FRAMEWORK FOR INVESTIGATING

BUILDING ENVELOPE DEFECTS

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EXECUTIVE SUMMARY

Diagnosing envelope problems is a complex task aimed at determining causes and remedial measures to overcome the situation. The diagnostic process involves a thorough examination of design details, the actual construction and the performance. In order to analyze the envelope problems, Canada Mortgage and Housing Corporation has developed a "Building Problem Survey" (CMHC-BPS) database system. The objective of CMHC-BPS is to document building construction problems and descriptions, and to provide a search technique to establish the relationship between current construction practices and problem occurrences.

The present study utilizes the CMHC-BPS system to analyze envelope problems reported in fifty Québec residential buildings. Data on these buildings was collected from the Association Provinciale des Constructeurs d'Habitations du Québec (APCHQ) warranty files consisting of inspection reports, conciliation reports, building registration forms and other relevant documents. Analysis of this data shows that moisture and cracking are the most frequent amongst the eight types of problems reported. A large number of these problems are attributed to improper or lack of specifications, poor choice of materials, poor workmanship, and a lack of understanding of certain building science principles. Builders need to be better informed of the role of flashings, importance of air barriers and its construction details, and also the shrinkage properties of wood. During data collection and analysis, it is found that the CMHC-BPS system in its present form is best suited only to document high rise masonry building details and problems. Since most APCHQ warranty program files deal with low-rise residential construction, a modified and simplified version of CMHC-BPS will be needed for APCHQ's use.

Subsequent to the problem survey, SIRICON undertook the development of a diagnostic framework to systematically investigate envelope problems, and prepared a list of recommendations to builders. Description of residential envelope problem scenarios have been developed to identify problem categories, time of occurrence, possible causes, test

methods and remedial measures. There are 32 scenarios representing the most common problems encountered in the following envelope components: (i) Basement walls and foundations, (ii) Exterior walls, (iii) Windows and doors, and (iv) Roof and attic.

Diagnostic matrices have been developed to show the relationship between envelope components, problem categories and test methods. These matrices will be useful to quickly identify the scenario and obtain more detailed information on causes and remedial measures. Eight diagnostic test methods including smoke pencil, wax plug and water test have been described in this study. These test methods are inexpensive and easy to use by building inspectors and contractors.

This diagnostic framework has been implemented in a prototype expert system named BEFD (Building Envelope Failure Diagnosis system). This expert system is implemented in MS Windows environment using LEVEL 5 Object development tool. An end-user of the system can specify the envelope component, problem category and retrieve the detailed scenario description for diagnosing the problem. The knowledge base for this expert system is developed using efficient knowledge representation techniques and the knowledge base can be easily modified or extended to include other problem categories and scenarios. This framework and expert system prototype offer a practical approach to classify and disseminate the available expertise in building envelope failure diagnosis.

RÉSUMÉ

Le diagnostic des problèmes liés à l'enveloppe des bâtiments est une tâche complexe qui vise à déterminer les causes d'une situation et les mesures permettant de la corriger. Le processus de diagnostic requiert un examen complet des détails de conception, de la construction comme telle et du comportement du bâtiment. En vue d'analyser les problèmes touchant l'enveloppe, la Société canadienne d'hypothèques et de logement a mis sur pied une base de données servant à relever les problèmes de bâtiment (CMHC-BPS). Le système CMHC-BPS sert à consigner les problèmes de construction et leur description et offre une technique de recherche permettant d'établir des liens entre les méthodes de construction actuelles et l'apparition de problèmes.

La présente étude a recours au système CMHC-BPS pour analyser les problèmes d'enveloppe signalés dans cinquante bâtiments résidentiels construits au Québec. Les données concernant ces bâtiments ont été tirées des dossiers de garantie de l'Association provinciale des constructeurs d'habitations du Québec (APCHQ) constitués de rapports d'inspection, rapports de règlement, formules d'inscription des bâtiments et autres documents pertinents. L'analyse de ces données révèle que l'humidité et les fissures sont les problèmes les plus fréquents parmi les huit genres de problèmes relevés. Un grand nombre de ces problèmes sont attribuables à des devis déficients ou inexistants, à un mauvais choix de matériaux, à une exécution de qualité médiocre et à une mauvaise compréhension de certains principes de la science du bâtiment. Les constructeurs doivent être mieux informés du rôle des solins, de l'importance des pare-air et de leurs techniques d'exécution, et aussi de la tendance du bois à se contracter. Pour la collecte et l'analyse des données, le système CMHC-BPS, dans sa forme actuelle, ne relève efficacement que les détails et les problèmes des tours d'habitation en maçonnerie. Comme la plupart des dossiers de l'APCHQ portent sur des bâtiments résidentiels de faible hauteur, il faudra modifier et simplifier la présente version du système CMHC-BPS pour que l'APCHQ puisse s'en servir.

À la suite du relevé des problèmes, le groupe SIRICON a entrepris l'élaboration d'un cadre d'étude diagnostique visant à relever les problèmes d'enveloppe de façon systématique et a dressé une liste de recommandations

destinées aux constructeurs. Une description des scénarios de problèmes d'enveloppe de bâtiments résidentiels a été créée pour cerner les catégories de problème, le moment de leur apparition, les causes possibles, les méthodes d'essai et les mesures correctrices. Trente-deux scénarios ont été décrits relativement aux problèmes les plus fréquents des éléments d'enveloppe suivants : i) murs et fondations du sous-sol, ii) murs extérieurs, iii) portes et fenêtres, iv) toit et vide sous toit.

Des matrices diagnostiques ont été mises au point pour établir le lien entre les éléments de construction, les catégories de problème et les méthodes d'essai. Ces matrices seront utiles pour repérer rapidement un scénario et obtenir de l'information détaillée sur les causes et les solutions. Huit méthodes d'essai diagnostiques mettant à contribution un crayon fumigène, un bouchon de cire et de l'eau sont décrites dans cette étude. Elles sont peu coûteuses et faciles à utiliser par les inspecteurs de bâtiments et les entrepreneurs.

Le cadre d'étude diagnostique a été introduit dans un système expert appelé BEFD (Building Envelope Failure Diagnosis system [système de diagnostic des défaillances de l'enveloppe]). Ce système expert fonctionne dans l'environnement Windows, de Microsoft, et emploie l'outil logiciel LEVEL 5 Object. L'utilisateur du système peut préciser un élément de l'enveloppe et une catégorie de problème, puis extraire une description détaillée du scénario permettant de diagnostiquer le problème. La base de connaissances pour ce système expert est élaborée au moyen de techniques efficaces de représentation des connaissances. Il est facile de la modifier ou de l'augmenter afin d'y inclure d'autres catégories de problème et d'autres scénarios. Ce cadre d'étude et ce prototype de système expert offrent une méthode pratique de classification et de diffusion du savoir-faire existant en matière de diagnostic des défaillances de l'enveloppe.

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1. INTRODUCTION

The investigation of building envelope problems requires the knowledge of the construction details used and the description of the problems encountered. The Canada Mortgage and Housing Corporation has developed a Building Problem Survey (CMHC-BPS) database system to address these two aspects of the investigative process. The present study aims at assessing the suitability of this CMHC-BPS system to analyze residential envelope problems and developing a diagnostic framework. The primary objectives of this study are to:

(i) collect data from fifty New Home Warranty Program files of the Association Provinciale des Constructeurs d'Habitations du Québec (APCHQ) and analyze this data using the CMHC-BPS system

(ii) assess the suitability of CMHC-BPS for future adaptation by APCHQ

(iii) compile a list of residential envelope problem scenarios identifying symptoms, causes, test methods and remedial measures

(iv) develop a framework for diagnosis and implement a prototype expert system

(v) develop recommendations for builders to overcome these problems

This report describes the APCHQ warranty files data collection process, summary of the data, comparison with ONHWP data, recommendations for future use of the CMHC-BPS system, scenarios of envelope problems, the diagnostic framework, details of the expert system prototype and the recommendations.

2. APCHQ WARRANTY FILES DATA

2.1. Data collection process

Fifty buildings covered by the APCHQ New Home Warranty program having building envelope problems were analyzed. Each was studied to extract the necessary data to be input into the CMHC-BPS database. Of the 50 buildings studied, 26 had building details, construction drawings and conciliation reports. The remainder had incomplete building details with no drawings. Therefore, some of the data collected relies on visual inspection reports and building registration forms.

The CMHC-BPS database has many levels of menus to describe building details and associated problems. Data input forms have been developed for each building detail and problem description screen. During data collection, the most appropriate menu choice is identified for each envelope problem. The "Other" option is used to describe situations that are not identified in the menu choices. The "Comments" field is used to describe the magnitude of problems and repair costs.

The original CMHC-BPS database containing the Ontario New Home Warranty Program (ONHWP) problem files information is extended to include the APCHQ problem files. The APCHQ files data are uniquely identified by the term "APCHQ" in the file number field. Similarly, the ONHWP files data are identified by "ONHWP". Thus it is possible to simultaneously search the database to compare the ONHWP and APCHQ files for building details and occurrences of problems.

2.2. Summary of APCHQ Data

Of the fifty APCHQ problem files studied, 22 represent condominium buildings and the remaining 28 include single family, duplex, triplex and quadruplexes. Table 1 shows the summary of envelope problems encountered, their frequency and the number of buildings affected.

Problem Category	Frequency of Occurrence	No. of Buildings Affected
Moisture	87	44
Cracks	41	31
Drafts	14	11
Displacement	11	9
Noise & Vibration	7	6
Mortar	5	4
Loose Components	4	4
Staining	3	3

Table 1: Summary of Envelope Problems

The collected data indicates that more than 80% of the buildings have moisture related problems. Water infiltration as a result of rain, melting snow or ground water is the most frequent problem observed. This occurs mainly in exterior walls, roofs, openings and basements. Figure 1 indicates the various building components where moisture problems occurred. It is found that faulty flashings are the major cause of moisture related problems. This is due to improper specifications, poor choice of materials and workmanship, and a general lack of understanding of the role of flashings. Some balconies and roofs had ponding problems due to insufficient slopes and faulty drainage.

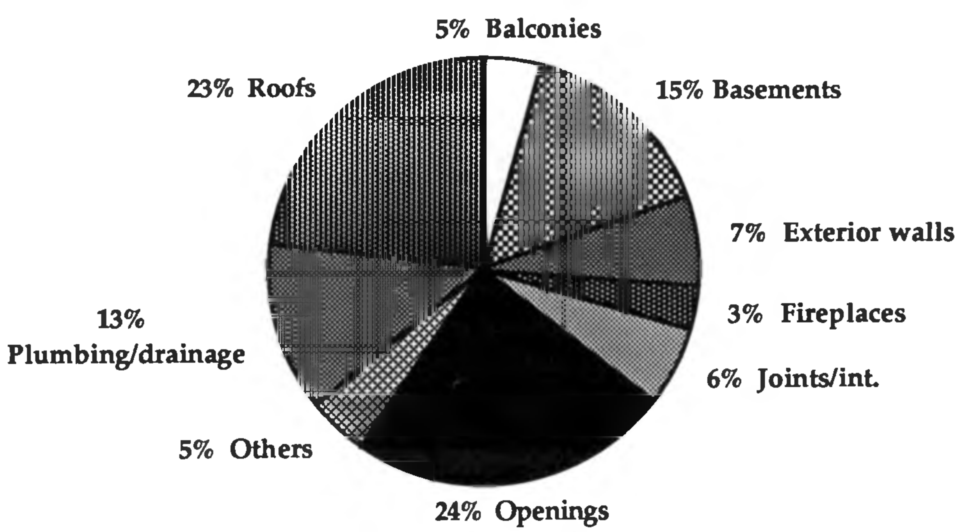


Figure 1: Distribution of Moisture Problems

The second major problem encountered are cracks in the exposed surfaces either inside or outside. Figure 2 shows the components where cracking problems occur. About 40% of all the cracking problems occur in the interior finishes. Cracks often occur at wall to ceiling joints; many are caused by shrinkage of the wood components and/or truss uplift. A significant number of cracks are observed in the brick veneer adjacent to openings. These are due to insufficient stiffness of the supporting framing elements and stress concentrations. Cracks are often found in foundation walls. They are mainly due to the shrinkage of concrete. However, in some cases they may be due to differential settlement.

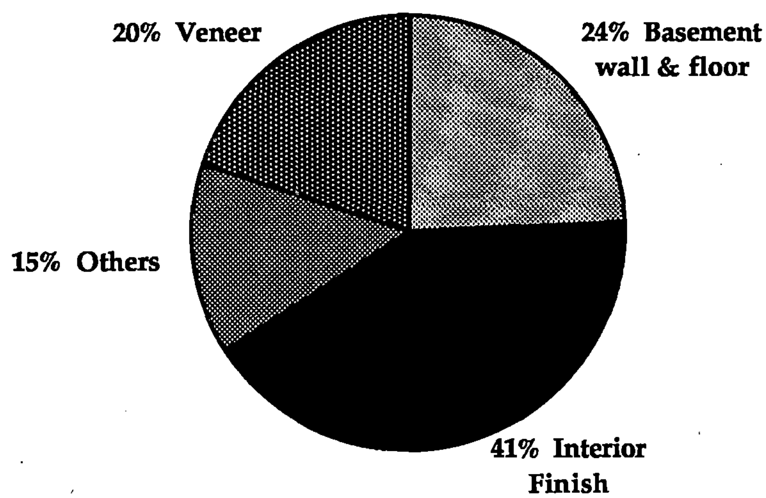


Figure 2: Distribution of Cracking Problems

Draft problems are reported in about 20% of the buildings. Draft problems often occur in the bottom half of the building because the air-barrier systems are inadequate to resist the negative pressure in that zone. Most of the draft problems have been attributed to faulty weather-stripping and faulty seals around windows and doors.

Displacement problems are reported in 20% of the buildings investigated. A frequently reported problem is that of uneven floors which can be attributed to the warpage of the beams and joists, due to the drying of the wood. Truss uplift is another common problem reported. This is caused by differential moisture content in the top and bottom chords of the truss. The moisture content of the wood members is affected by the relative humidity of the surrounding air.

Excessive floor vibration and noise transmission in the dwellings are also reported in a few cases. Floor vibrations are mainly caused by excessive spans of wood joists. Noises emanating from the plumbing and mechanical systems are also reported and are due to improper anchoring and inadequate acoustical treatment.

2.3. Comparison between APCHQ and ONHWP data

A comparison between APCHQ and ONHWP data has been made by analyzing the database information. This comparison is based on a typical set of fifty APCHQ and forty nine ONHWP problem files. The fifty APCHQ files represent both single family and multi-family dwellings whereas all the ONHWP files represent only multi-family condominium buildings. Also there is wide variation between the types of buildings in terms of structural and cladding systems, backup wall types and other details. Most of the APCHQ problem buildings are wood frame buildings in contrast to ONHWP problem buildings which are primarily steel stud and concrete masonry buildings.

Figure 3 shows the number of buildings affected in each problem category for the APCHQ and ONHWP data. This comparison is based on the above described limited scope of data collection and represents only a small portion of the files processed by the warranty programs. Nevertheless, it shows the relative magnitude of problems encountered in both provinces. Generally, moisture and cracking problems are most frequently encountered in both cases. There are no noise and vibration problem reported in ONHWP files but there is a large number of buildings with efflorescence and staining.

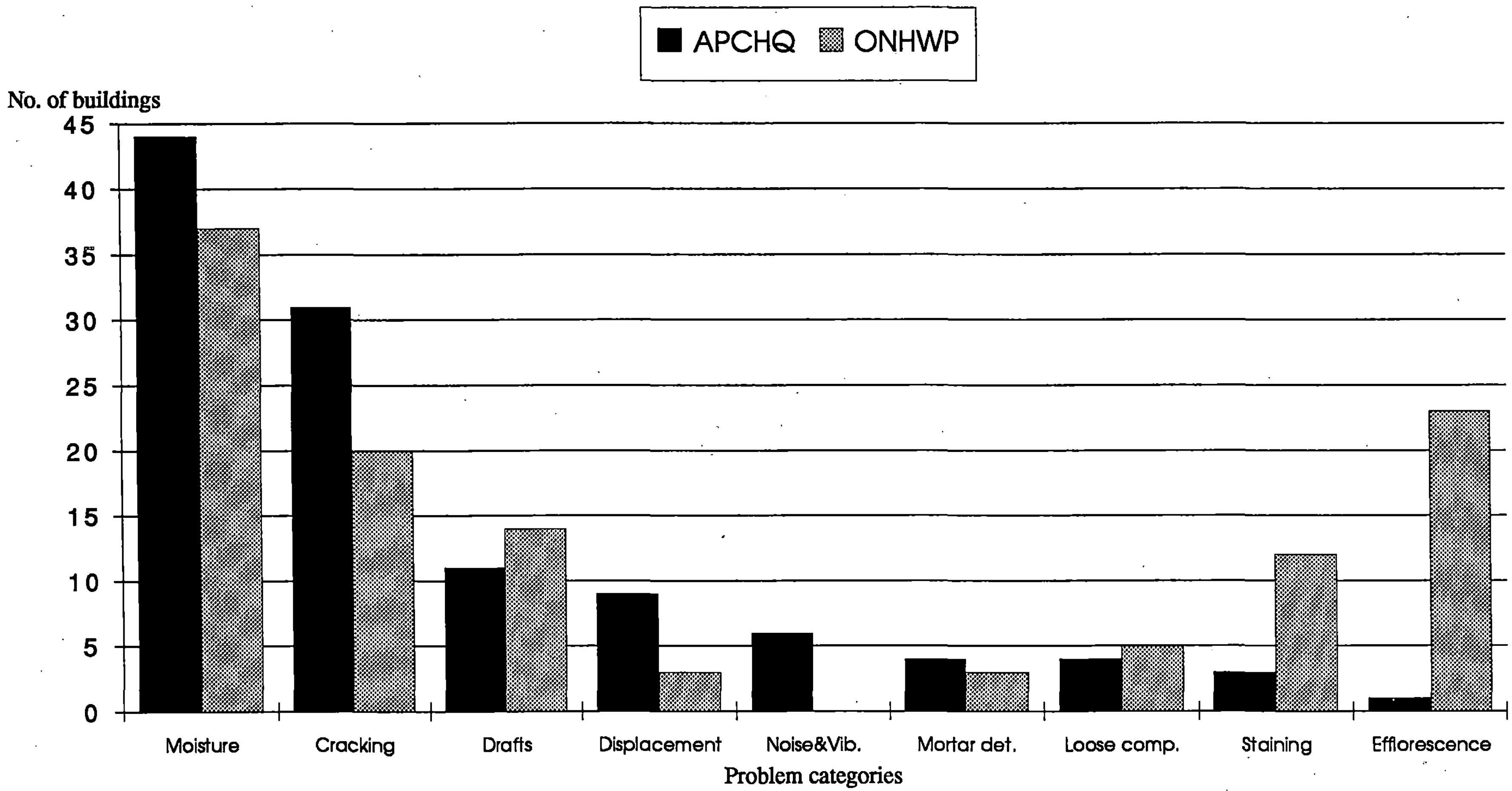


Figure 3: Comparison between APCHQ and ONHWP problem data

3. CMHC-BPS DATABASE SYSTEM - OBSERVATIONS

The data collection and analysis of APCHQ warranty files were made with the objective of evaluating CMHC-BPS database system for future use by APCHQ. The following observations will contribute to the potential modifications and adaptation of CMHC-BPS by APCHQ:

(i) The most interesting aspect of the CMHC-BPS system is the potential to retrieve appropriate cases and their information for future investigation of similar problems. Also the statistical information can be used to establish training programs for APCHQ members.

(ii) The primary intent of CMHC-BPS is to document and evaluate construction details and problems in building envelope of multi-family residential buildings, specifically high rise condominiums. Hence the database framework is very comprehensive to describe building details for constructions such as brick masonry on steel stud, but does not have the same level of emphasis for low-rise and single family dwelling constructions.

(iii) All APCHQ warranty program files contain two standard documents known as inspection reports and conciliation reports. Though the information available in these two documents is sufficient to describe a building and its problems, it is not adequate to provide all the details required by the CMHC-BPS system. Besides, APCHQ does not retain drawings or design details in its files. Hence, a simplified version of CMHC-BPS database will be appropriate for APCHQ's use.

(iv) Program modifications for listing noise and vibration problems have been made to the CMHC-BPS database system. Further modifications to the system to perform diagnosis is not feasible due to the original scope of database development which is aimed at documenting case studies. In order to assist in diagnosis, a knowledge base is developed in this study and a prototype expert system has been implemented. This expert system may be interfaced to the CMHC-BPS database.

4. DIAGNOSTIC FRAMEWORK

One of the prime objectives of this study is to develop a framework for diagnosing residential building envelope problems. As a first step, we have compiled a list of envelope problem scenarios in terms of symptoms, causes, test methods and remedial measures. For each envelope component, the most frequently encountered problems are identified along with the attributes for diagnosis. These problem scenarios are developed to reflect the most common ones encountered in the residential sector.

4.1. Scenarios of envelope problems

A thorough analysis of existing literature and consultation with industry experts have been done to identify these problem scenarios. These are classified according to each envelope component and problem category as shown in Figure 4. Once the problem and the affected component are identified, the user can refer to the appropriate scenario description. For example, cracking in basement walls are described in scenarios 1.1.1, 1.1.2 and 1.1.3. There are thirty two scenarios in total, classified under the four major categories of envelope components namely:

(i) Basement walls and foundations,
(ii) Exterior walls
(iii) Windows and doors
(iv) Roof and attic

Each scenario is identified by a unique reference number. All scenario descriptions include the location of problem, time of occurrence, possible causes, test methods and remedial measures. Some of the scenarios are supplemented with photographs to illustrate and explain the problem. Simple test methods have been identified for diagnosing each problem. The description of test methods and their application are described later in this report.

Problems \ Components affected	Basements and Foundations	Exterior Walls	Windows and Doors	Attic and Roof
Cracks	● (1.1.1, 1.1.2, 1.1.3)	● (2.1.1, 2.1.2, 2.1.3)		
Settlement	● (1.2.1)			
Water infiltration	● (1.3.1, 1.3.2, 1.3.3)	● (2.2.1, 2.2.2)	● (3.1.1, 3.1.2)	● (4.1.1, 4.1.2, 4.1.3, 4.1.4)
Air infiltration		● (2.3.1, 2.3.2)	● (3.2.1)	
Condensation	● (1.4.1)	● (2.4.1)	● (3.3.1)	● (4.2.1, 4.2.2)
Cold spots		● (2.7.1)		
Efflorescence	● (1.5.1)	● (2.5.1)		
Ice dam				● (4.3.1)
Mould & Mildew		● (2.6.1)		
Rotting of wood				● (4.4.1)

Figure 4: Matrix of envelope problems and components affected

Note: Scenario numbers are identified in parantheses

Scenario 1.1.1 : Basement Cracks - 2mm or less

Crack width	*2mm or less*
Time of occurrence	*First two years after construction*
Location of crack	• *Corners of openings* • *Centre of a long wall*
Cause	*Shrinkage of concrete during curing*
Test methods	• *Visual inspection* • *Wax plugs*
Remedial measures	• *If the cracks remain stable, they can be repaired using epoxy injection* • *In some cases, a mastic & a water-proofing membrane on the outside of the foundation may be adequate to prevent water entry.*

Scenario 1.1.2 : Basement Cracks - 3mm or more

Crack width	*3mm or more*
Time of occurrence	*After a dry spell*
Location of crack	*Foundation wall* ***(Photo 1)***
Cause	• *Shrinkage of soil* • *Growing trees close to building*
Test methods	• *Visual inspection* • *Wax plugs*
Remedial measures	*Consult a foundation engineer*

Scenario 1.1.3 : Basement Cracks - 3mm or more

Crack width	*3mm or more*
Time of occurrence	*Shortly after construction*
Location of crack	*Foundation walls and footings*
Cause	*Foundation on* • *disturbed or frozen soil* • *soil with insufficient bearing capacity*
Test methods	• *Visual inspection* • *Wax plugs*
Remedial measures	*Consult a foundation engineer*

Scenario 1.2.1 : Settlement of Foundation

Time of occurrence	• *Shortly after construction* • *Following dry spells*
Location	*Foundation walls and footings*
Cause	• *Low bearing capacity of soil* • *Under design/overloading of foundation* • *Under-compaction of soil* • *Shrinkage of soil due to removal of water by trees, trenches or pumping*
Test methods	• *Visual inspection* • *Elevations*
Remedial measures	*Consult a foundation engineer*

Scenario 1.3.1 : Water infiltration - through cracks

Time of occurrence	• *Rain* • *Spring thaw*
Location	*Through cracks*
Cause	*Refer to basement cracks 1.1.1 - 1.1.3*
Test methods	• *Visual inspection*
Remedial measures	*Refer to basement cracks 1.1.1 - 1.1.3*

Scenario 1.3.2 : Water infiltration - top of foundation wall

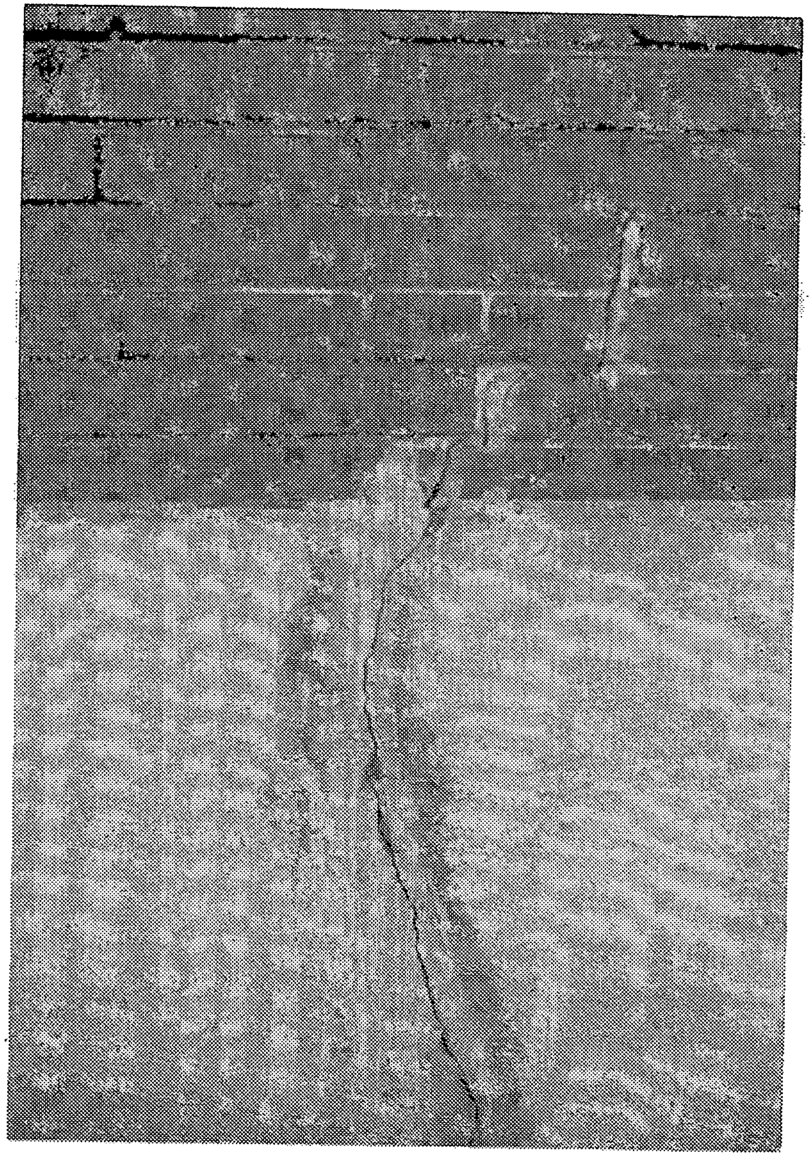
Time of occurrence	*Wind-driven rain*
Location	*Top of foundation wall* ***(Photo 2)***
Cause	• *Lack of inadequate flashing at bottom of exterior wall* • *Cavity filled with mortar*
Test methods	• *Visual inspection* • *Removal of bricks or siding element at exterior wall*
Remedial measures	• *Redo flashings: flashings must be installed 150 mm behind the sheathing paper and extend at least 5 mm outside the outer face of the foundation wall* • *Provide for adequate surface drainage*

Scenario 1.3.3 : Water infiltration - basement wall to slab joint

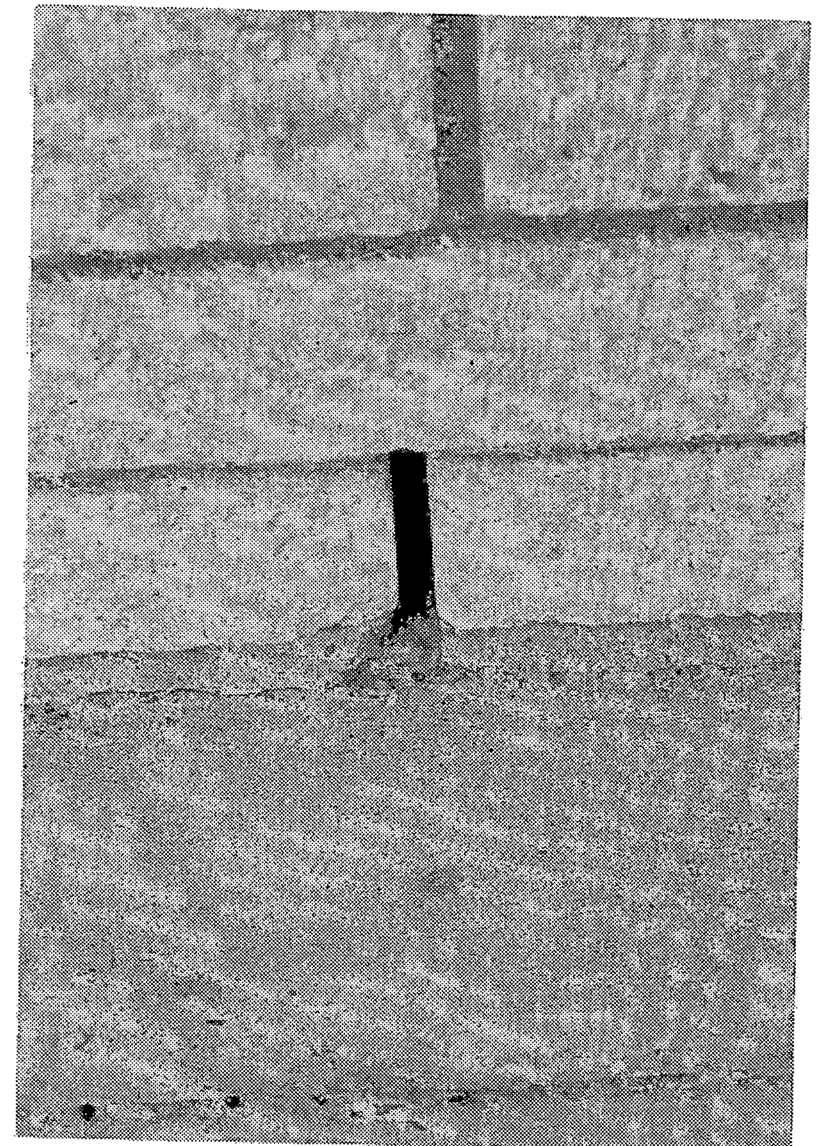
Time of occurrence	*Spring thaw and rain*
Location	*Joint between basement floor & foundation wall*
Cause	• *Water table raising above basement floor* • *Water not reaching drainage system* • *Lack of or non-functioning french drains*
Test methods	• *Visual inspection* • *Dig up the drain for inspection*
Remedial measures	• *Ensure that there is sufficient granular fill (6 in. min.) above the drain to permit water flow* • *Unclog the drain*

Scenario 1.4.1 : Condensation

Time of occurrence	*Summer or winter*
Location	*Interior surface of foundation wall*
Cause	• *High indoor relative humidity* • *Low surface temperatures* • *Lack of insulation* • *Lack of adequate ventilation*
Test methods	• *Visual inspection* • *R.H. and temperature measurement*
Remedial measures	• *Provide adequate insulation.* • *Increase basement ventilation rate*



1. Foundation wall cracking 3mm or more



2. Lack of flashing at bottom of exterior wall

Scenario 1.5.1 : Efflorescence

Time of occurrence	*Any time*
Location	*Inside foundation walls*
Cause	*Water seepage due to inadequate drainage or damp-proofing*
Test methods	• *Visual inspection* • *Local excavation to check drainage*
Remedial measures	• *Provide adequate drainage for foundations* • *Provide proper damp-proofing or water-proofing of foundation walls*

Scenario 2.1.1 : Exterior wall cracks - in bricks or mortar joints

Time of occurrence	*Anytime*
Location	*Bricks or mortar joints*
Cause	• *Movement of foundations* • *Moisture / thermal expansion of bricks* • *Too strong or too weak mortar*
Test methods	• *Visual inspection* • *Wax plug*
Remedial measures	• *Non moving crack: replace bricks or mortar joints* • *Moving crack: contact foundation engineer*

Scenario 2.1.2 : Exterior wall cracks - in caulked joints

Time of occurrence	*Anytime*
Location	*Caulked joints*
Cause	• *Excessive movement of joints* • *Incompatibility of caulking and surface* • *Omission of primer* • *Weather exposure of caulking*
Test methods	*Visual inspection*
Remedial measures	*Replace caulked joint*

Scenario 2.1.3: Wall - ceiling cracks

Time of occurrence	*Winter*
Location	*Wall to ceiling joint of interior partitions*
Cause	*Truss uplift*
Test methods	*Visual inspection*
Remedial measures	*Float wall-ceiling joint*

Scenario 2.2.1: Water infiltration - through masonry veneer

Time of occurrence	*Rain or wind-driven rain*
Location	*Through masonry veneer walls*
Cause	• *Absence, damage or inadequate installation of flashings* • *Absence, damage or inadequate installation of sheathing paper* • *Mortar bridges or uncentered ties*
Test methods	• *Visual inspection* • *Water test* • *Removal of bricks near infiltration*
Remedial measures	• *Redo flashings* • *Lap sheathing paper*

Scenario 2.2.2: Water infiltration - through cladding

Time of occurrence	*Rain or wind-driven rain*
Location	*Through the wall cladding*
Cause	• *Absence, damage or inadequate installation of cladding* • *Absence, damage or inadequate installation of flashing* • *Absence, damage or inadequate installation of sheathing paper* • *Inadequate caulking of joints*
Test methods	• *Visual inspection* • *Water test* • *Removal of cladding near infiltration*
Remedial measures	• *Redo flashings* • *Lap cladding* • *Lap sheathing paper*

Scenario 2.3.1: Air infiltration - around electrical outlets

Time of occurrence	*Winter*
Location	*Around electrical outlets*
Cause	*Absence of or inadequate installed air barrier*
Test methods	*Smoke pencil*
Remedial measures	• *Provide adequate air-barrier and caulking* • *Install air-tight boxes*

Scenario 2.3.2: Air infiltration - at sill-foundation joint

Time of occurrence	*Winter*
Location	*At sill to foundation joint*
Cause	*Absence of seal*
Test methods	*Smoke pencil*
Remedial measures	• *Provide adequate air-barrier and caulking* • *Apply urethane foam at the junction of sill and foundation wall*

Scenario 2.4.1 : Condensation - within the wall

Time of occurrence	*Winter*
Location	*Hidden within the exterior wall*
Cause	• *Air exfiltration from the heated space*
Test methods	• *Visual inspection (local demolition)* • *Thermography*
Remedial measures	• *Provide adequate air-vapour barrier on the warm side of insulation*

Scenario 2.5.1 : Efflorescence - on brick veneer

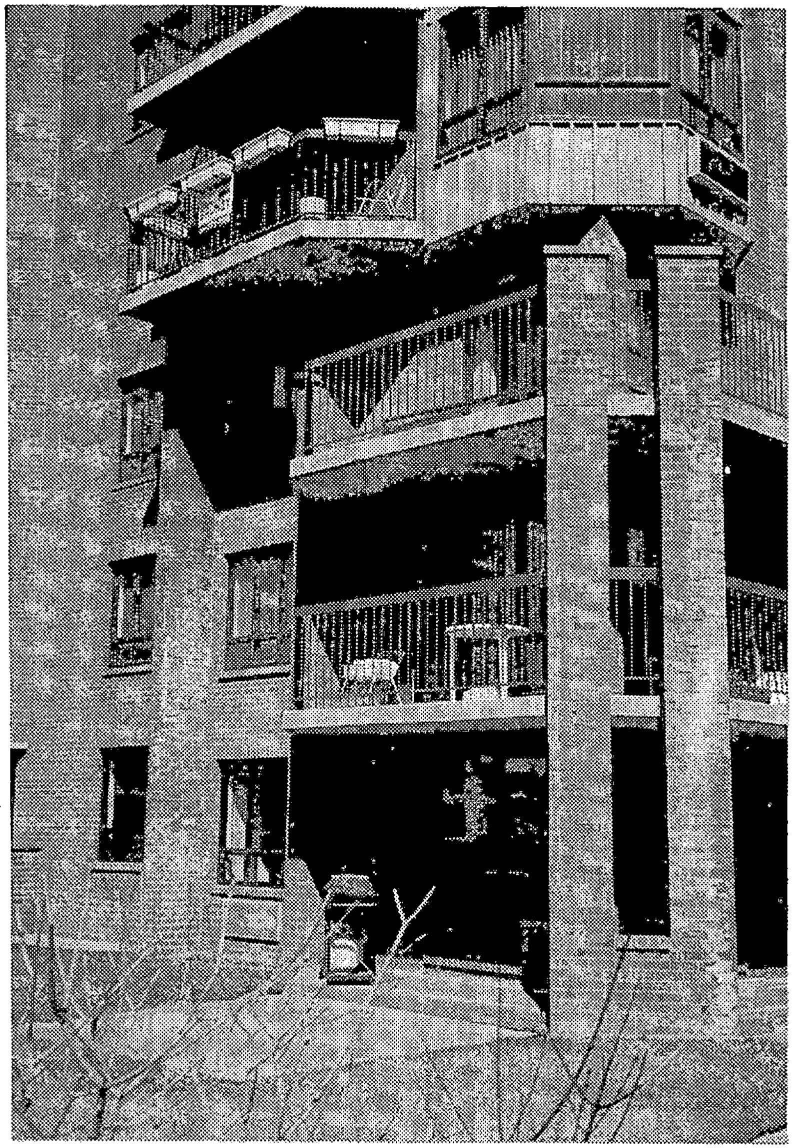
Time of occurrence	*Winter*
Location	*Exterior walls* ***(Photo 3)***
Cause	• *Vapour migration due to defective air barrier* • *Water infiltration*
Test methods	• *Visual inspection*
Remedial measures	• *Provide a continuous air-barrier* • *Eliminate water run-off from roofs onto brick walls*

Scenario 2.6.1 : Mould and mildew

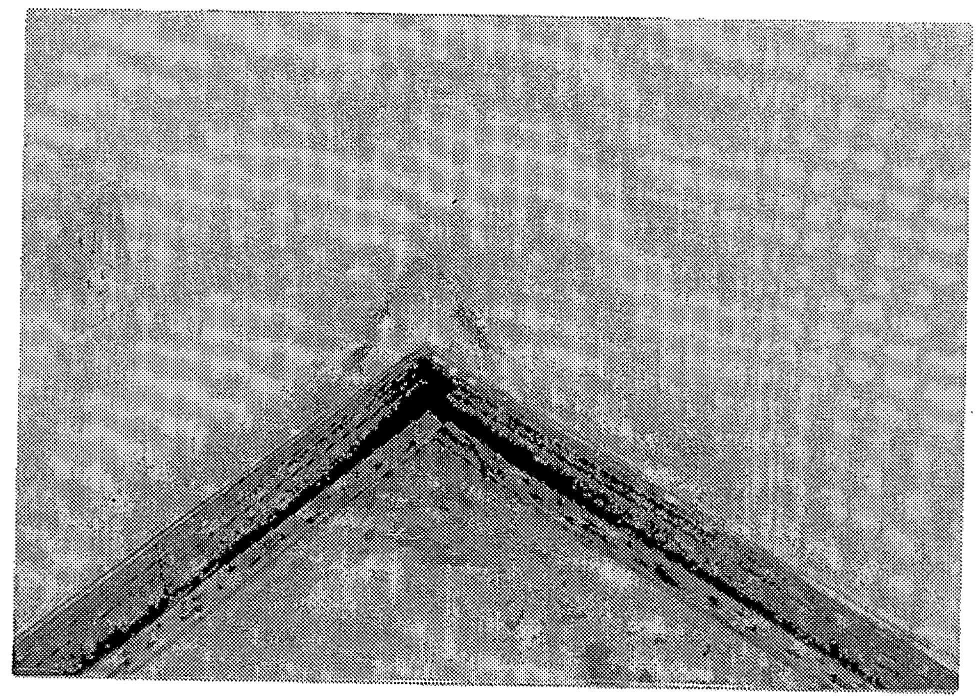
Time of occurrence	*Winter*
Location	*Interior wall surfaces* ***(Photo 4)***
Cause	• *High relative humidity at local areas* • *Low surface temperature*
Test methods	• *Visual inspection*
Remedial measures	• *Improve insulation in wall* • *Increase ventilation to lower relative humidity*

Scenario 2.7.1 : Cold spots

Time of occurrence	*Winter*
Location	*Inside face of exterior walls*
Cause	• *Absence, inadequate installation or deterioration of insulations* • *Thermal bridges*
Test methods	• *Visual inspection* • *Surface temperature measurement* • *Thermography*
Remedial measures	• *Improve insulation in wall* • *Avoid thermal bridges*



3. Efflorescence in exterior walls



4. Mildew in interior wall surface

Scenario 3.1.1: Water infiltration - at head of openings

Time of occurrence	*Rain or wind-driven rain*
Location	*At head of openings*
Cause	*Absent, damaged or poorly installed flashing*
Test methods	• *Visual inspection* • *Removal of bricks above lintels* ***(Photo 5)***
Remedial measures	• *Install adequate flashings and weep holes in brick veneer* • *For other sidings, install adequate flashing*

Scenario 3.1.2: Water infiltration - at bottom of openings

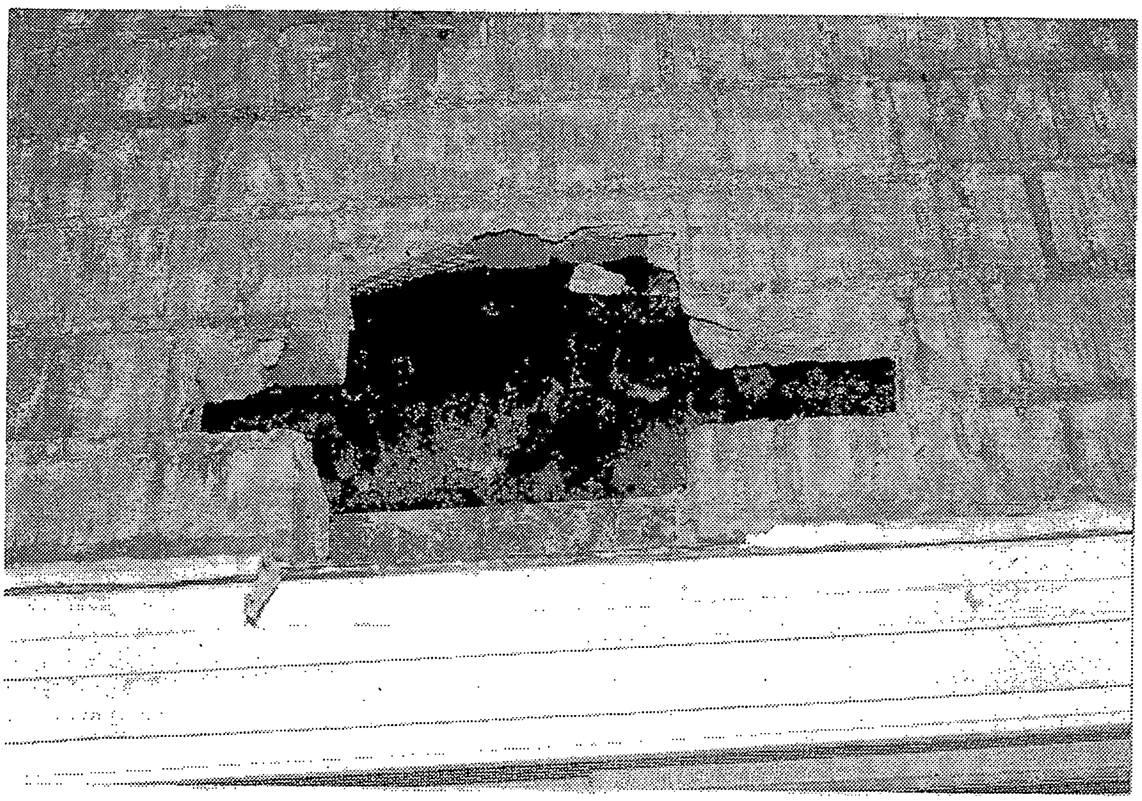
Time of occurrence	*Rain*
Location	*At bottom of openings*
Cause	• *Absent, damaged or poorly installed flashing* • *Absence or lack of slope on sills & balconies* • *Cracked caulking* ***(Photo 6)***
Test methods	• *Visual inspection* • *Removal of bricks above lintels* ***(Photo 5)***
Remedial measures	• *Install adequate flashing at bottom of opening* • *Provide 10% slope for sill & 2% slope for balcony* • *Redo the caulking*

Scenario 3.2.1: Air infiltration - around openings

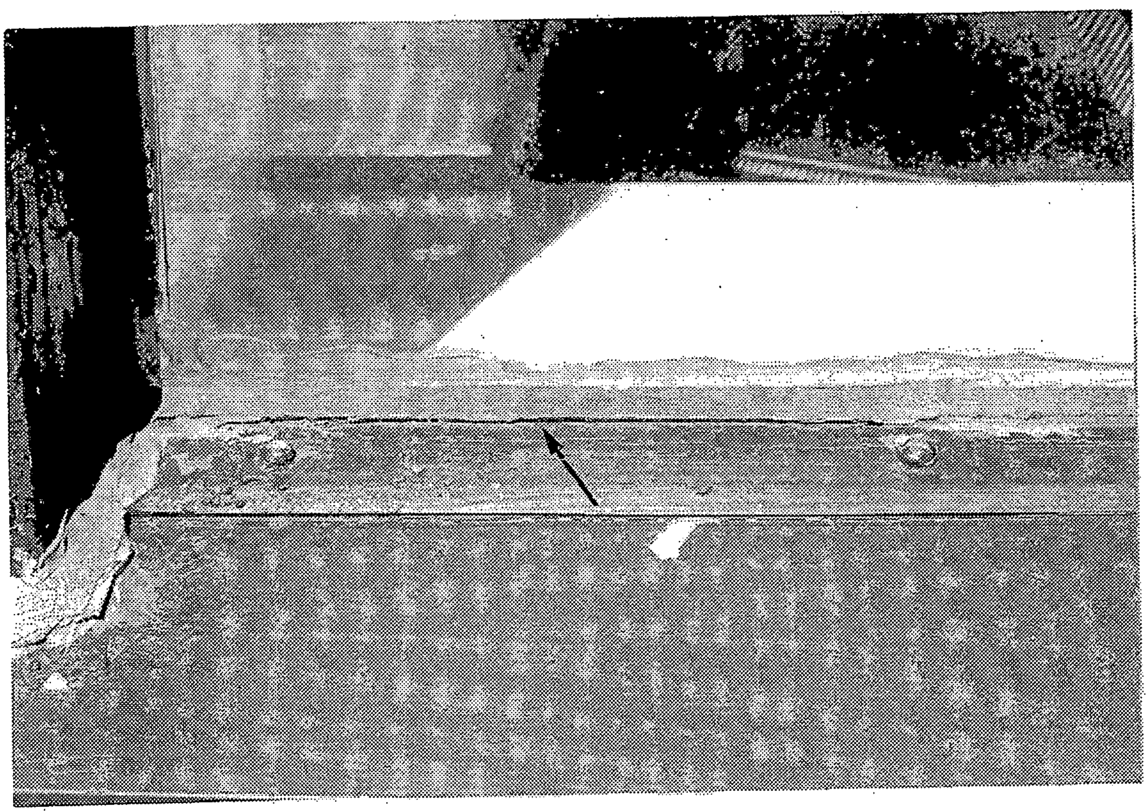
Time of occurrence	*Winter*
Location	*Around openings*
Cause	*Absence, damage or inadequate installation of air barrier*
Test methods	• *Smoke pencil* • *Thermography*
Remedial measures	• *Install a continuous air barrier around openings*

Scenario 3.3.1: Condensation

Time of occurrence	*Winter*
Location	*On windows, doors and frames*
Cause	• *High indoor relative humidity* • *Low surface temperatures* • *Poor insulation of frames* • *Air-infiltration around openings*
Test methods	• *Visual inspection* • *Smoke pencil* • *R.H. and temperature measurement* • *Thermography*
Remedial measures	• *Increase ventilation to lower relative humidity* • *Provide adequate insulation for the frames* • *Provide continuous air barrier around opening*



5. Removal of bricks above lintels to inspect flashing



6. Cracked caulking at bottom of openings

Scenario 4.1.1: Water infiltration - built-up roof

Time of occurrence	*Rain*
Location	*In built-up roofing*
Cause	*Splitting, erosion or puncture of membrane*
Test methods	• *Visual inspection* • *Water test* • *Thermography*
Remedial measures	• *Repair cracked, eroded or punctured membrane* • *Replace entire roof covering with a minimum of 2% slope*

Scenario 4.1.2: Water infiltration - shingle roof

Time of occurrence	*Rain*
Location	*In shingles*
Cause	• *Blown off shingles* • *Inadequately installed, damages or aged shingles* • *Inadequate roof slope*
Test methods	*Visual inspection*
Remedial measures	• *Replace damaged shingles* • *Provide adequate eave protection using rubberized membrane* • *Replace entire roof covering*

Scenario 4.1.3: Water infiltration - around openings in roof

Time of occurrence	*Rain*
Location	*Around chimneys, vents and stacks*
Cause	*Absence of or inadequately installed flashings*
Test methods	*Visual inspection*
Remedial measures	*Install adequate flashings around elements penetrating roof covering*

Scenario 4.1.4: Water infiltration - in ceiling

Time of occurrence	*Mild days after a cold spell*
Location	*Ceilings*
Cause	*Melting of frost present in attic or roof assembly because of condensation*
Test methods	*Visual inspection (during cold periods)*
Remedial measures	• *Ventilate the attic* • *Repair ceiling*

Scenario 4.2.1: Condensation - in attic

Time of occurrence	*Winter*
Location	*In attic space or within the roof assembly* • *under roof covering* ***(Photo 7)*** • *around access trap* ***(Photo 8)***
Cause	• *Air leakage from heated space* • *Lack or poor distribution of ventilation*
Test methods	• *Visual inspection (during cold periods)* • *R.H. and temperature measurement*
Remedial measures	• *Prevent air leakage from heated space* • *Provide adequate ventilation of attic or roof*

Scenario 4.2.2: Condensation - on ducts

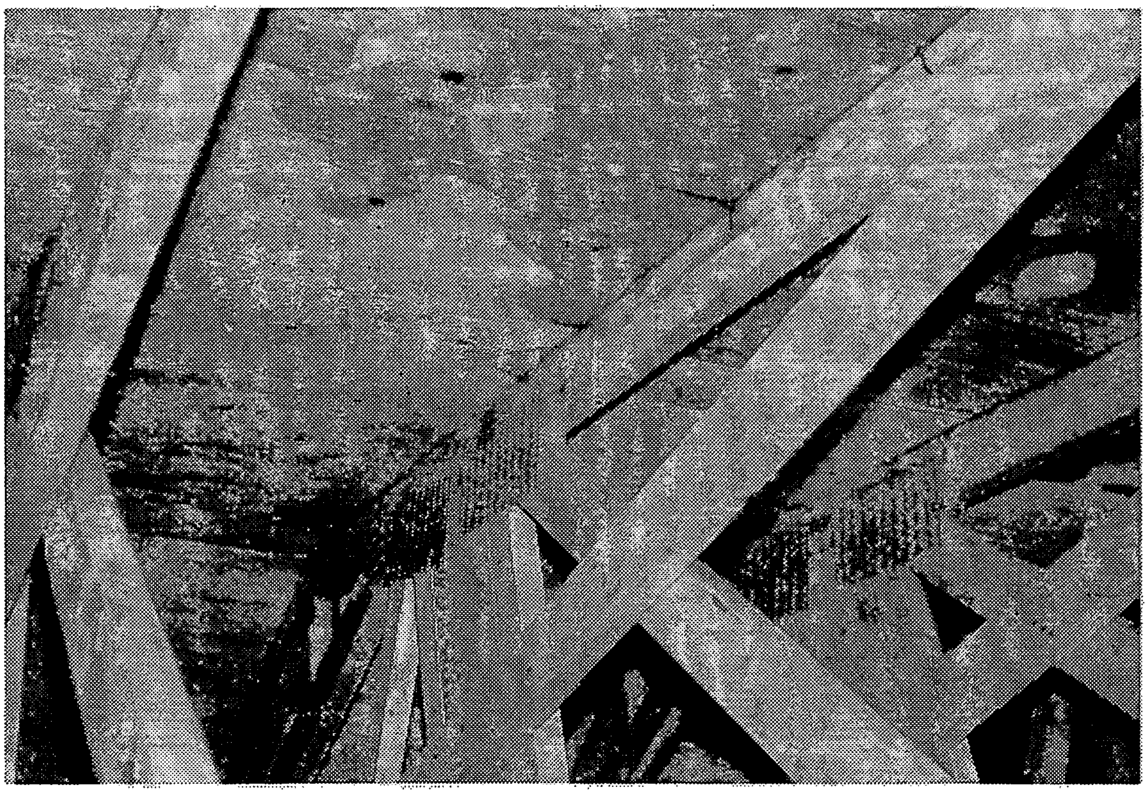
Time of occurrence	*Winter*
Location	*On ducts passing through the attic space*
Cause	*Absence of insulation on ducts*
Test methods	*Visual inspection*
Remedial measures	*Provide adequate insulation around ducts*

Scenario 4.3.1: Ice dam

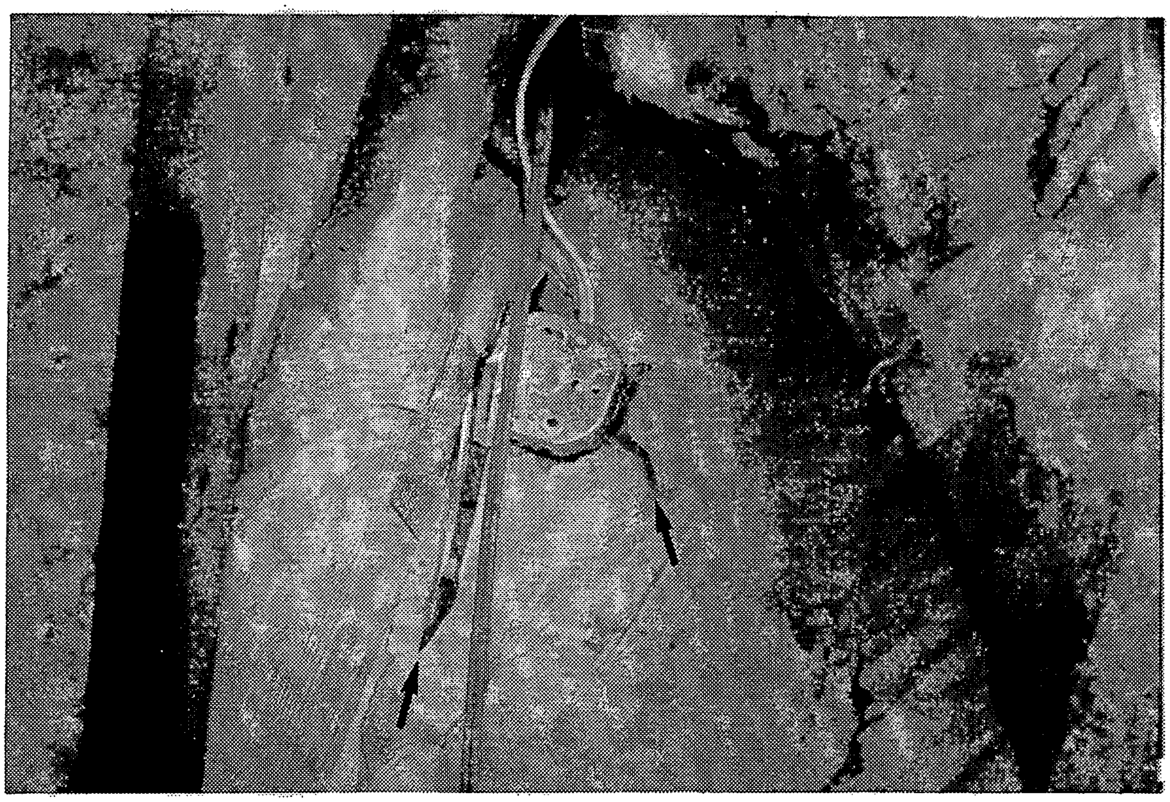
Time of occurrence	*Winter*
Location	*Roof eaves*
Cause	• *Inadequate ventilation of attic or roof* • *Inadequate insulation of attic or roof* • *Air leakage from heated space*
Test methods	• *Visual inspection* • *Smoke pencil* • *Thermography*
Remedial measures	• *Minimize air leakage by sealing openings in air or vapour barrier (particularly around openings, traps and lights)* • *Improve ventilation of attic or roof* • *Provide adequate insulation in attic*

Scenario 4.4.1: Rotting of wood

Time of occurrence	*Any time*
Location	*Wood components*
Cause	*Wetting and drying of wood due to* • *Water infiltration* • *Condensation*
Test methods	• *Visual inspection*
Remedial measures	• *Refer to appropriate water-infiltration and condensation problem* • *Replace rotten wood*



7. Condensation under coverings



8. Damaged vapour barrier around traps & lights

4.2. Diagnostic test methods

Figures 5, 6, 7, and 8 show the matrices of test methods required to investigate the various problems for each envelope component. Once the envelope component and problem category are known, the user can identify the appropriate test methods from the corresponding matrix. A brief description of the test methods is given below:

i. Wax plug

Purpose:	To determine if a crack is moving
Materials required:	Butane torch, sealing wax, lighter (Photo 9)
Application:	The sealing wax is softened using the butane torch and applied to form a bridge across the crack. If the crack does not move, the sealing wax remains intact. If there is movement, the wax plug cracks and the movement can be measured.

ii. Removal of bricks

Purpose:	To check the flashing at various locations of a brick veneer wall (Photo 5)
Materials required:	Chisel and hammer
Application:	Using the chisel, remove the mortar between the bricks, so that they can be removed without breakage. Once the bricks are removed, check for the adequacy of the flashing and verify if the cavity behind the bricks is free of mortar permitting drainage.

iii. Water test -roofs

Purpose:	To locate leaks in Built-up membrane roofing
Material required:	Garden hose
Application:	Start spraying water on a surface of 4 to 6 sq. m. at a point lower on the slope of the roof where the water seems to enter. Spray for 15 minutes and observe if the water infiltrates the building. If no water enters, spray another area moving gradually up the slope for 15 minutes and check for water infiltration. Repeat the process until the location is determined.

iv. Smoke pencil

Purpose:	To determine air leakage
Material required:	Drager smoke tubes (Photo 10)
Application:	Direct smoke where air leakage is assumed to take place and observe the movement of the smoke.

v. Thermography

Purpose:	To determine areas of air leakage, missing insulation or concealed condensation
Materials required:	Infra-red scanning equipment and professional thermography kit
Application:	Certified and trained thermographers needed to take thermograph pictures and interpret the results.

vi. Relative humidity and temperature measurement

Purpose:	To determine the temperature and relative humidity in a room
Materials required:	Combined thermometer and hygrometer
Application:	Measure temperature and relative humidity at the same location.

vii. Excavation for inspection

Purpose:	To inspect foundation walls and french drain
Materials required:	Shovel or small backhoe
Application:	Excavate by hand with a small backhoe where water enters the basement or where efflorescence is present. Excavation should be done down to the french drain.

viii. Levelling

Purpose:	To determine the elevation of the structure and the floors at different points
Materials required:	Engineers level or water level
Application:	Take readings at different points in the building to determine the difference in elevation in order to assess the differential movement.

BASEMENTS AND FOUNDATIONS	Visual inspection	Wax plug	R.H & temperature measurement	Exacavation for inspection	Elevations	Scenarios
1.1 Cracks	●	●				1.1.1., 1.1.2 1.1.3
1.2 Settlement	●				●	1.2.1
1.3 Water infiltration	●			●		1.3.1., 1.3.2 1.3.3
1.4 Condensation	●		●			1.4.1
1.5 Efflorescence	●			●		1.5.1

Figure 5: Matrix of test methods for basement and foundation problems

EXTERIOR WALLS	Visual inspection	Wax plug	Water test	R.H & temperature measurement	Remove brick or cladding	Smoke pencil	Thermography	Scenarios
2.1 Cracks	●	●						2.1.1., 2.1.2 2.1.3
2.2 Water infiltration	●		●		●			2.2.1 2.2.2
2.3 Air infiltration						●		2.3.1 2.3.2
2.4 Condensation	●						●	2.4.1
2.5 Efflorescence	●							2.5.1
2.6 Mould & Mildew	●		●					2.6.1
2.7 Cold spots				●			●	2.7.1

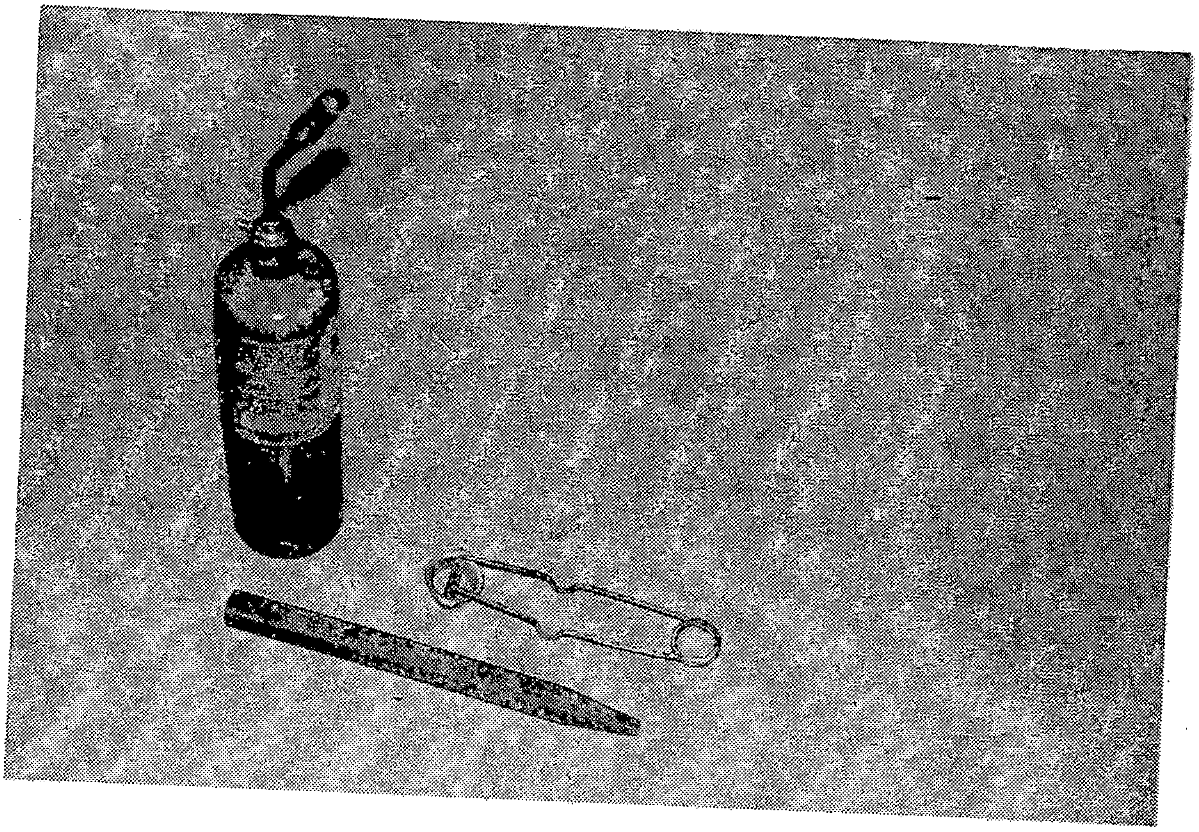
Figure 6: Matrix of test methods for exterior wall problems

WINDOWS AND DOORS	Visual inspection	Water test	Remove bricks for inspection	R.H. & temperature measurement	Smoke pencil	Thermography	Scenarios
3.1 Water infiltration	●	●	●				3.1.1 3.1.2
3.2 Air infiltration					●	●	3.2.1
3.3 Condensation	●			●	●	●	3.3.1

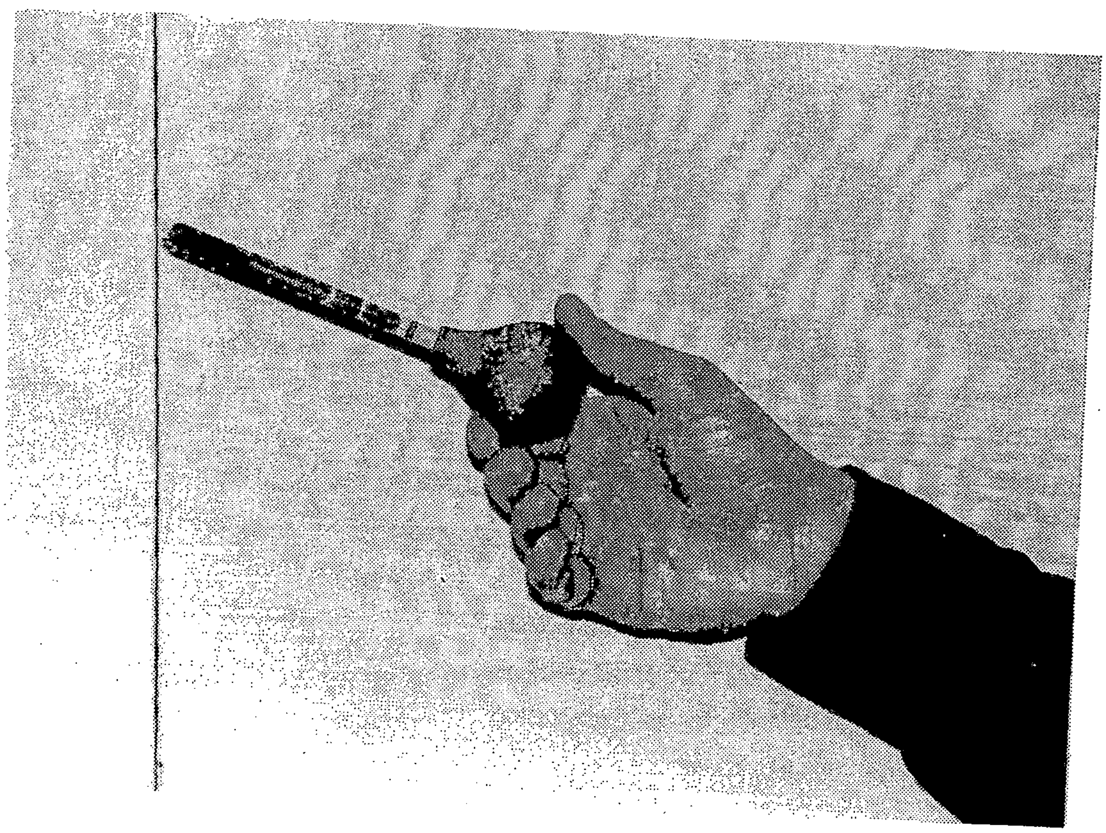
Figure 7: Matrix of test methods for windows and doors problems

ATTIC AND ROOF	Visual inspection	Water test	R.H. & temperature measurement	Smoke pencil	Thermography	Scenarios
4.1 Water infiltration	●	●			●	4.1.1., 4.1.2 4.1.3., 4.1.4
4.2 Condensation	●		●		●	4.2.1 4.2.2
4.3 Ice dam	●			●	●	4.3.1
4.4 Rotting of wood	●					4.4.1

Figure 8: Matrix of test methods for attic and roof problems



9. Wax plug test tools



10. Smoke pencil

4.3 Expert system prototype

The framework and scenario descriptions developed in this study have been represented in the knowledge base of an expert system prototype. This expert system presents a series of menu choices to the user to identify the envelope component, problem category and detailed description of the problem. Based on the user input the system concludes by displaying the appropriate scenario describing the causes, test methods and remedial measures.

This expert system prototype is implemented in LEVEL 5 Object, a commercially available development environment for the IBM personal computers. This system runs under Microsoft Widows 3.0 and offers versatile knowledge representation and user-interface development features. The prototype implementation is provided in a file named BEFD, acronym for Building Envelope Failure Diagnosis system. This prototype system has 32 rules, 10 demons, 6 query displays and 10 objects in its knowledge base. The knowledge base is modular and hence new problem categories and scenarios can be easily added to extend the scope of diagnosis.

The end-users of the system do not need any prior knowledge of expert systems. The program is supplied in a run-time format which can be easily installed. The installation steps are provided in Appendix A. The end-user must have an IBM Personal computer with a minimum of 2 Meg RAM and have MS Windows 3.0.

5. RECOMMENDATIONS TO BUILDERS

Based on the analysis of the envelope problems and scenarios, the following recommendations are made to builders and contractors to eliminate the occurrence of these problems.

5.1. Avoiding foundation problems

1. The number of cracks can be greatly reduced or even eliminated if two #15 steel reinforcement bars are placed at the top and bottom of the foundation wall as shown in Figure 9.

2. Foundations must be placed on non-disturbed soil containing no organic materials. It is also desirable that the excavation to be kept dry at all times since excess wetting of the soil can create abnormal expansion. In certain cases, test soil borings may be required to determine its bearing capacity.

3. Footings and floor slab must never be placed on frozen soil and must be protected against frost at all times. Also foundations should not be too close to fast growing trees, to avoid settlement problems.

4. To prevent the entry of water at the top of the foundation wall, it is necessary that the flashing be properly installed and that proper material be used. The flashing shall be laid out as shown in Figure 10. It shall extend at least 5 mm past the outside face and rise at least 150 mm behind the sheathing paper.

5. After the concrete has been placed and forms removed, it is necessary to break the form ties and seal each one of these before applying the damp-proofing. The damp-proofing should consist of two applications of asphalt emulsions to seal all the pores.

6. French drains must be installed on undisturbed soil below the level of basement floor. Once the foundation drain has been laid on undisturbed

soil, it should be covered with at least 8 inches of clean granular fill then the remainder could be backfilled with material from the site.

7. To prevent abnormal moisture in the basement, it is necessary to put a 0.15 mm thick polyethylene film below the basement floor.

5.2. Avoiding exterior wall problems

1. Formerly, the sill plate was laid in mortar which ensured that the joint between the foundation wall and the sill was air tight. This practice has been discontinued, however it is still necessary that this joint be air tight. This can be done by applying a continuous bed of plastic cement to the sill plate before placing it on the foundation wall. Other solutions would be
    i. to have a continuous air barrier which is tied into the vapour-barrier of the basement and first floor wall (Figure 11)
    ii. to apply sprayed urethane from top of the concrete foundation to the underside of the floor support as shown in Figure 12.

2. Condensation within the exterior walls are often caused by air leakage and this can be prevented by installing a continuous air barrier around the entire building frame.

3. Efflorescence on brick masonry indicates that the brick is being wetted in an abnormal manner. This excessive humidity can result from rain water flowing down the wall or from air leakage. To prevent air leakage, it is necessary that there be a continuous air-barrier on all surfaces and that water from the roof be diverted away from the facades.

4. To eliminate the possibilities of cracks at the junction of the ceiling and interior partitions, it is necessary that the gypsum board in the ceiling be floating a certain distance on each side of the partition wall as shown in Figure 13.

5.3. Avoiding window and door problems

1. To ensure that there is no water entry at the top of openings, it is necessary to install a proper flashing as shown Figure 14 and 15.

2. In order to prevent any water from entering at the bottom of the openings, the flashing needs to be placed below the sill and to extend at least to the outer face of the wall as shown in Figures 16 and 17. Also it is necessary to caulk all the joints between different materials which are susceptible to permit water infiltration.

3. Air leakage around windows and doors can be prevented by providing an air barrier properly sealed to the frame as shown in Figures 18 and 19.

5.4. Avoiding roof and attic problems

1. Most water infiltration problems in roofs are due to improper flashing details around openings. Many good details to overcome these problems are provided by the Canadian Roofing Contractors Association and Quebec Master Roofers Association manuals.

2. In order to prevent condensation in attics, it is necessary that the air barrier be continuous so that no air from the heated space can enter the attic space. Even thought the air barrier is continuous it is necessary to have proper ventilation of the air space located above the insulation. In cases where the roof slope is more than 1 in 6, the unobstructed area of the air entry and air outlet for ventilation purposes of the attic space should be equivalent to the roof surface area divided by 300. However if the roof slope is less than 1 in 6, these areas need to be increased to be equivalent to the roof area divided by 150.

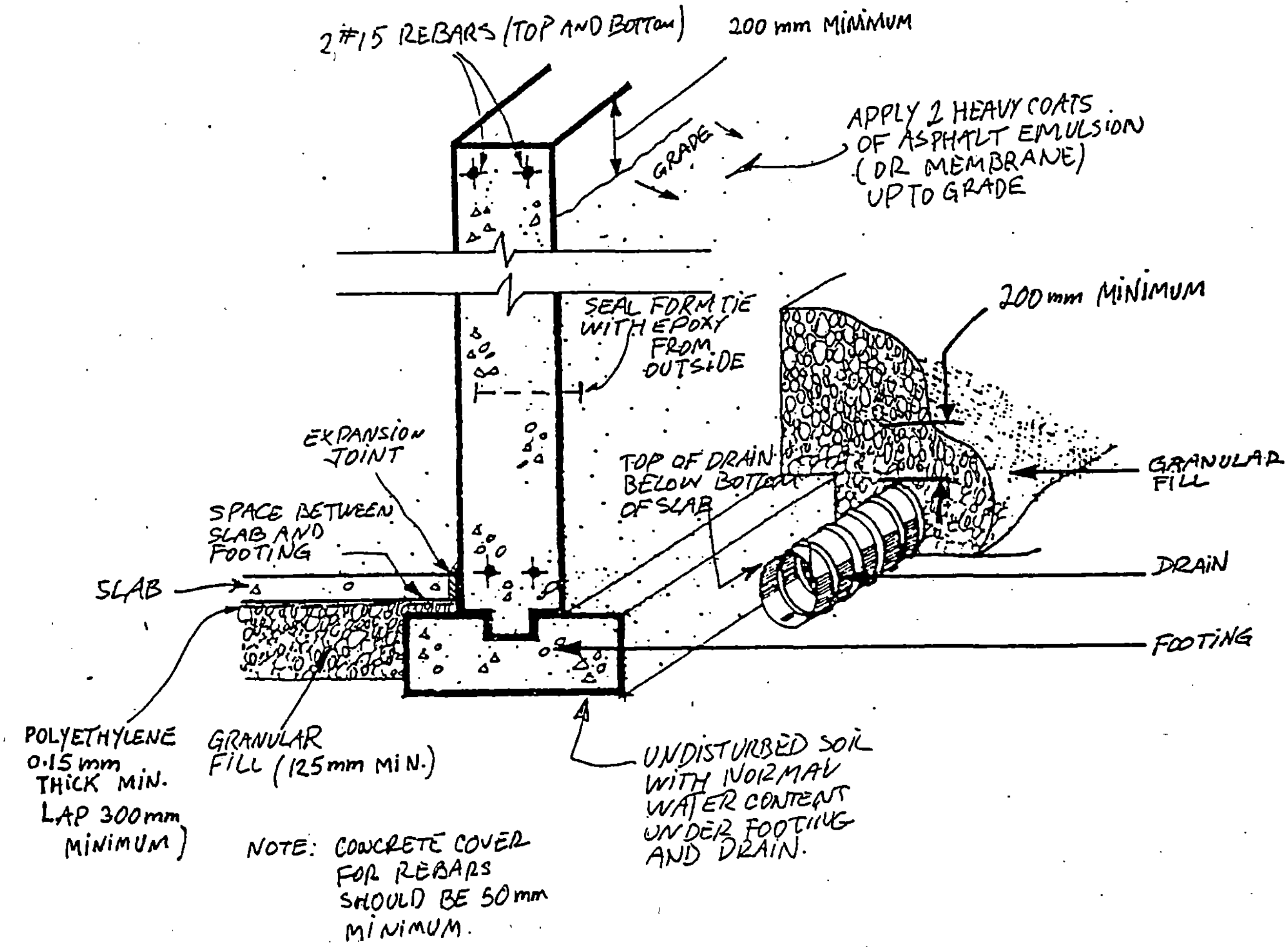


Figure 9: Foundations - drainage
dampproofing and reinforcement

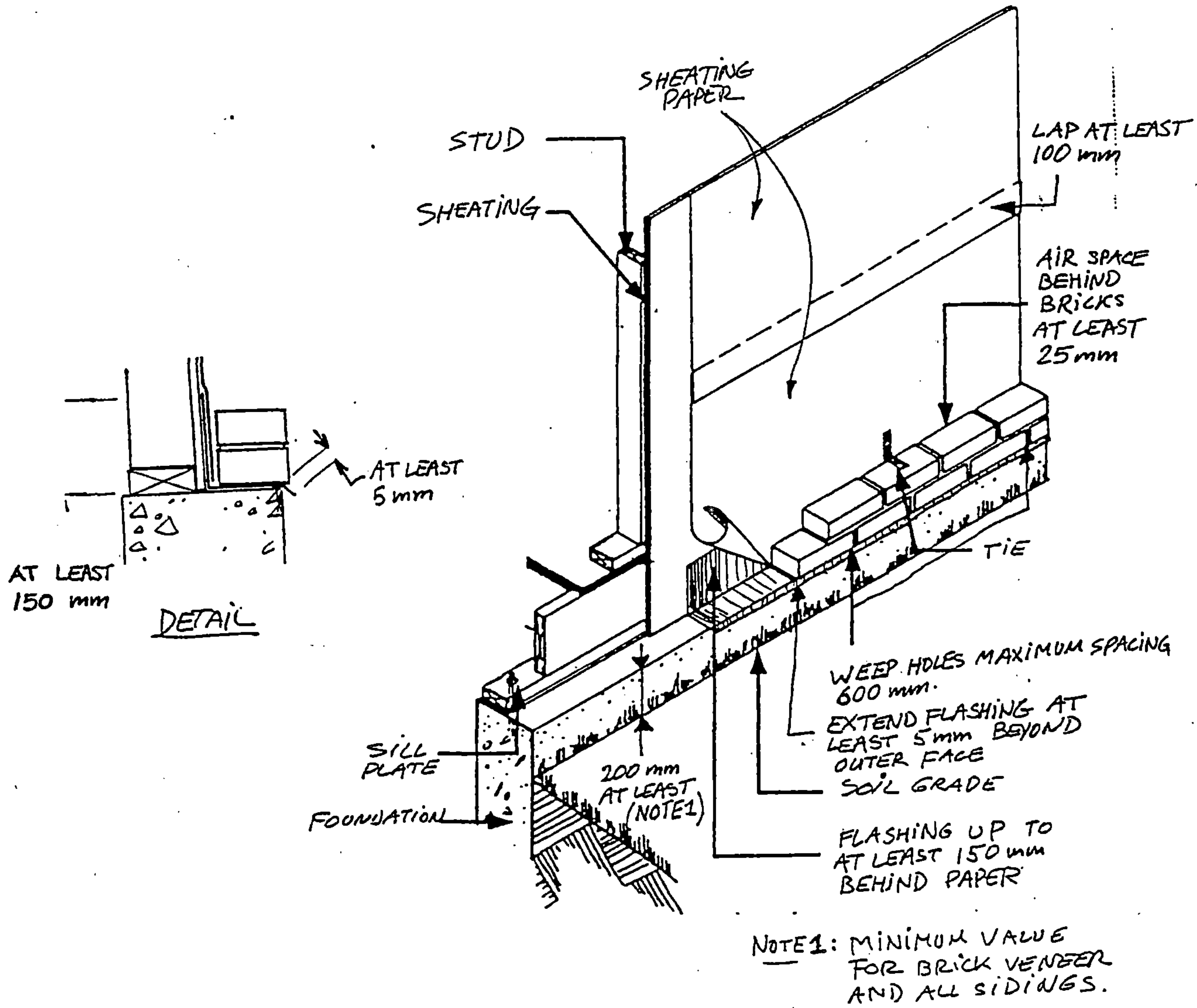


Figure 10: Flashing at bottom of brick veneer

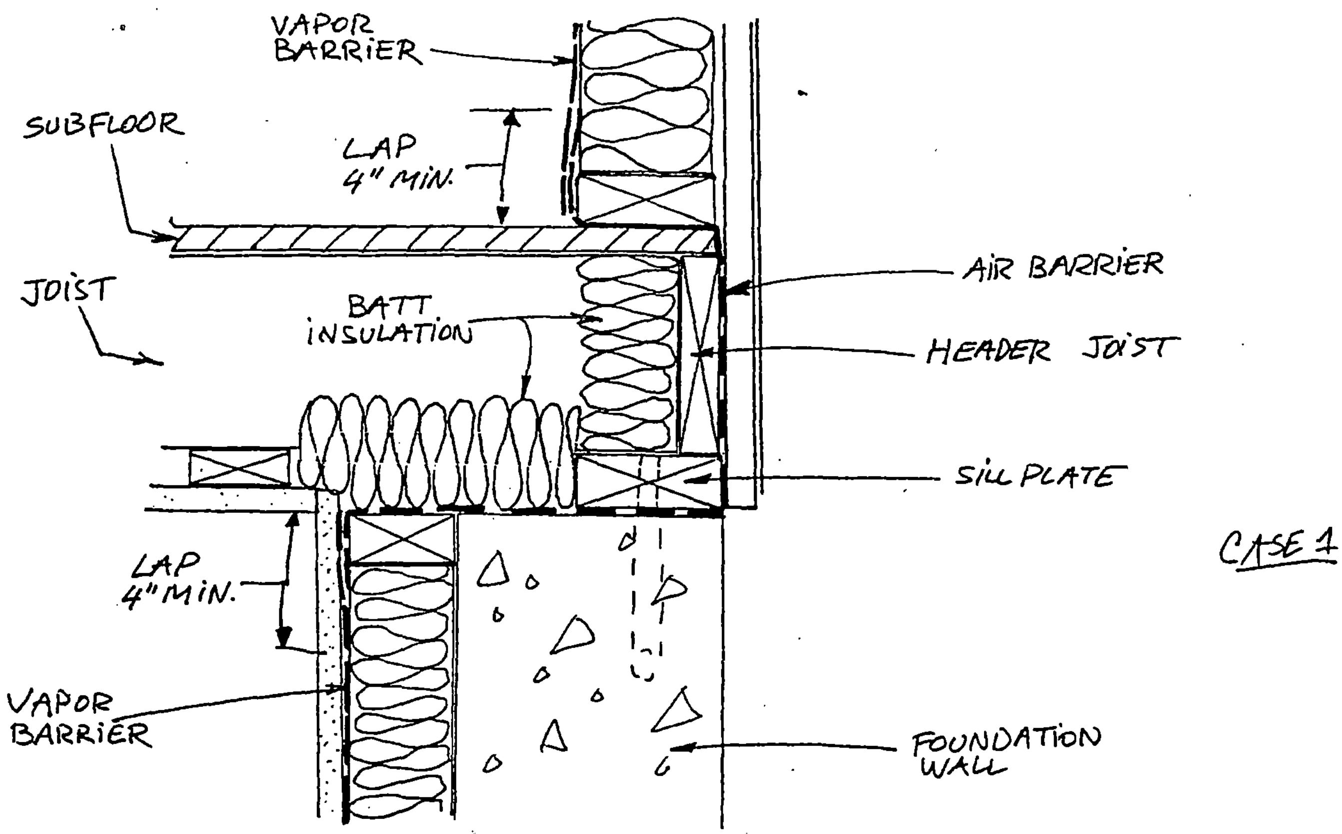


Figure 11: Eliminating air infiltration at sill-foundation joint

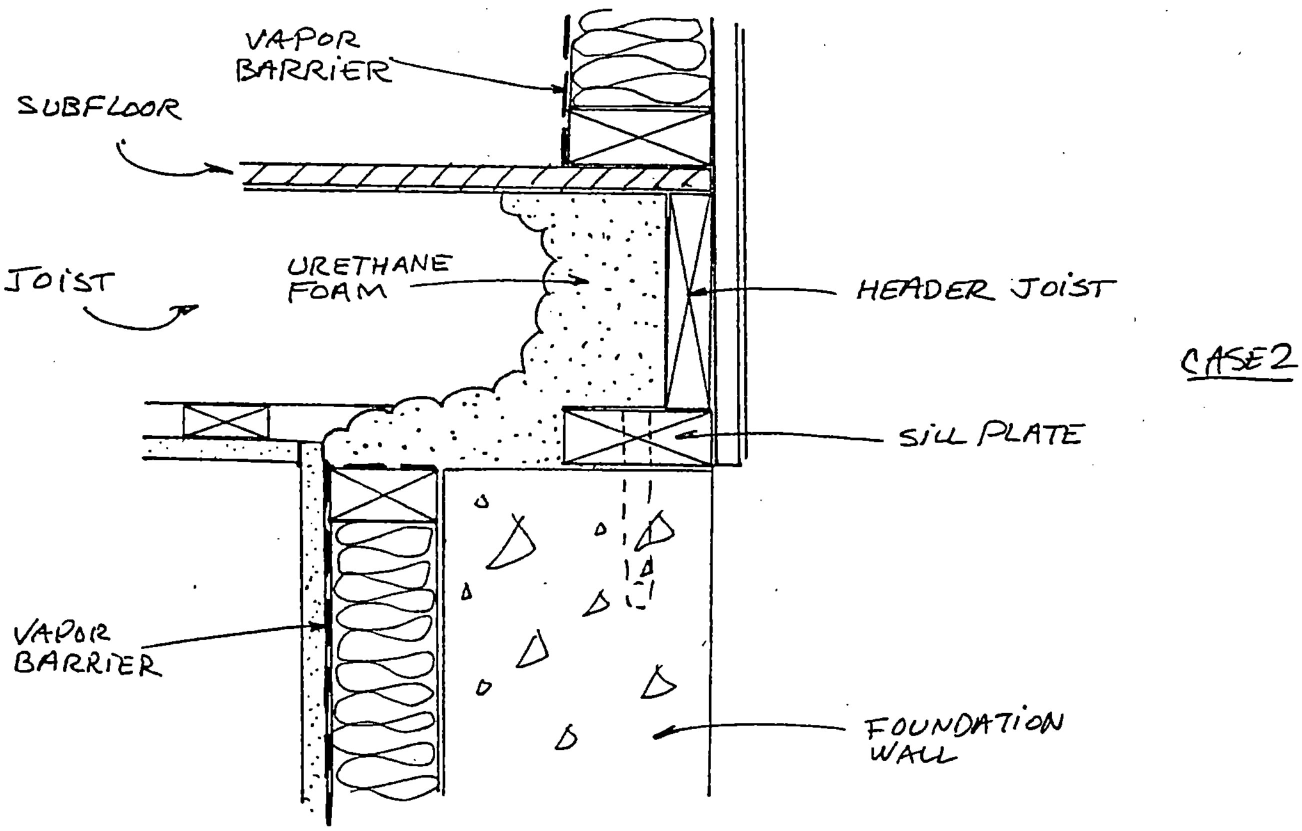
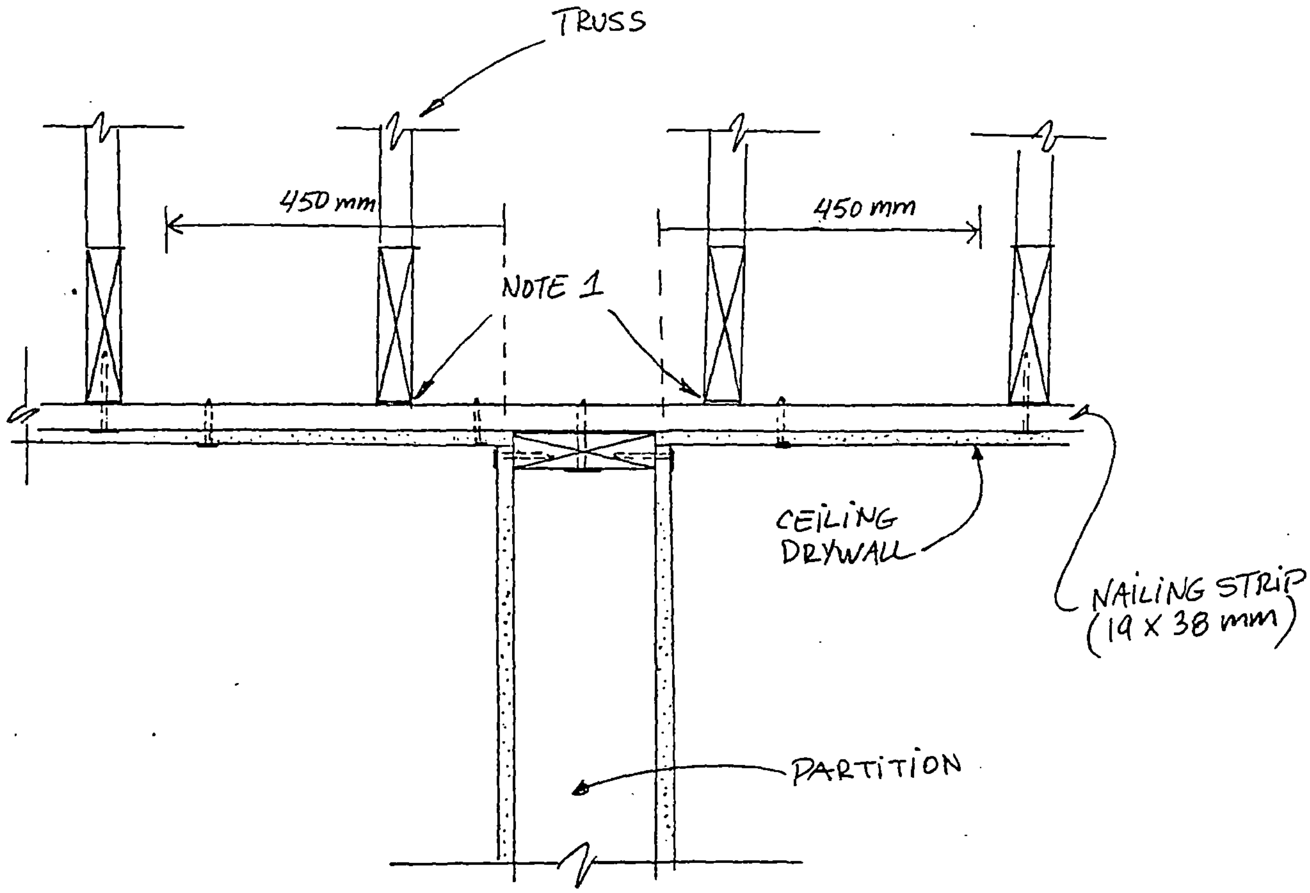


Figure 12: Eliminating air infiltration at sill-foundation joint-
Urethane foam



NOTE 1 : DO NOT NAIL NAILING STRIP TO BOTTOM CHORD OF TRUSSES THAT ARE WITHIN 450 mm OF PARTITION WALL.

Figure 13: Eliminating damages due to truss uplift

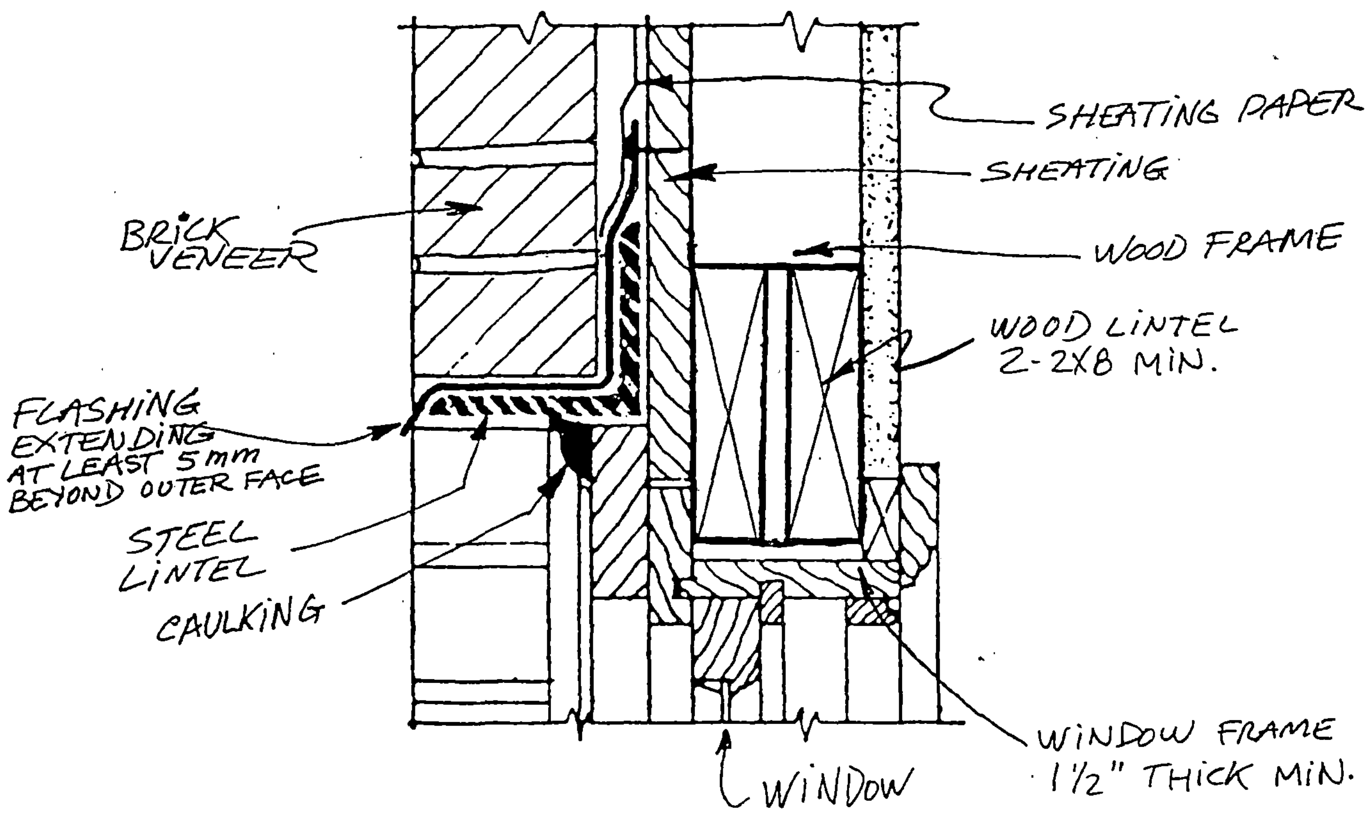


Figure 14: Flashing at head of window
brick veneer

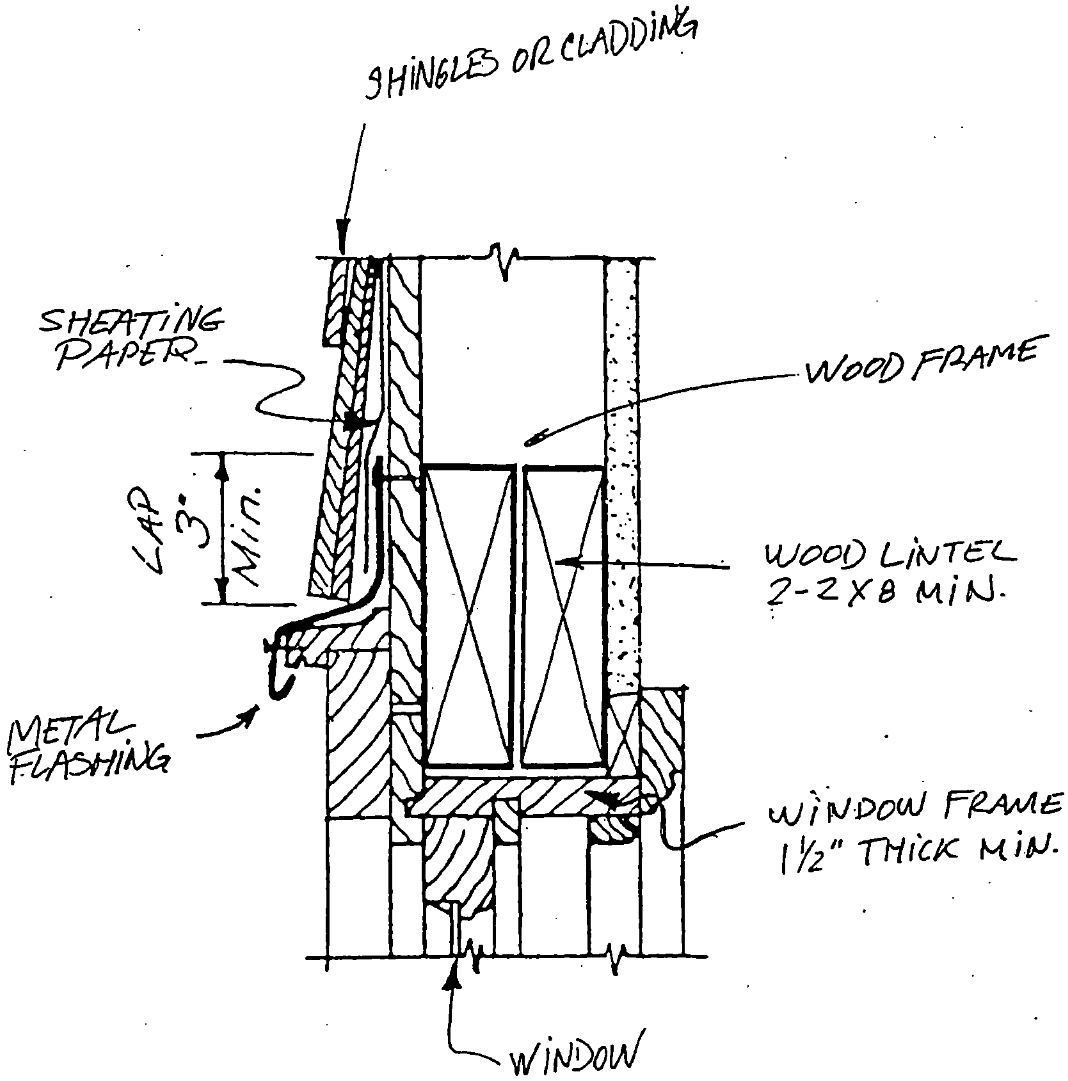
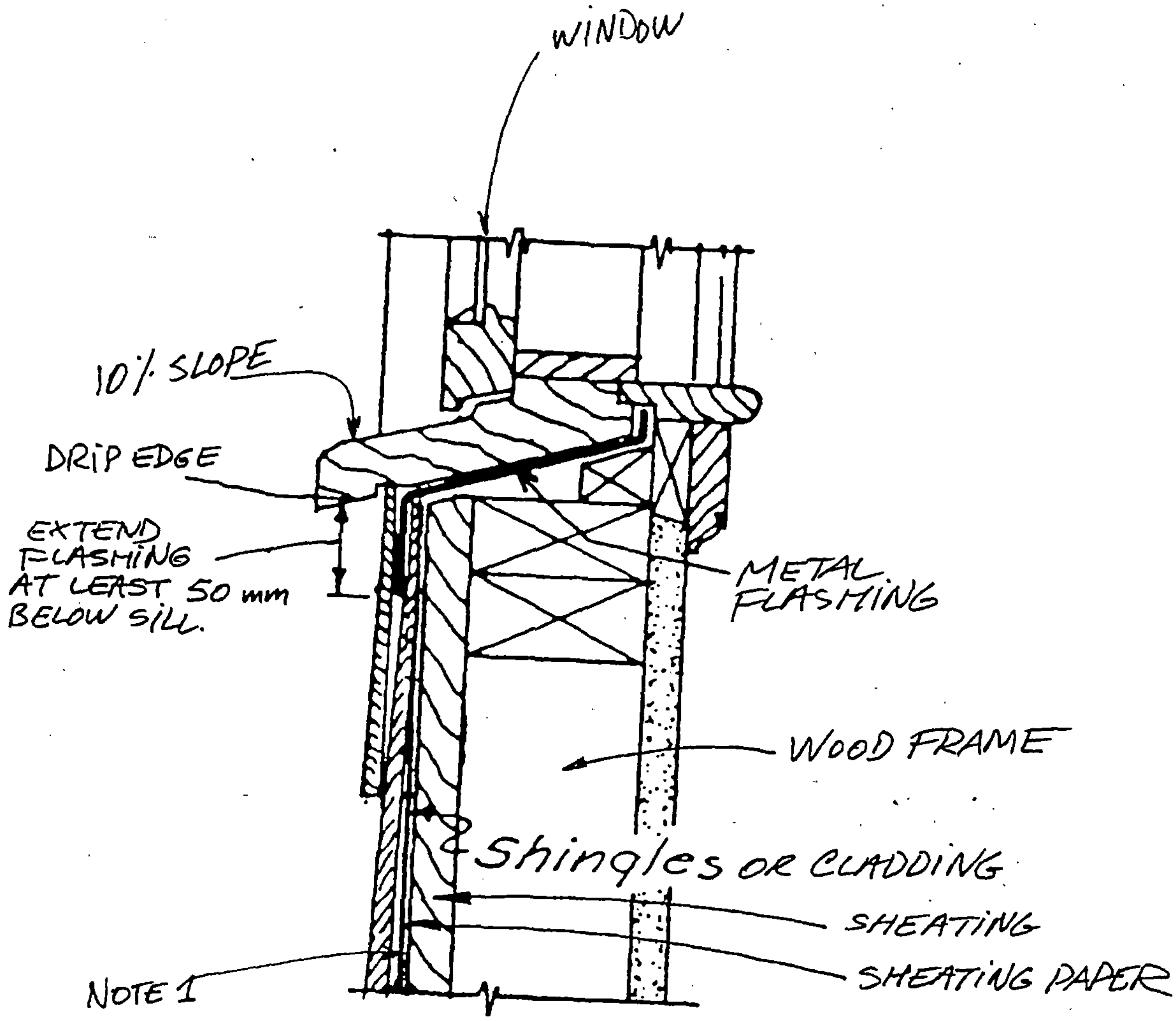


Figure 15: Flashing at head of window
shingles or cladding



NOTE 1:
IN HUMID REGIONS, PROVIDE AN AIR SPACE BY INSTALLING CLADDING ON FURRING.

Figure 16: Flashing at window sill
shingles or cladding

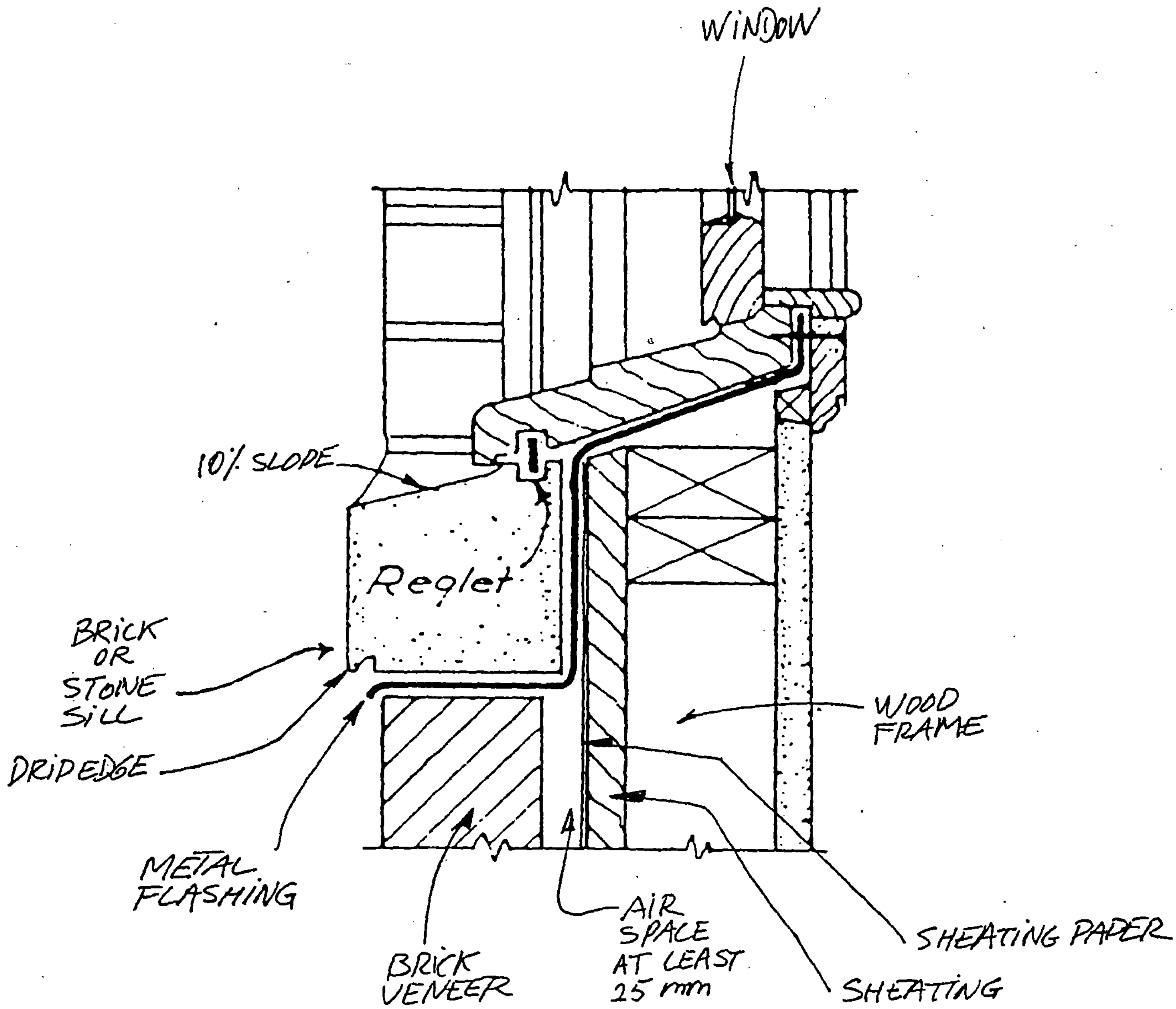


Figure 17: Flashing at window sill
brick veneer

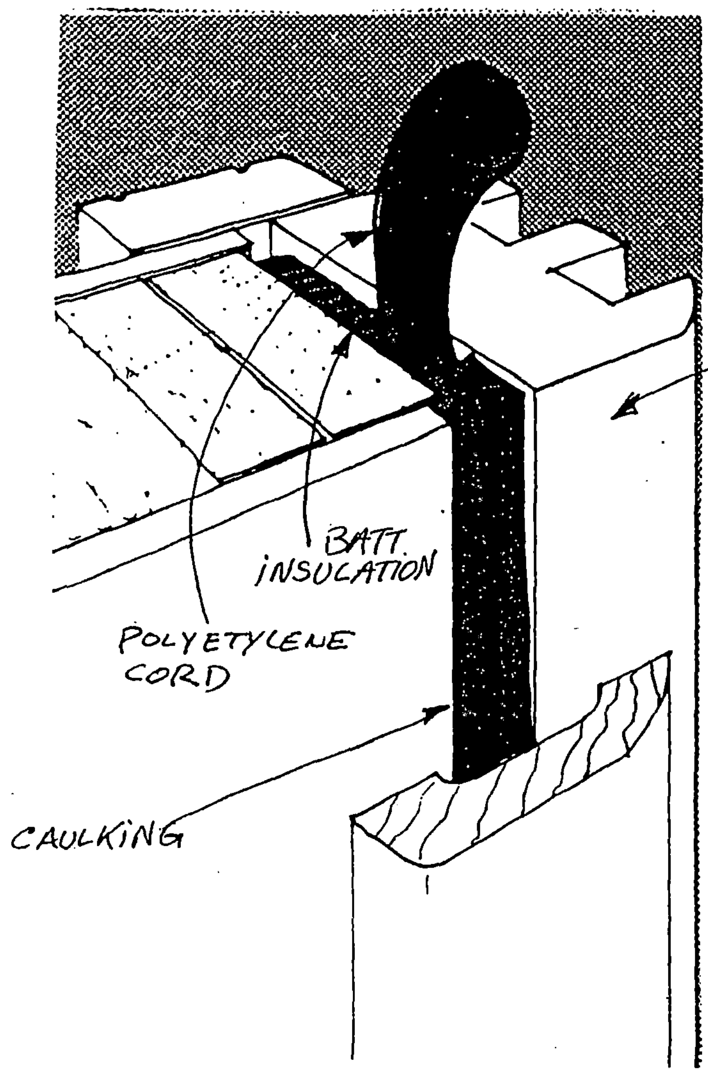


Figure 18: Eliminating air infiltration
around openings - caulking

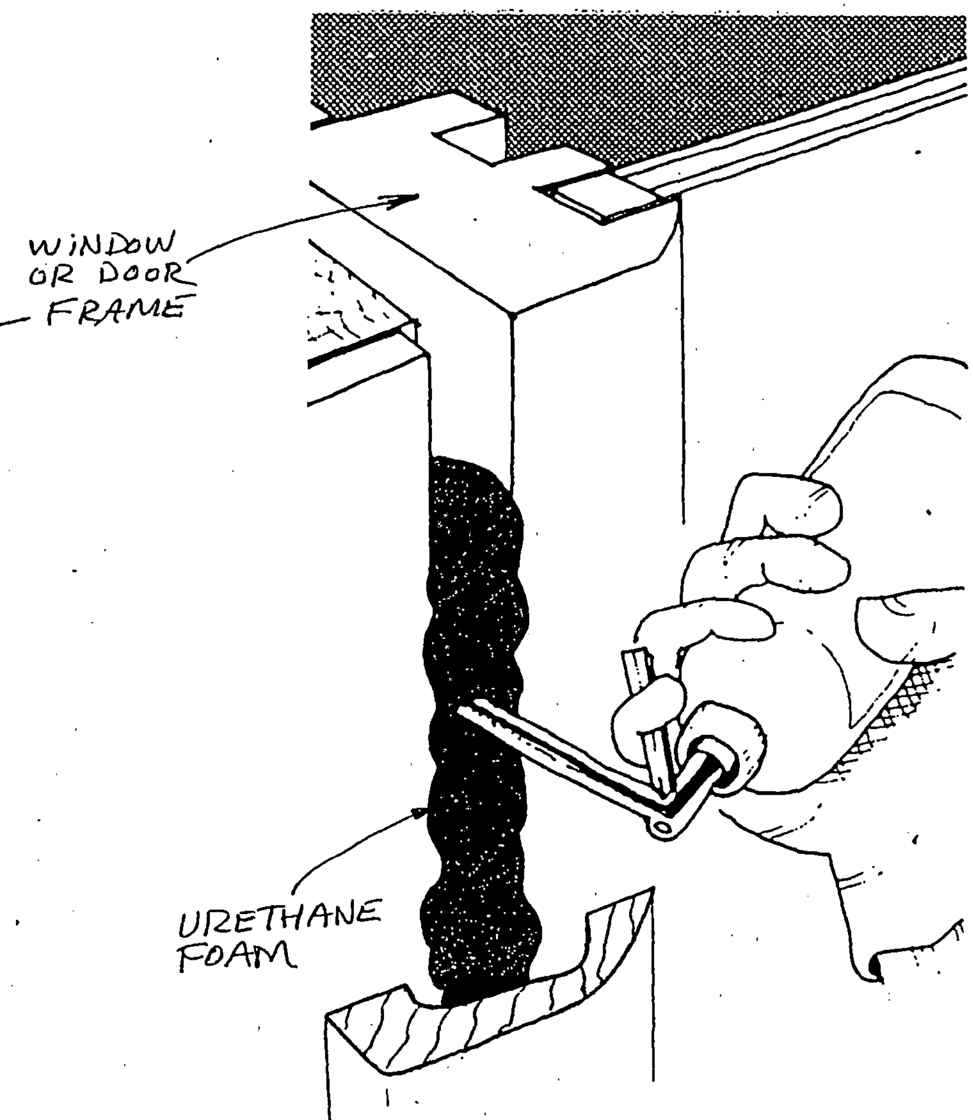


Figure 19: Eliminating air infiltration around
openings - urethane foam

6. CONCLUSIONS

The present study has collected and analyzed data on residential envelope problems reported in fifty buildings from the APCHQ warranty program files. The collected data is provided in Disk 1 in the database format of the CMHC-BPS system. An analysis of this data shows that moisture and cracking problems are the most prevalent among the eight types of envelope problems reported. Most of these problems are attributed to improper or lack of specifications, poor construction details, poor workmanship, and a lack of understanding of certain building science principles. It is found that there is a general lack of knowledge regarding the role of flashing, importance of air barrier and the performance of wood components. A technology update seminar on these important issues would be appropriate to inform builders and members of APCHQ.

During data collection and problem survey it was recognized that the CMHC-BPS system requires many design details which are not readily available in the APCHQ warranty files. Besides this, the present CMHC-BPS focuses specifically on high rise masonry condominium buildings whereas most of the APCHQ warranty files correspond to low-rise residential buildings. Hence, a simplified and modified version of CMHC-BPS will be appropriate for APCHQ's use.

The objective of developing a diagnostic framework is accomplished by compiling a list of scenarios representing the most common residential building envelope problems. Each scenario description consists of the problem type, location, time of occurrence, possible causes, test methods and remedial measures. A literature review and consultation with industry experts were carried out to develop 32 such scenarios. Envelope components and problems are categorized in a matrix form for identifying appropriate scenario descriptions. Diagnostic test method descriptions for eight simple techniques are presented for investigating envelope problems. These test methods and their suitability to diagnose the various problems are also represented in a matrix form. The classification format is specific to generic residential envelope problems, but can be extended to more specific and other problem types.

The diagnostic framework and scenario descriptions are represented in the knowledge base of an expert system prototype. This expert system can provide diagnostic information specific to particular problem scenarios. Typically an end-user of this system selects the envelope component and problem category, and obtains information regarding causes, test methods and remedial measures. This prototype demonstrates the feasibility and advantages of documenting the available expertise and provides easy access to a knowledge base of diagnostic information.

Further research and development in extending the framework and expert system should be undertaken to address more specific envelope problems and providing graphical presentation of construction details. It is also possible to interface expert systems with databases such as the CMHC-BPS, so that case-based diagnosis can be used to give an estimate of repair costs and magnitude of problems. Also, if a building with a particular set of design details (already in the database) is found to have problems, and if a similar building is being registered for construction, then the program can alert the building inspector to rectify the situation. Provincial home warranty programs can greatly benefit from this approach by providing the database with building design details at construction and commissioning stage.

APPENDIX A: EXPERT SYSTEM INSTALLATION AND INSTRUCTIONS TO USER

1. System Requirements:

   Hardware - IBM PS/2 or 386 compatible with 2MB RAM and 1 MB hard disk space

   Software - Microsoft Windows 3.0

2. Installation instruction:

   i. Create a new directory C:\BEFD in the hard disk
   ii. Copy the two files L5RO.EXE and BEFD.APP files from the floppy disk to hard disk, in directory C:\BEFD
   iii. Run MSWINDOWS
   iv. Select "New" in the "File" menu
   v. Choose option "Program item"
   vi. Enter "C:\BEFD\L5RO.EXE BEFD.APP" in the command line
   vii. Enter "BEFD" in the description line
   viii. Click "OK" to return to program manager
   ix. Double click the "BEFD" icon and you will see the introductory screen for the expert system

3. User Instruction

   i. The introduction screen click on "Continue" button
   ii. In the envelope component menu select the appropriate one & click "OK!"
   iii. Select problem category and click "OK!" again
   iv. For other menus, select the appropriate choice and click "OK!"
   v. To restart the session, select "Restart" from the "File" menu.

APPENDIX B: BIBLIOGRAPHY

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