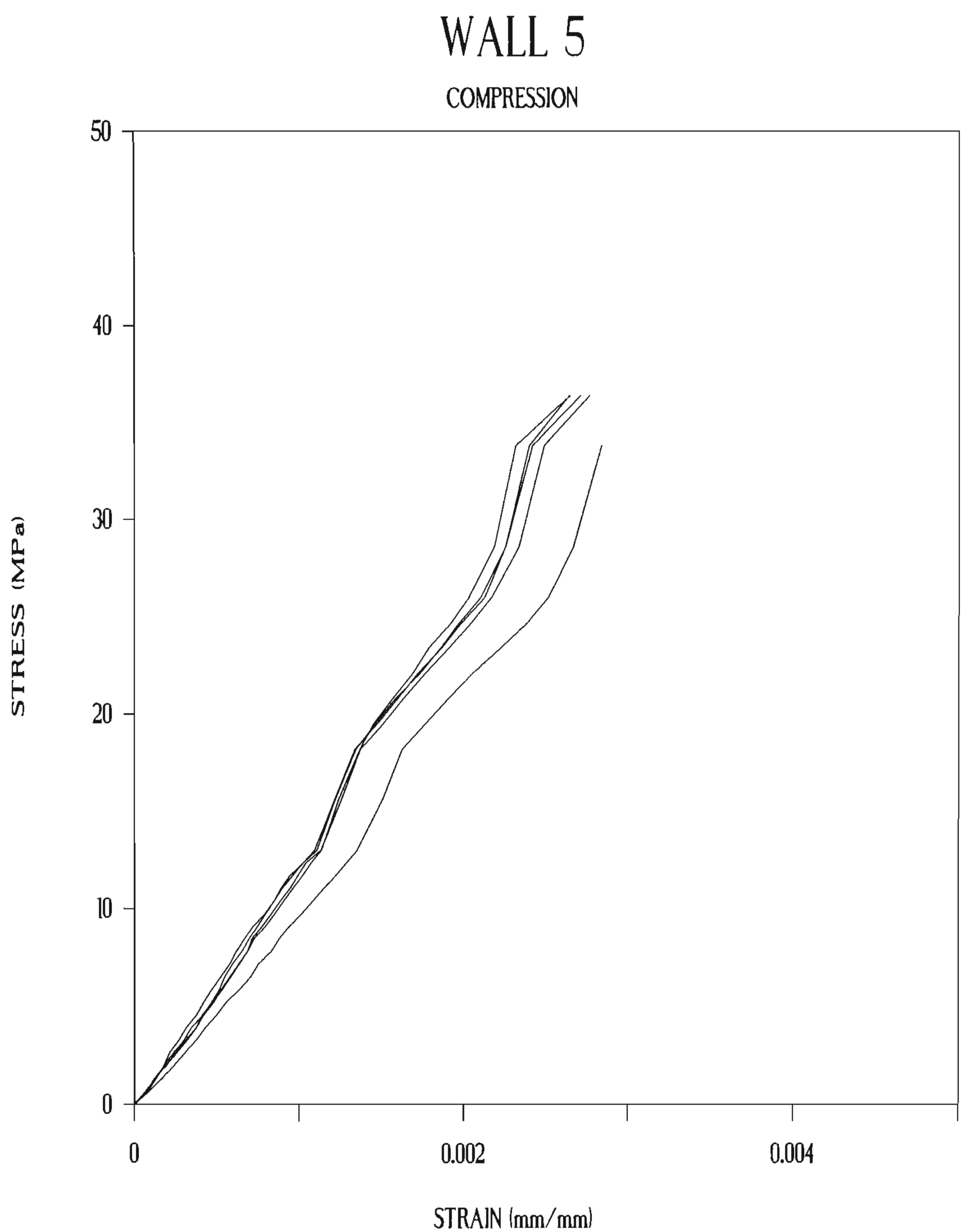
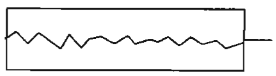


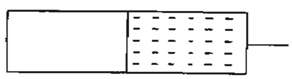
FIGURE A1.5 STRESS STRAIN CURVES - WALL5 PRISMS

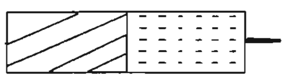
APPENDIX 2

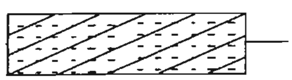
LEGEND FOR FOLLOWING FIGURES

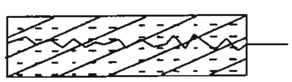

STRUCTURAL TEST ON UNCRACKED WALL WITH NO RAIN


STRUCTURAL TEST ON CRACKED WALL WITH NO RAIN


RAIN PENETRATION TEST ON INITIALLY DRY HALF WALL


RAIN PENETRATION TEST ON INITIALLY WET HALF WALL


RAIN PENETRAION TEST ON INITIALLY WET WHOLE WALL


RAIN PENETRATION TEST ON CRACKED WALL

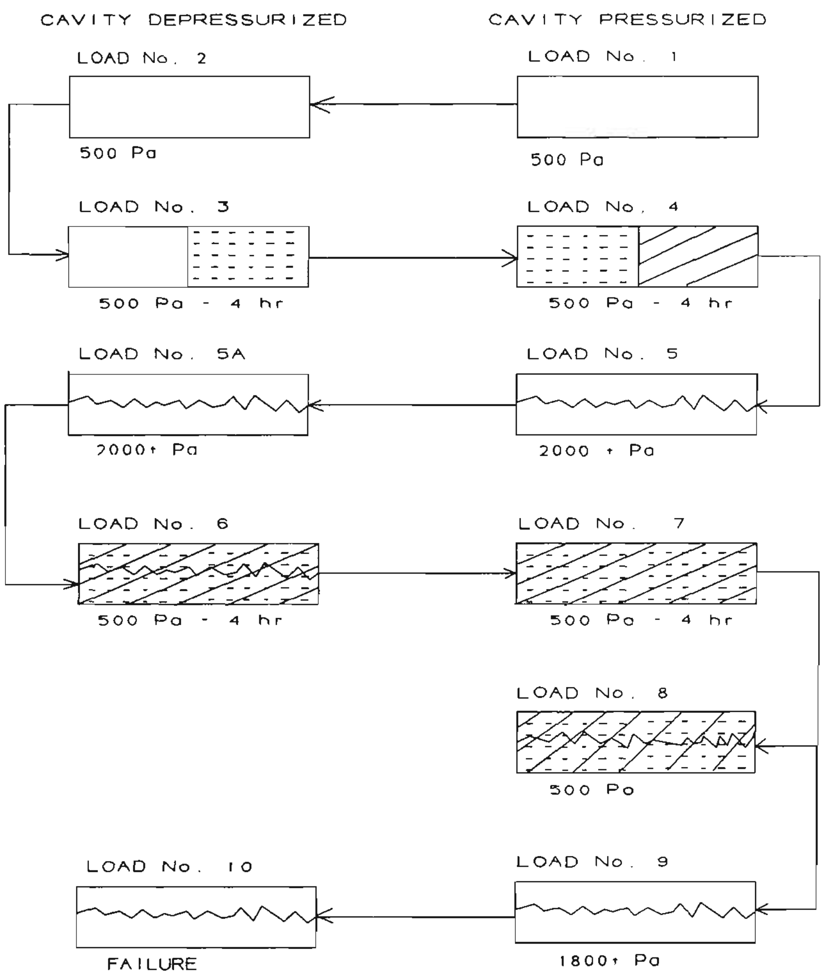


FIGURE A2.1 LOAD SEQUENCE FOR WALL1

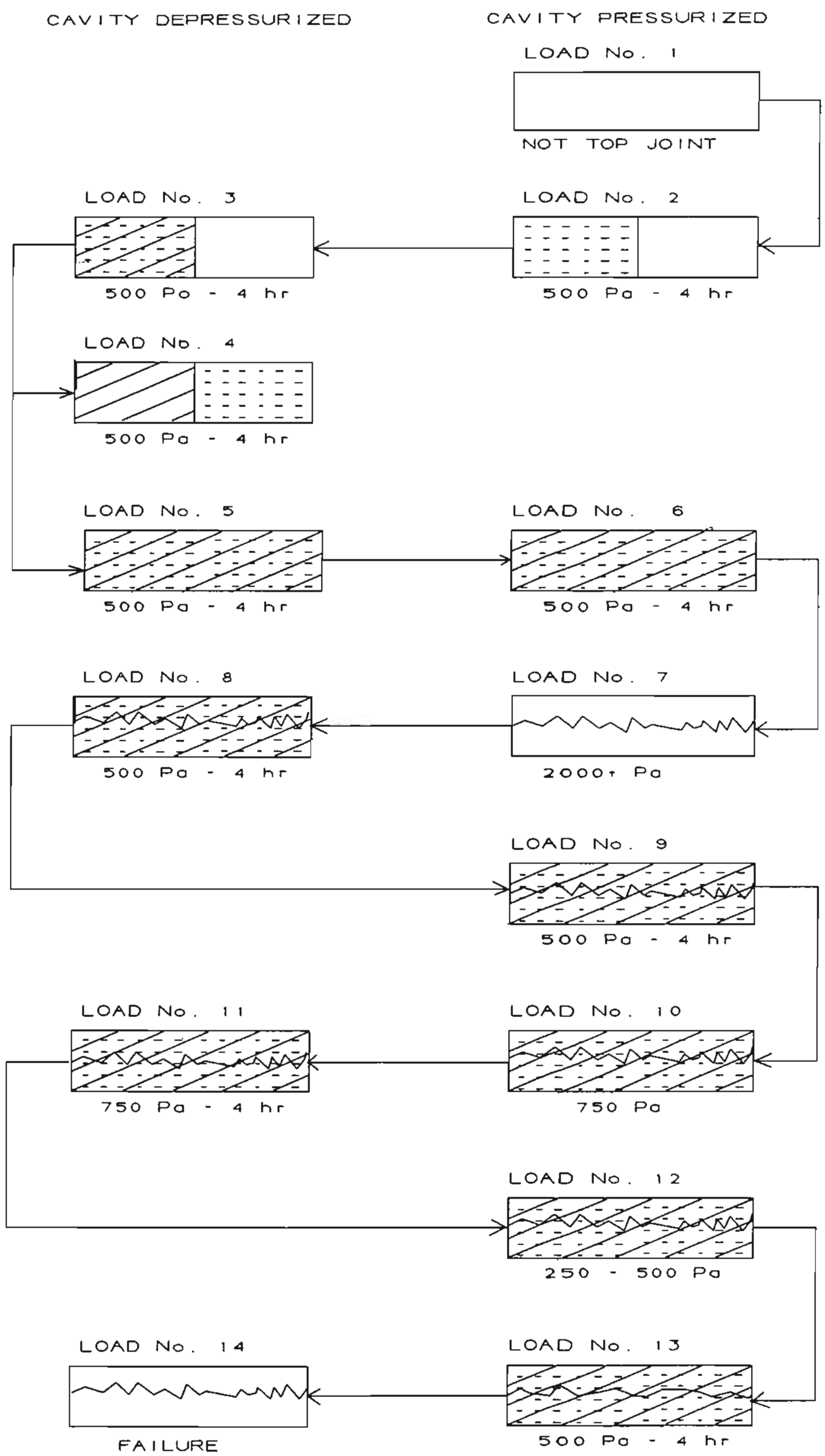


FIGURE A2.2 LOAD SEQUENCE FOR WALL2

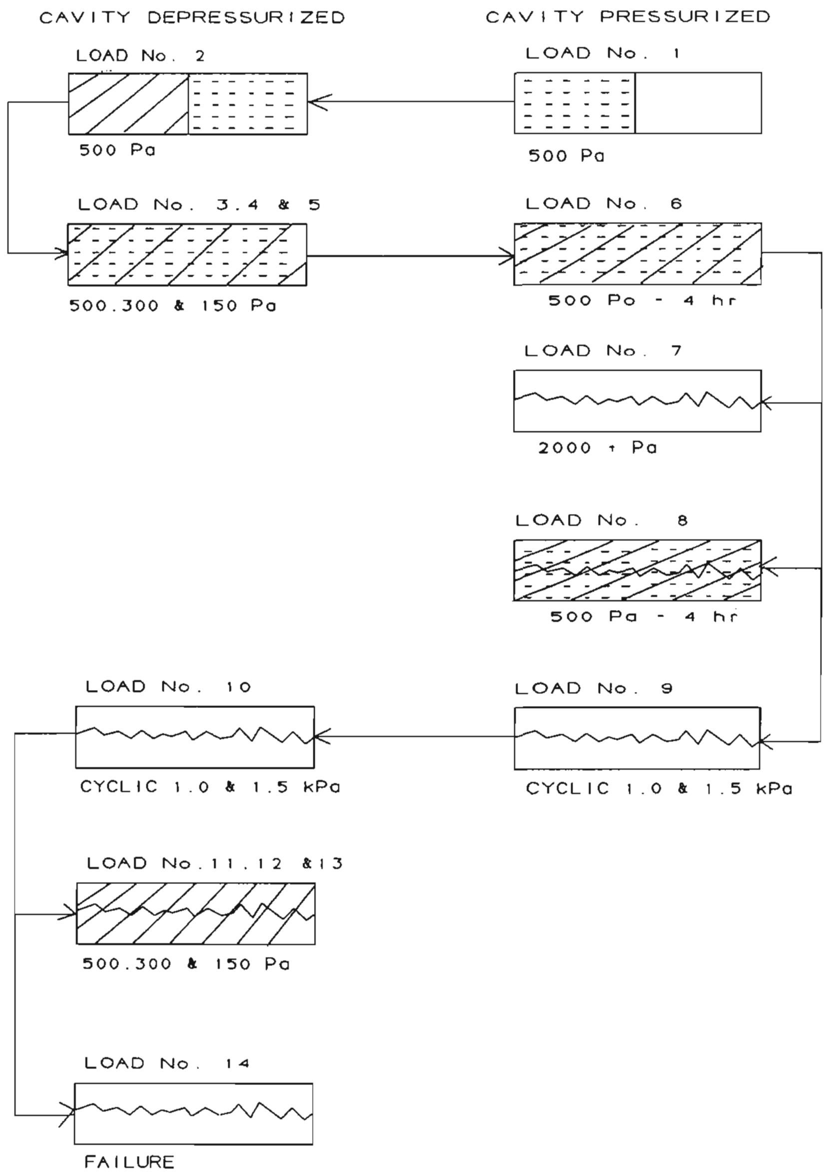


FIGURE A2.3 LOAD SEQUENCE FOR WALL3

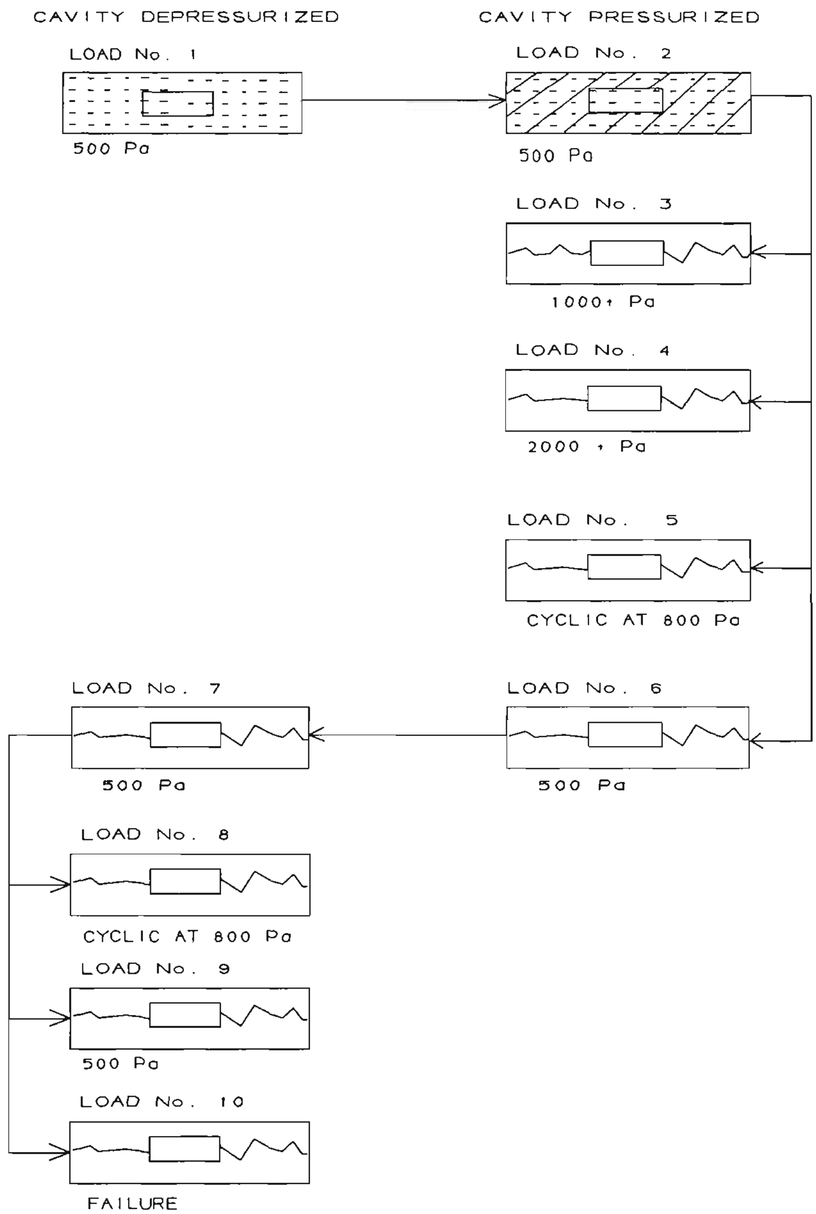


FIGURE A2.4 LOAD SEQUENCE FOR WALL4

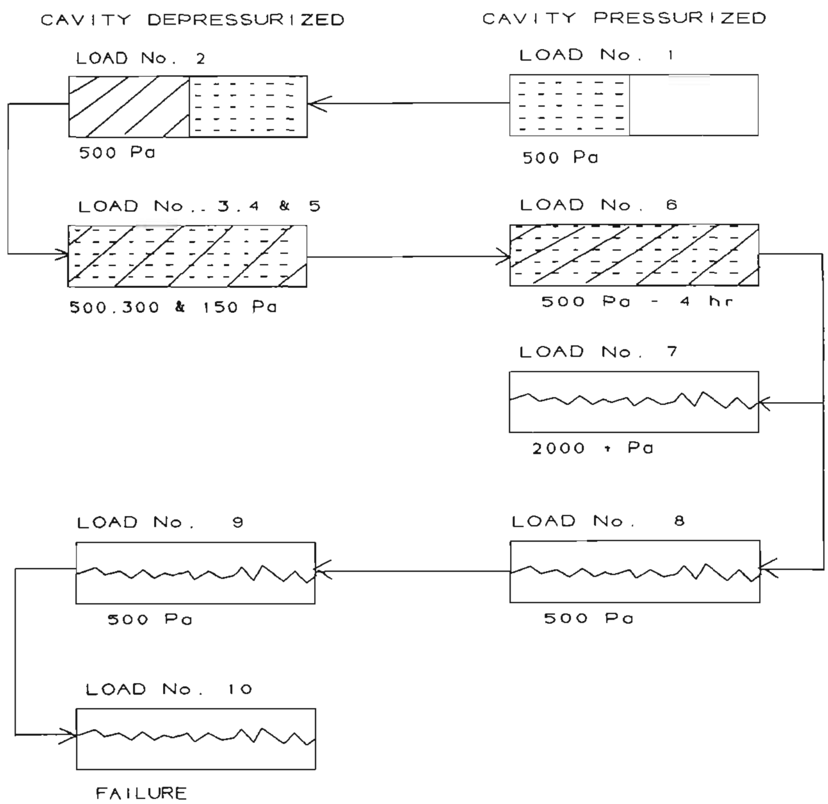


FIGURE A2.5 LOAD SEQUENCE FOR WALL5

APPENDIX 3

TABLE A3.1 RAIN PENETRATION DATA FOR WALL1

Loading 3.0 - Cavity Vented
left side of Wall
Exposed Area 6.6875 m^2 Initially Dry

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	499	50	449	0	0.0000
30	520	44	476	0	0.0000
60	529	46	483	0	0.0000
90	502	44	458	590	0.0029
120	512	43	470	870	0.0043
150	513	42	471	1540	0.0077
180	507	42	464	1420	0.0071
210	533	41	491	1450	0.0072
240	550	43	507	1420	0.0071

Loading 4.0 - Cavity Equalized
Whole Wall
Exposed Area 13.375 m^2 Right Half Initially Dry
Poor Air Barrier

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/sec /m^2)
0	507	50	457	0	0.0000
30	508	44	464	0	0.0000
60	517	46	471	0	0.0000
90	518	44	474	1025	0.0026
120	515	43	472	1132	0.0028
150	514	42	472	1119	0.0028
180	521	42	479	1120	0.0028
210	520	41	478	1115	0.0028
240	518	43	475	1000	0.0025

TABLE A3.1 - RAIN PENETRATION DATA FOR WALL1, continued.....

Loading 6.0 -

Cavity Vented
Whole Wall

Exposed Area 13.375

Initially Wet
Good Air Barrier

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min/m)
0	485	7	478	0	0.0000
30	490	3	488	4042	0.0101
60	494	41	454	4472	0.0111
90	537	33	504	6901	0.0172
120	544	37	508	6757	0.0168

Loading 7.0 -

Cavity Equalized
Whole Wall

Exposed Area 13.375

Initially Wet
Good Air Barrier

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min/m)
0	495	461	34	0	0.0000
30	539	502	37	1100	0.0027
60	534	509	25	1250	0.0031
90	528	497	31	1360	0.0034
120	231	203	28	1300	0.0032

TABLE A3.2 RAIN PENETRATION DATA FOR WALL2

Loading 2.0 - Cavity **Equalized**
top joint leakage
Exposed Area 6.7325 left side of wall
initially dry

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	496	473	23	0	0
30	486	464	22	0	0
60	483	462	21	380	0.0019
90	484	462	23	900	0.0045
120	484	460	24	820	0.0041
150	483	469	14	1250	0.0062
180	503	480	23	1500	0.0074
210	501	482	18	2250	0.0111
240	499	481	18	2260	0.0112

Loading 3.0 - Cavity Vented
top joint Leakage
Exposed Area 6.7325 left side of Wall
Initially Wet

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	516	294	221	0	
30	527	277	250	1900	0.0094
60	494	262	232	1650	0.0082
90	500	264	236	1485	0.0074
120	498	260	238	1425	0.0071
150	500	262	237	2000	0.0100
180	498	260	237	2020	0.0100
210	498	259	239	2740	0.0136
240	496	257	240	2875	0.0142

TABLE A3.2 - RAIN PENETRATION DATA FOR WALL2, continued.....

Loading 4.0 - Cavity Vented
ride side of wall
Exposed Area 6.7325 initially dry

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	507	227	280	0	0
30	519	200	319	350	0.0017
60	521	202	320	330	0.0016
90	522	201	320	570	0.0028
120	522	201	321	560	0.0028
150	520	202	318	620	0.0031
180	520	201	319	580	0.0029
210	524	201	323	690	0.0034
240	522	202	320	760	0.0038

Loading 5.0 - Cavity Vented
initially wet
Exposed Area 13.465 whole wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	515	125	391	0	0
30	510	101	410	1640	0.0041
60	509	100	409	1830	0.0045
90	511	99	412	1965	0.0049
120	509	100	409	2160	0.0053
150	511	98	413	1870	0.0046
180	511	99	412	2020	0.0050
210	510	100	410	1980	0.0049
240	508	100	408	2010	0.0050

TABLE A3.2 - RAIN PENETRATION DATA FOR WALL2, continued.....

Loading 6.0 -
Exposed Area 13.465

Cavity Equalization
initially wet
whole wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	511	490	21	0	0
30	500	488	11	60	0.0002
60	502	487	16	140	0.0003
90	502	486	16	250	0.0006
120	500	486	14	350	0.0009
150	499	485	14	340	0.0008
180	498	487	11	370	0.0009
210	499	483	16	370	0.0009
240	502	487	15	350	0.0009

Loading 8.0 -
Exposed Area 13.465

Cavity Vented
initially wet
whole wall
cracked wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	492	52	440	0	0
30	486	26	460	2690	0.0067
60	491	25	466	5950	0.0147
90	484	24	460	6030	0.0149
120	488	24	465	7110	0.0176
150	502	23	479	6350	0.0158
180	496	23	473	6260	0.0155
210	498	23	475	6700	0.0166
240	497	23	475	6670	0.0165

TABLE A3.2 - RAIN PENETRATION DATA FOR WALL2, continued.....

Loading 9.0 - Cavity Equalized
initially wet
whole wall
Exposed Area 13.465 cracked wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	501	491	10	0	0
30	513	500	13	40	0.0001
60	518	509	9	200	0.0005
90	515	503	12	210	0.0005
120	516	505	11	285	0.0007
150	515	503	12	420	0.0010
180	516	502	14	545	0.0013
210	512	497	14	680	0.0017
240	512	502	10	650	0.0016

Loading 10 - Cavity Equalized 15 psf
initially wet
whole wall
Exposed Area 13.465 cracked wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	729	708	21	0	0
30	722	699	23	820	0.0020
60	720	700	20	870	0.0022
90	719	700	19	840	0.0021
120	723	701	22	830	0.0021

Loading 11 - Cavity Equalized 15 psf
initially wet
whole wall
Exposed Area 13.465 cracked wall
cavity not comparted

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	692	613	78	0	0
30	666	551	115	1840	0.0046
60	661	546	115	1750	0.0043
90	662	548	114	1820	0.0045
120	661	547	115	1780	0.0044

TABLE A3.2 - RAIN PENETRATION DATA FOR WALL2, continued.....

Loading 12 - Cavity Equalized 10 & 5 psf
initially wet
whole wall
Exposed Area 13.465 cracked wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	0	0	0	0	0
60	498	491	7	0	0
120	542	530	12	580	0.0007
180	539	519	20	730	0.0009
240	541	522	19	750	0.0009

Loading 13 - Cavity Equalized
initially wet
whole wall
Exposed Area 13.465 cracked wall

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	0	0	0	0	0
30	510	505	4	0	0
60	525	503	22	0	0
90	524	511	14	0	0
120	526	505	22	20	0.0001
150	522	509	13	120	0.0003
180	522	509	13	220	0.0005
300	518	505	13	1400	0.0009
390	519	505	14	1100	0.0009

TABLE A3.3 RAIN PENETRATION DATA FOR WALL3

Loading 1.0 - Cavity Equalized
left side of wall
Exposed Area 6.7325 initially dry

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	514	458	56	0	0
30	513	447	66	0	0
60	514	454	60	0	0
90	523	463	60	0	0
120	523	463	60	0	0
150	524	464	60	0	0
180	520	461	59	0	0
210	520	459	62	0	0
240	520	459	62	0	0
0	0	0	0	0	0

Wall #3.0 Loading 2.0 - Cavity Vented
left side of Wall
Exposed Area 6.7325 Initially Wet

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	518	1	517	0	0.0000
30	524	0	524	160	0.0008
60	519	0	519	420	0.0021
90	518	0	517	440	0.0022
120	519	0	518	560	0.0028
150	516	0	516	580	0.0029
180	521	0	521	580	0.0029
210	517	0	517	600	0.0030
240	517	0	517	600	0.0030

TABLE A3.3 - RAIN PENETRATION DATA FOR WALL3, continued.....

Loading 3,4 & 5 - Cavity Vented whole wall

Exposed Area 13.465 initially WET

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	524	0	524	0	0.0000
30	505	0	505	610	0.0015
60	510	0	510	1330	0.0033
90	510	4	505	1320	0.0033
120	510	6	504	1250	0.0031
150	511	7	504	1310	0.0032
180	510	7	503	1380	0.0034
210	529	7	522	1270	0.0031
240	510	8	502	1290	0.0032
30	301	8	293	720	0.0018
60	304	8	296	480	0.0012
90	299	8	291	480	0.0012
120	300	8	291	460	0.0011
150	302	8	294	510	0.0013
180	301	5	297	440	0.0011
210	304	5	299	460	0.0011
240	304	5	299	480	0.0012
30	156	0	156	450	0.0011
60	154	0	154	400	0.0010
90	152	0	152	360	0.0009
120	154	0	154	380	0.0009
150	154	0	154	340	0.0008
180	154	1	153	350	0.0009
210	149	2	147	340	0.0008
240	149	2	147	360	0.0009

Wall #3.0 Loading 6.0 - Cavity Equalization whole wall

Exposed Area 13.465 initially wet

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	517	493	24	0	0.0000
30	520	500	20	210	0.0005
60	520	500	19	320	0.0008
90	521	501	20	300	0.0007
120	522	502	20	280	0.0007
150	523	502	21	260	0.0006
180	521	501	20	260	0.0006
210	523	501	21	250	0.0006
240	522	502	20	260	0.0006

TABLE A3.3 - RAIN PENETRATION DATA FOR WALL3, continued.....

Loading 10 - Cavity Equalized, whole wall, initially wet, cracked wall

Exposed Area 13.465

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	514	484	30	0	0.0000
30	516	490	26	80	0.0002
60	519	489	30	80	0.0002
90	520	490	30	120	0.0003
120	519	492	27	160	0.0004
150	521	492	29	180	0.0004
180	520	489	31	210	0.0005
210	518	489	29	200	0.0005
240	522	493	29	220	0.0005

Loading 11 - Cavity Vented, whole wall, initially wet, cracked wall

Exposed Area 13.465

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	527	12	515	0	0.0000
30	538	19	519	1280	0.0032
60	511	23	488	2100	0.0052
90	512	22	490	2400	0.0059
120	524	24	500	3300	0.0082
150	532	26	506	3600	0.0089
180	527	27	500	3500	0.0087
210	526	27	499	3600	0.0089
240	538	28	511	3500	0.0087
30	367	27	340	2700	0.0067
60	345	27	319	2400	0.0059
90	330	27	303	2000	0.0050
120	325	25	300	2100	0.0052
150	327	26	301	2000	0.0050
180	331	25	305	1920	0.0048
210	332	25	306	2100	0.0052
240	337	27	310	2000	0.0050
30	166	17	149	1300	0.0032
60	164	16	149	1220	0.0030
90	166	18	148	1140	0.0028
120	165	17	148	1050	0.0026
150	165	19	147	1100	0.0027
180	161	19	142	1120	0.0028
210	161	16	145	1050	0.0026
240	161	16	145	1200	0.0030

TABLE A3.4 RAIN PENETRATION DATA FOR WALL4

Wall #4.0 Loading 1.0 - Cavity Vented whole wall

Exposed Area 9.6257 initially dry

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	514	10	504	0	0.0000
30	511	11	501	900	0.0031
60	510	11	499	1500	0.0052
90	515	10	505	2250	0.0078
120	521	11	510	2400	0.0083
150	520	11	509	2350	0.0081
180	524	12	512	2500	0.0087
210	519	11	508	2400	0.0083
240	520	12	508	2550	0.0088

Wall #4.0 Loading 2.0 - Cavity Equalized whole wall

Exposed Area 9.6257 Initially Wet

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	519	461	58	0	0.0000
30	515	461	54	120	0.0004
60	512	455	57	650	0.0023
90	515	458	57	550	0.0019
120	519	468	51	790	0.0027
150	519	468	51	580	0.0020
180	519	470	49	700	0.0024
210	520	468	52	650	0.0023
240	521	476	45	700	0.0024

TABLE A3.5 RAIN PENETRATION DATA FOR WALL5

TABLE A3.5 - RAIN PENETRATION DATA FOR WALL5

Loading 1.0 - Cavity Equalized
left side of wall
Exposed Area 6.6875 initially dry

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	510	304	219	0	0
30	516	297	219	0	0
60	513	295	221	0	0
90	514	293	218	0	0
120	512	294	218	0	0
150	513	294	219	0	0
180	512	294	219	0	0
210	512	294	217	0	0
240	508	291	217	0	0

Loading 2.0 - Cavity Vented
left side of Wall
Exposed Area 6.6875 Initially Wet

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	511	7	504	0	0.0000
30	505	5	500	0	0.0000
60	504	5	498	90	0.0004
90	504	5	499	140	0.0007
120	502	5	496	280	0.0014
150	497	5	491	410	0.0020
180	498	5	493	380	0.0019
210	499	5	494	400	0.0020
240	520	6	514	420	0.0021

TABLE A3.5 - RAIN PENETRATION DATA FOR WALL5, continued.....

Loading 3,4 & 5 - Cavity Vented whole wall

Exposed Area 13.465 initially WET

Time (min)	Pressure (Pa) Load	Cavity	Difference	Cavity Water (ml)	Flow (l/min /m^2)
0	509	6	504	0	0.0000
30	510	4	506	130	0.0003
60	508	4	504	260	0.0006
90	504	4	500	370	0.0009
120	510	4	507	540	0.0013
150	509	4	505	600	0.0015
180	508	4	505	690	0.0017
210	517	4	513	790	0.0020
240	513	5	509	780	0.0019
270	515	5	510	810	0.0020
30	511	4	507	420	0.0010
60	326	3	323	360	0.0009
90	314	3	311	320	0.0008
120	320	3	318	330	0.0008
150	315	3	313	340	0.0008
180	316	2	314	330	0.0008
210	322	2	319	340	0.0008
240	323	3	320	320	0.0008
30	148	1	147	230	0.0006
60	153	2	151	160	0.0004
90	162	2	161	190	0.0005
120	160	1	159	220	0.0005
150	158	2	157	210	0.0005
180	155	2	154	200	0.0005
210	163	2	161	190	0.0005
240	158	1	157	210	0.0005

APPENDIX 4

TABLE A4.1 DISPLACEMENT DATA FOR WALL1: BACKUP PANEL

	WALL LOCATION		RESIDUAL (mm)	RECORDED (mm)	DELTA RESIDUAL (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0.000	0.000	0.025	0.000	0.025	504.635	0.025
CE		0.250	0.000	0.508	0.000	0.508		0.503
		0.500	0.000	0.508	0.000	0.508		0.503
		0.750	0.000	0.483	0.000	0.483		0.478
		1.000	0.000	0.127	0.000	0.127		0.126
LOADING	2	0.000	0.025	0.076	0.025	0.051	521.926	0.049
CV		0.250	0.025	0.559	0.025	0.533		0.511
		0.500	0.102	0.686	0.102	0.584		0.560
		0.750	0.102	0.686	0.102	0.584		0.560
		1.000	0.051	0.254	0.051	0.203		0.195
LOADING	3	0.000	0.076	0.102	0.051	0.025	520.005	0.024
CV		0.250	0.076	0.533	0.051	0.457		0.440
		0.500	0.229	0.737	0.127	0.508		0.488
		0.750	0.279	0.686	0.178	0.406		0.391
		1.000	0.178	0.254	0.127	0.076		0.073
LOADING	4	0.000	0.254	0.305	0.178	0.051	507.197	0.050
CE		0.250	0.102	0.610	0.025	0.508		0.501
		0.500	0.305	0.864	0.076	0.559		0.551
		0.750	0.330	0.787	0.051	0.457		0.451
		1.000	0.203	0.330	0.025	0.127		0.125
LOADING	5	0.000	0.330	0.330	0.076	0.000	525.380	0.000
CE		0.250	0.356	0.737	0.254	0.381		0.363
		0.500	0.356	0.940	0.051	0.584		0.556
		0.750	0.330	0.914	0.000	0.584		0.556
		1.000	0.203	0.330	0.000	0.127		0.121
LOADING	5	0.000	0.406	0.432	0.076	0.025	519.977	0.024
CV		0.250	0.813	1.473	0.457	0.660		0.635
CRACKING		0.500	1.168	2.083	0.813	0.914		0.879
		0.750	1.321	2.210	0.991	0.889		0.855
		1.000	1.016	1.270	0.813	0.254		0.244
LOADING	6	0.000	0.584	0.584	0.178	0.000	537.296	0.000
CV		0.250	1.575	2.362	0.762	0.787		0.733
CRACKED		0.500	2.159	3.277	0.991	1.118		1.040
		0.750	2.438	3.454	1.118	1.016		0.945
		1.000	1.854	2.134	0.838	0.279		0.260
LOADING	7	0.000	0.533	0.584	-0.051	0.051	495.029	0.051
CE		0.250	1.575	2.337	0.000	0.762		0.770
CRACKED		0.500	2.184	3.277	0.025	1.092		1.103
		0.750	2.489	3.505	0.051	1.016		1.026
		1.000	1.854	2.159	0.000	0.305		0.308
LOADING	8	0.000	0.584	0.610	0.051	0.026	492.980	0.026
CE		0.250	1.600	2.311	0.025	0.711		0.721
CRACKED		0.500	2.311	3.327	0.127	1.016		1.030
		0.750	2.667	3.607	0.178	0.940		0.953
		1.000	1.880	2.159	0.026	0.279		0.283
LOADING	9	0.000	0.559	0.584	-0.025	0.025	401.531	0.031
CE		0.250	1.640	2.230	0.040	0.590		0.735
ULTIMATE		0.500	2.388	3.200	0.077	0.812		1.011
		0.750	2.769	3.505	0.102	0.736		0.916
		1.000	1.905	2.108	0.025	0.203		0.253
LOADING	10	0	0.254	0.279	-0.305	0.025	578.665	0.022
CV		0.250	1.700	2.650	0.060	0.950		0.821
ULTIMATE		0.500	3.853	5.182	1.465	1.329		1.148
		0.750	4.953	6.147	2.184	1.194		1.032
		1.000	1.981	2.362	0.076	0.381		0.329

TABLE A4.2 DISPLACEMENT DATA FOR WALL1: VENEER PANEL

		WALL LOCATION	RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0	0.000	0.000	0.000	0.000	504.635	0.000
CE		0.25	0.000	0.000	0.229	0.229		0.227
		0.5	0.000	0.000	0.457	0.457		0.453
		0.75	0.000	0.000	0.432	0.432		0.428
		1	0.000	0.000	0.254	0.254		0.252
LOADING	2	0	0.000	0.000	0.000	0.000	521.926	0.000
CV		0.25	0.051	0.051	0.533	0.483		0.462
		0.5	0.102	0.102	0.914	0.813		0.779
		0.75	0.102	0.102	0.864	0.762		0.730
		1	0.051	0.051	0.432	0.381		0.365
LOADING	3	0	0.000	0.000	0.000	0.000	520.005	0.000
CV		0.25	0.076	0.025	0.584	0.508		0.488
		0.5	0.152	0.051	0.965	0.813		0.782
		0.75	0.076	-0.025	0.813	0.737		0.708
		1	0.102	0.051	0.508	0.406		0.391
LOADING	4	0	0.000	0.000	0.000	0.000	507.197	0.000
CE		0.25	0.254	0.178	0.559	0.305		0.300
		0.5	0.483	0.330	0.965	0.483		0.476
		0.75	0.457	0.381	0.889	0.432		0.426
		1	0.229	0.127	0.508	0.279		0.275
LOADING	5	0	0.000	0.000	0.000	0.000	525.380	0.000
CE		0.25	0.254	0.000	0.559	0.305		0.290
		0.5	0.508	0.025	1.041	0.533		0.508
		0.75	0.457	0.000	0.889	0.432		0.411
		1	0.279	0.051	0.559	0.279		0.266
LOADING	5A	0	0.000	0.000	0.000	0.000	519.977	0.000
CV		0.25	1.016	0.762	1.727	0.711		0.684
		0.5	1.397	0.889	2.362	0.965		0.928
		0.75	1.473	1.016	2.337	0.864		0.830
		1	1.499	1.219	1.854	0.356		0.342
LOADING	6	0	0.000	0.000	0.000	0.000	537.296	0.000
CV		0.25	1.143	0.127	2.032	0.889		0.827
		0.5	2.286	0.889	3.505	1.219		1.135
		0.75	2.565	1.092	3.708	1.143		1.064
		1	2.184	0.686	2.997	0.813		0.756
LOADING	7	0	0.000	0.000	0.000	0.000	495.029	0.000
CE		0.25	1.270	0.127	1.880	0.610		0.616
		0.5	2.667	0.381	3.581	0.914		0.924
		0.75	2.642	0.076	3.454	0.813		0.821
		1	2.235	0.051	2.794	0.559		0.564
LOADING	8	0	0.000	0.000	0.000	0.000	492.980	0.000
CE		0.25	1.270	0.000	2.159	0.889		0.902
		0.5	2.642	-0.025	3.023	0.381		0.386
		0.75	2.743	0.102	3.556	0.813		0.824
		1	2.286	0.051	2.819	0.533		0.541
LOADING	9	0	0.000	0.000	0.000	0.000	401.531	0.000
CE		0.25	1.651	0.381	2.591	0.940		1.170
		0.5	2.642	0.000	3.251	0.610		0.759
		0.75	2.819	0.076	3.785	0.965		1.202
		1	2.337	0.051	2.946	0.610		0.759
LOADING	10	0	0.000	0.000	0.000	0.000	578.665	0.000
CV		0.25	1.829	0.178	3.200	1.372		1.185
		0.5	2.972	0.330	4.242	1.270		1.097
		0.75	2.972	0.152	4.242	1.270		1.097
		1	2.388	0.051	3.327	0.940		0.812

TABLE A4.3 DISPLACEMENT DATA FOR WALL2: BACKUP PANEL

	WALL LOCATION	RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING 1	0	0.000	0.000	0.051	0.051	510.527	0.050
CE NO TOP	0.25	0.000	0.000	0.860	0.860		0.842
JOINT	0.5	0.000	0.000	1.040	1.040		1.019
	0.75	0.000	0.000	0.910	0.910		0.891
	1	0.000	0.000	0.203	0.203		0.199
LOADING 2	0	0.051	0.051	0.076	0.025	495.670	0.026
CE TOP	0.25	0.140	0.140	0.980	0.840		0.847
JOINT	0.5	0.170	0.170	1.120	0.950		0.958
INSTALLED	0.75	0.110	0.110	0.960	0.850		0.857
	1	0.025	0.025	0.229	0.203		0.205
LOADING 3	0	0.102	0.051	0.178	0.060	515.500	0.058
CV	0.25	0.630	0.490	1.420	0.790		0.766
	0.5	0.770	0.600	1.800	1.010		0.980
	0.75	0.550	0.440	1.390	0.840		0.815
	1	0.152	0.127	0.305	0.152		0.148
LOADING 4	0	0.127	0.025	0.152	0.025	506.500	0.025
CV	0.25	0.810	0.180	1.540	0.730		0.721
	0.5	1.090	0.310	2.080	0.990		0.977
	0.75	0.780	0.230	1.570	0.790		0.780
	1	0.178	0.025	0.305	0.127		0.125
LOADING 5	0	0.127	0.000	0.178	0.051	501.200	0.051
CV	0.25	0.890	0.150	1.610	0.720		0.718
	0.5	1.260	0.310	2.270	0.980		0.978
	0.75	0.890	0.170	1.700	0.810		0.808
	1	0.178	0.000	0.330	0.152		0.152
LOADING 6	0	0.152	0.025	0.229	0.076	504.600	0.076
CE	0.25	0.970	0.010	1.840	0.870		0.862
	0.5	1.420	0.030	2.430	1.010		1.001
	0.75	1.000	0.050	1.890	0.890		0.882
	1	0.203	0.025	0.381	0.178		0.176
LOADING 7	0	0.203	0.051	0.254	0.051	480.800	0.053
CV	0.25	1.120	0.150	1.800	0.680		0.707
cracking	0.5	1.540	0.120	2.470	0.930		0.967
	0.75	1.100	0.100	1.850	0.750		0.780
	1	0.254	0.051	0.381	0.127		0.132
LOADING 8	0	0.203	0.000	0.254	0.051	492.083	0.052
CV	0.25	1.370	0.250	2.110	0.740		0.752
cracked	0.5	1.910	0.470	2.970	1.060		1.077
	0.75	1.460	0.360	2.300	0.840		0.854
	1	0.356	0.102	0.508	0.152		0.155
LOADING 9	0	0.203	0.000	0.279	0.076	501.305	0.076
& 10, 11	0.25	1.480	0.110	2.390	0.910		0.908
CE	0.5	2.050	0.040	3.180	1.130		1.127
cracked	0.75	1.610	0.150	2.610	1.000		0.997
	1	0.381	0.025	0.610	0.229		0.228
LOADING 12	0	0.254	0.051	0.538	0.284	497.719	0.285
CE	0.25	1.800	0.320	2.650	0.850		0.854
cracked	0.5	2.470	0.420	3.500	1.030		1.035
	0.75	1.910	0.300	2.850	0.940		0.944
	1	0.457	0.076	0.636	0.179		0.180
LOADING 13	0	0.321	0.067	0.388	0.067	509.502	0.066
CE	0.25	1.980	0.180	2.750	0.770		0.756
cracked	0.5	2.750	0.280	3.760	1.010		0.991
	0.75	2.110	0.200	3.080	0.970		0.952
	1	0.483	0.026	0.610	0.127		0.125
LOADING 15	0	0.354	0.033	0.416	0.062	508.425	0.061
CV	0.25	2.210	0.230	2.910	0.700		0.688
ultimate	0.5	3.190	0.440	4.170	0.980		0.964
	0.75	2.530	0.420	3.380	0.850		0.836
	1	0.432	-0.051	0.636	0.204		0.201

TABLE A4.4 DISPLACEMENT DATA FOR WALL2 : VENEER PANEL

	WALL LOCATION	RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING 1	0	0.000	0.000	0.102	0.102	510.527	0.100
CE NO TOP	0.25	0.000	0.000	0.381	0.381		0.373
JOINT	0.5	0.000	0.000	0.729	0.729		0.714
	0.75	0.000	0.000	0.849	0.849		0.832
	1	0.000	0.000	0.986	0.986		0.965
LOADING 2	0	0.000	0.000	0.076	0.076	495.670	0.077
CE TOP	0.25	0.051	0.051	0.381	0.330		0.333
JOINT	0.5	0.076	0.076	0.660	0.584		0.589
INSTALLED	0.75	0.051	0.051	0.737	0.686		0.692
	1	0.127	0.127	0.762	0.635		0.641
LOADING 3	0	0.025	0.025	0.152	0.127	515.500	0.123
CV	0.25	0.229	0.178	0.737	0.508		0.493
	0.5	0.457	0.381	1.321	0.864		0.838
	0.75	0.406	0.356	1.372	0.965		0.936
	1	0.229	0.102	1.118	0.889		0.862
LOADING 4	0	0.025	-0.000	0.229	0.203	506.500	0.201
CV	0.25	0.406	0.178	1.041	0.635		0.627
	0.5	0.559	0.102	1.626	1.067		1.053
	0.75	0.508	0.102	1.651	1.143		1.128
	1	0.559	0.330	1.524	0.965		0.953
LOADING 5	0	0.076	0.051	0.279	0.203	515.394	0.197
CV	0.25	0.559	0.152	1.219	0.660		0.641
	0.5	0.787	0.229	1.905	1.118		1.084
	0.75	0.711	0.203	1.905	1.194		1.158
	1	0.762	0.203	1.753	0.991		0.961
LOADING 6	0	0.102	0.025	0.254	0.152	511.423	0.149
CE	0.25	0.711	0.152	1.194	0.483		0.472
	0.5	1.041	0.254	1.880	0.838		0.819
	0.75	0.914	0.203	1.829	0.914		0.894
	1	0.914	0.152	1.626	0.711		0.695
LOADING 7	0	0.127	0.025	0.330	0.203	501.100	0.203
CV	0.25	0.813	0.102	1.473	0.660		0.659
cracking	0.5	1.245	0.203	2.362	1.118		1.115
	0.75	1.092	0.178	2.286	1.194		1.191
	1	1.067	0.152	2.134	1.067		1.064
LOADING 8	0	0.229	0.102	0.457	0.229	492.083	0.232
CV	0.25	1.143	0.330	1.956	0.813		0.826
cracked	0.5	1.778	0.533	3.200	1.422		1.445
	0.75	1.524	0.432	2.870	1.346		1.368
	1	1.321	0.254	2.540	1.219		1.239
LOADING 9	0	0.229	0.000	0.356	0.127	501.305	0.127
& 10 ,11	0.25	1.194	0.051	1.702	0.508		0.507
CE	0.5	1.829	0.051	2.718	0.889		0.887
cracked	0.75	1.575	0.051	2.464	0.889		0.887
	1	1.346	0.025	2.184	0.838		0.836
LOADING 12	0	0.229	0.000	0.428	0.199	497.719	0.200
CE	0.25	1.321	0.127	1.651	0.330		0.332
cracked	0.5	1.981	0.152	3.070	1.089		1.094
	0.75	1.778	0.203	2.733	0.955		0.959
	1	1.473	0.127	2.339	0.866		0.870
LOADING 13	0	0.297	0.068	0.504	0.207	509.502	0.203
CE	0.25	1.397	0.076	2.134	0.737		0.723
cracked	0.5	1.981	0.000	3.342	1.361		1.336
	0.75	2.160	0.382	3.307	1.147		1.126
	1	1.677	0.204	2.644	0.967		0.949
LOADING 15	0	0.366	0.069	0.607	0.241	508.425	0.237
CV	0.25	1.981	0.584	2.591	0.610		0.600
ultimate	0.5	2.435	0.454	3.887	1.452		1.428
	0.75	2.351	0.191	3.689	1.338		1.316
	1	1.880	0.203	3.000	1.120		1.101

TABLE A4.5 DISPLACEMENT DATA FOR WALL3: BACKUP PANEL

	WALL LOCATION		RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0	0.000	0.000	0.000	0.000	506.000	0.000
CE		0.25	0.000	0.000	0.483	0.483		0.477
		0.5	0.000	0.000	0.711	0.711		0.703
		0.75	0.000	0.000	0.432	0.432		0.427
		1	0.000	0.000	0.025	0.025		0.025
LOADING	2	0	0.000	0.000	0.000	0.000	518.000	0.000
CV		0.25	0.025	0.025	0.483	0.458		0.442
		0.5	0.051	0.051	0.635	0.584		0.564
		0.75	0.025	0.025	0.356	0.331		0.319
		1	0.000	0.000	0.025	0.025		0.024
LOADING	3	0	0.000	0.000	0.000	0.000	524.000	0.000
CV		0.25	0.051	0.026	0.483	0.432		0.412
		0.5	0.102	0.051	0.711	0.609		0.581
		0.75	0.051	0.026	0.406	0.355		0.339
		1	0.000	0.000	0.025	0.025		0.024
LOADING	5	0	0.000	0.000	0.000	0.000	519.000	0.000
CV		0.25	0.051	0.000	0.483	0.432		0.416
		0.5	0.102	0.000	0.737	0.635		0.612
		0.75	0.051	0.000	0.381	0.330		0.318
		1	0.000	0.000	0.025	0.025		0.024
LOADING	6	0	0.000	0.000	0.000	0.000	517.000	0.000
CE		0.25	0.051	0.000	0.533	0.482		0.466
		0.5	0.127	0.025	0.864	0.737		0.713
		0.75	0.051	0.000	0.457	0.406		0.393
		1	0.000	0.000	0.025	0.025		0.024
LOADING	7	0	0.000	0.000	0.051	0.051	582.000	0.044
CE		0.25	0.076	0.025	0.635	0.559		0.480
cracking		0.5	0.152	0.025	0.914	0.762		0.655
		0.75	0.051	0.000	0.559	0.508		0.436
		1	0.000	0.000	0.051	0.051		0.044
LOADING	8	0	0.000	0.000	0.025	0.025	514.000	0.024
CE		0.25	0.076	0.000	0.725	0.649		0.631
cracked		0.5	0.152	0.000	1.067	0.915		0.890
		0.75	0.051	0.000	0.615	0.564		0.549
		1	0.000	0.000	0.025	0.025		0.024
LOADING	11	0	0.025	0.025	0.025	0.000	527.000	0.000
CV		0.25	0.178	0.102	0.813	0.635		0.602
cracked		0.5	0.254	0.102	1.016	0.762		0.723
		0.75	0.178	0.127	0.711	0.533		0.506
		1	0.000	0.000	0.051	0.051		0.048
LOADING	14	0	0.025	0.000	0.051	0.026	526.000	0.025
CV		0.25	0.178	0.000	0.711	0.533		0.507
ultimate		0.5	0.254	0.000	0.889	0.635		0.604
		0.75	0.178	0.000	0.508	0.330		0.314
		1	0.000	0.000	0.000	0.000		0.000

TABLE A4.6 DISPLACEMENT DATA FOR WALL3: VENEER PANEL

	WALL LOCATION		RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING CE	1	0	0.000	0.000	0.076	0.076	506.000	0.075
		0.25	0.000	0.000	0.356	0.356		0.352
		0.5	0.000	0.000	0.508	0.508		0.502
		0.75	0.000	0.000	0.559	0.559		0.552
		1	0.000	0.000	0.584	0.584		0.577
LOADING CV	2	0	0.000	0.000	0.127	0.127	518.000	0.123
		0.25	0.000	0.000	0.406	0.406		0.392
		0.5	0.025	0.025	0.686	0.661		0.638
		0.75	0.051	0.051	0.762	0.711		0.686
		1	0.025	0.025	0.762	0.737		0.711
LOADING CV	3	0	0.000	0.000	0.127	0.127	524.000	0.121
		0.25	0.051	0.051	0.432	0.381		0.364
		0.5	0.025	0.000	0.686	0.661		0.631
		0.75	0.102	0.051	0.864	0.762		0.727
		1	0.076	0.051	0.914	0.838		0.800
LOADING CV	5	0	0.000	0.000	0.102	0.102	519.000	0.098
		0.25	0.051	0.000	0.381	0.330		0.318
		0.5	0.025	0.000	0.635	0.610		0.588
		0.75	0.102	0.000	0.838	0.736		0.709
		1	0.076	0.000	0.889	0.813		0.783
LOADING CE	6	0	0.025	0.025	0.051	0.026	517.000	0.025
		0.25	0.051	0.000	0.381	0.330		0.319
		0.5	0.025	0.000	0.533	0.508		0.491
		0.75	0.102	0.000	0.635	0.533		0.515
		1	0.102	0.026	0.640	0.538		0.520
LOADING CE cracking	7	0	0.025	0.000	0.025	0.000	582.000	0.000
		0.25	0.051	0.000	0.483	0.432		0.371
		0.5	0.025	0.000	0.635	0.610		0.524
		0.75	0.102	0.000	0.711	0.609		0.523
		1	0.102	0.000	0.762	0.660		0.567
LOADING CE cracked	8	0	0.025	0.000	0.102	0.077	514.000	0.075
		0.25	0.051	0.000	0.432	0.381		0.371
		0.5	0.025	0.000	0.610	0.585		0.569
		0.75	0.102	0.000	0.686	0.584		0.568
		1	0.102	0.000	0.660	0.558		0.543
LOADING CV cracked	11	0	0.102	0.077	0.203	0.101	527.000	0.096
		0.25	0.152	0.101	0.813	0.661		0.627
		0.5	0.127	0.102	1.067	0.940		0.892
		0.75	0.203	0.101	1.118	0.915		0.868
		1	0.178	0.076	1.041	0.863		0.819
LOADING CV ultimate	14	0	0.102	0.000	0.178	0.076	526.000	0.072
		0.25	0.178	0.026	0.813	0.635		0.604
		0.5	0.178	0.051	1.041	0.863		0.820
		0.75	0.203	0.000	1.041	0.838		0.797
		1	0.178	0.000	0.991	0.813		0.773

TABLE A4.7 DISPLACEMENT DATA FOR WALL4: BACKUP PANEL

	WALL LOCATION		RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0	0.000	0.000	0.025	0.025	514.000	0.024
CV		0.25	0.000	0.000	0.432	0.432		0.420
		0.5	0.000	0.000	0.686	0.686		0.667
		0.75	0.000	0.000	0.635	0.635		0.618
		1	0.000	0.000	0.457	0.457		0.445
LOADING	2	0	0.000	0.000	0.076	0.076	519.000	0.073
CE		0.25	0.025	0.025	0.533	0.508		0.489
		0.5	0.051	0.051	0.838	0.787		0.758
		0.75	0.025	0.025	0.762	0.737		0.710
		1	0.025	0.025	0.559	0.534		0.514
LOADING	3	0	0.000	0.000	0.025	0.025	503.000	0.025
CE		0.25	0.051	0.026	0.508	0.457		0.454
CRACKING		0.5	0.102	0.051	0.889	0.787		0.782
		0.75	0.025	0.000	0.711	0.686		0.682
		1	0.025	0.000	0.533	0.508		0.505
LOADING	4	0	0.051	0.051	0.152	0.101	519.000	0.097
CE		0.25	0.127	0.076	0.813	0.686		0.661
CRACKED		0.5	0.178	0.076	1.118	0.940		0.905
		0.75	0.025	0.000	0.940	0.915		0.881
		1	0.076	0.051	0.686	0.610		0.588
LOADING	6	0	0.051	0.000	0.152	0.101	508.000	0.099
CE		0.25	0.254	0.127	0.914	0.660		0.650
CRACKED		0.5	0.330	0.152	1.219	0.889		0.875
		0.75	0.203	0.178	1.067	0.864		0.850
		1	0.152	0.076	0.737	0.585		0.576
LOADING	7	0	0.051	0.000	0.127	0.076	517.000	0.074
CV		0.25	0.279	0.025	0.737	0.458		0.443
CRACKED		0.5	0.330	0.000	1.118	0.788		0.762
		0.75	0.229	0.026	0.940	0.711		0.688
		1	0.152	0.000	0.660	0.508		0.491
LOADING	9	0	0.051	0.000	0.127	0.076	510.000	0.075
CV		0.25	0.305	0.026	0.762	0.457		0.448
CRACKED		0.5	0.432	0.102	1.245	0.813		0.797
		0.75	0.279	0.050	1.016	0.737		0.723
		1	0.203	0.051	0.762	0.559		0.548
LOADING	10	0	0.051	0.000	0.127	0.076	507.000	0.075
CV		0.25	0.330	0.025	0.813	0.483		0.476
CRACKED		0.5	0.432	0.000	1.270	0.838		0.826
		0.75	0.279	0.000	1.016	0.737		0.727
		1	0.203	0.000	0.762	0.559		0.551

TABLE A4.8 DISPLACEMENT DATA FOR WALL4: VENEER PANEL

	WALL LOCATION		RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0	0.000	0.000	0.152	0.152	514.000	0.148
CV		0.25	0.000	0.000	0.559	0.559		0.544
		0.5	0.000	0.000	0.762	0.762		0.741
		0.75	0.000	0.000	0.787	0.787		0.766
		1	0.000	0.000	0.813	0.813		0.791
LOADING	2	0	0.000	0.000	0.127	0.127	519.000	0.122
CE		0.25	0.076	0.076	0.533	0.457		0.440
		0.5	0.051	0.051	0.762	0.711		0.685
		0.75	0.025	0.025	0.737	0.712		0.686
		1	0.025	0.025	0.737	0.712		0.686
LOADING	3	0	0.000	0.000	0.152	0.152	503.000	0.151
CE		0.25	0.127	0.051	0.610	0.483		0.480
CRACKING		0.5	0.102	0.051	0.787	0.685		0.681
		0.75	0.076	0.051	0.787	0.711		0.707
		1	0.051	0.026	0.787	0.736		0.732
LOADING	4	0	0.051	0.051	0.203	0.152	519.000	0.146
CE		0.25	0.127	0.000	0.711	0.584		0.563
CRACKED		0.5	0.127	0.025	0.914	0.787		0.758
		0.75	0.127	0.051	0.914	0.787		0.758
		1	0.051	0.000	0.813	0.762		0.734
LOADING	6	0	0.127	0.076	0.254	0.127	508.000	0.125
CE		0.25	0.203	0.076	0.737	0.534		0.526
CRACKED		0.5	0.229	0.102	0.965	0.736		0.724
		0.75	0.228	0.101	0.965	0.737		0.725
		1	0.076	0.025	0.813	0.737		0.725
LOADING	7	0	0.152	0.025	0.330	0.178	517.000	0.172
CV		0.25	0.229	0.026	0.838	0.609		0.589
CRACKED		0.5	0.254	0.025	1.118	0.864		0.836
		0.75	0.254	0.026	1.117	0.863		0.835
		1	0.076	0.000	0.940	0.864		0.836
LOADING	9	0	0.178	0.026	0.356	0.178	510.000	0.175
CV		0.25	0.229	0.000	0.889	0.660		0.647
CRACKED		0.5	0.381	0.127	1.295	0.914		0.896
		0.75	0.330	0.076	1.194	0.864		0.847
		1	0.203	0.127	1.041	0.838		0.822
LOADING	10	0	0.178	0.000	0.356	0.178	507.000	0.176
CV		0.25	0.254	0.025	0.864	0.610		0.602
CRACKED		0.5	0.381	0.000	1.295	0.914		0.901
		0.75	0.330	0.000	1.219	0.889		0.877
		1	0.203	0.000	1.067	0.864		0.852

TABLE A4.9 DISPLACEMENT DATA FOR WALL5: BACKUP PANEL

	WALL LOCATION		RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0	0.000	0.000	0.000	0.000	510.373	0.000
CE		0.25	0.000	0.000	0.127	0.127		0.124
		0.5	0.000	0.000	0.229	0.229		0.224
		0.75	0.000	0.000	0.330	0.330		0.323
		1	0.000	0.000	0.432	0.432		0.423
LOADING	2	0	0.000	0.000	0.025	0.025	511.347	0.025
CV		0.25	0.051	0.051	0.229	0.178		0.174
		0.5	0.051	0.051	0.381	0.330		0.323
		0.75	0.076	0.076	0.483	0.406		0.397
		1	0.076	0.076	0.559	0.483		0.472
LOADING	3	0	0.000	0.000	0.025	0.025	509.399	0.025
L4 & L5		0.25	0.076	0.025	0.305	0.229		0.224
CV		0.5	0.076	0.025	0.432	0.356		0.349
		0.75	0.127	0.051	0.559	0.432		0.424
		1	0.102	0.025	0.584	0.483		0.474
LOADING	6	0	0.000	0.000	0.000	0.000	523.035	0.000
CE		0.25	0.051	-0.025	0.279	0.229		0.219
		0.5	0.102	0.025	0.483	0.381		0.364
		0.75	0.178	0.051	0.635	0.457		0.437
		1	0.127	0.025	0.635	0.508		0.486
LOADING	7	0	0.000	0.000	0.000	0.000	511.347	0.000
CE		0.25	0.050	-0.001	0.178	0.128		0.125
CRACKING		0.5	0.127	0.025	0.381	0.254		0.248
		0.75	0.228	0.050	0.610	0.382		0.373
		1	0.152	0.025	0.635	0.483		0.472
LOADING	8	0	0.025	0.025	0.025	0.000	512.808	0.000
CE		0.25	0.102	0.052	0.305	0.203		0.198
CRACKED		0.5	0.178	0.051	0.584	0.406		0.396
		0.75	0.254	0.026	0.787	0.533		0.520
		1	0.203	0.051	0.762	0.559		0.545
LOADING	9	0	0.025	0.000	0.025	0.000	501.607	0.000
CV		0.25	0.102	0.000	0.305	0.203		0.203
CRACKED		0.5	0.178	0.000	0.559	0.381		0.380
		0.75	0.254	0.000	0.254	0.559		0.557
		1	0.203	0.000	0.203	0.635		0.633
LOADING	10	0	0.025	-0.000	0.025	0.000	519.139	0.000
CV		0.25	0.127	0.025	0.305	0.178		0.171
ULTIMATE		0.5	0.203	0.025	0.584	0.381		0.367
		0.75	0.330	0.076	0.863	0.533		0.514
		1	0.279	0.076	0.889	0.610		0.587

TABLE A4.10 DISPLACEMENT DATA FOR WALL5: VENEER PANEL

	WALL LOCATION		RESIDUAL (mm)	DELTA RESIDUAL (mm)	RECORDED (mm)	INCREMENT (mm)	LOAD LEVEL (Pa)	ADJUSTED INCREMENT (mm)
LOADING	1	0	0.000	0.000	0.000	0.000	510.373	0.000
CE		0.25	0.000	0.000	0.152	0.152		0.149
		0.5	0.000	0.000	0.279	0.279		0.274
		0.75	0.000	0.000	0.381	0.381		0.373
		1	0.000	0.000	0.432	0.432		0.423
LOADING	2	0	0.000	0.000	0.051	0.051	511.347	0.050
CV		0.25	0.051	0.051	0.279	0.229		0.224
		0.5	0.051	0.051	0.432	0.381		0.373
		0.75	0.076	0.076	0.559	0.483		0.472
		1	0.076	0.076	0.660	0.584		0.571
LOADING	3	0	0.000	0.000	0.051	0.051	509.399	0.050
L4 & L5		0.25	0.076	0.025	0.356	0.279		0.274
CV		0.5	0.127	0.076	0.533	0.406		0.399
		0.75	0.127	0.051	0.635	0.508		0.499
		1	0.127	0.051	0.711	0.584		0.573
LOADING	6	0	0.000	0.000	0.025	0.025	523.035	0.024
CE		0.25	0.102	0.025	0.279	0.178		0.170
		0.5	0.152	0.025	0.457	0.305		0.291
		0.75	0.179	0.052	0.585	0.406		0.389
		1	0.179	0.052	0.687	0.508		0.486
LOADING	7	0	0.000	0.000	0.000	0.000	511.347	0.000
CE		0.25	0.127	0.025	0.254	0.127		0.124
CRACKING		0.5	0.177	0.025	0.432	0.255		0.249
		0.75	0.203	0.024	0.559	0.356		0.348
		1	0.203	0.024	0.686	0.483		0.472
LOADING	8	0	0.000	0.000	0.000	0.000	512.808	0.000
CE		0.25	0.178	0.051	0.356	0.178		0.173
CRACKED		0.5	0.203	0.026	0.508	0.305		0.297
		0.75	0.254	0.051	0.686	0.432		0.421
		1	0.254	0.051	0.762	0.508		0.495
LOADING	9	0	0.000	0.000	0.025	0.025	501.607	0.025
CV		0.25	0.178	0.000	0.457	0.279		0.279
CRACKED		0.5	0.203	0.000	0.686	0.483		0.481
		0.75	0.254	0.000	0.864	0.610		0.608
		1	0.254	0.000	0.965	0.711		0.709
LOADING	10	0	0.000	0.000	0.025	0.025	519.139	0.024
CV		0.25	0.228	0.050	0.483	0.255		0.245
ULTIMATE		0.5	0.254	0.051	0.686	0.432		0.416
		0.75	0.330	0.076	0.914	0.584		0.563
		1	0.330	0.076	1.041	0.711		0.685