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EFFECTS OF CONSTRUCTION TOLERANCES ON EXTERIOR WALLS

by

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ABSTRACT

This report examines the effects of construction tolerances on exterior walls. It focuses on walls constructed of one material and on walls incorporating two or more materials.

Measurement data was collected from three different buildings at different stages of construction. These buildings were constructed from steel, concrete, and concrete block. Column and wall plumbness, floor-to-ceiling heights, and wall cavity air space, along with general observations were documented. A statistical analysis on the collected data was carried out and compared with relevant Canadian Standards, as well as to previous studies done on plumbness.

The analysis found that poor workmanship and inspection practices are one of the main contributors to building components exceeding tolerance specifications. Other problems lie within the codes themselves, and their incompatibility with each other at elevations above 15000 mm. In addition, poor structural detailing influences the finished wall assembly which further complicates the building process.

The paper concludes with recommendations for changes to Canadian Standards, and to construction industry practices.

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Effects of Construction Tolerances on Exterior Walls submitted by Matthew Alexander Augustus Mis in partial fulfilment of the requirements for the degree of Master of Science in Structural Engineering.

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1. INTRODUCTION

1.1 OBJECTIVES AND SCOPE

The construction industry requires a seamless integration of various trades in order to produce a high quality product. To maximize efficiency and ensure cost effectiveness, it is essential that proper coordination and standardization is achieved.

One area where it is important to ensure commonality, is in the determination of tolerance limits in the construction of exterior walls. Most tolerance standards are material based. These tolerance limits are especially important when considering the interaction of different tolerances when combining various materials during construction. For example, the maximum allowable vertical plumb tolerances for the placement of concrete and masonry elements are ±50 mm and ±13 mm respectively.

This paper has three objectives in developing an understanding of the effects that construction tolerances have exterior walls:

1. To determine whether current tolerance limits of individual building materials as set out in the Canadian Standards are being met;
2. To examine the results of combining one or more building components that have different tolerance limits; and
3. To make recommendations based on the results of these findings.

Three buildings in the Edmonton area were chosen for the purpose of the study. Each was constructed of a different material. Building A was built using steel with masonry veneer. Building B was built with concrete. Building C was constructed using concrete blocks. Readings were taken of wall and column plumbness, wall cavity size, and floor-to-ceiling heights. Data from previous research on column and wall plumbness was also examined and compared to this paper's data in order to verify its validity.

1.2 ORGANIZATION OF THESIS

A literature review is presented in Chapter 2. Information on the frequency and associated costs of facade failure, common types of cladding failure, their causes and preventative design methods are included. Current design standards of Canadian and U.S. codes are presented and compared. A section is dedicated to illustrating the results when combining codes of different building materials. A summary of previously researched data on column and wall plumbness completes this Chapter.

Chapter 3 reviews case study Buildings A, B and C. Study of their plans, details of their construction, and the method and accuracy of the measuring devices used in collecting the data are discussed.

Chapter 4 presents the author's data. Qualitative observations are noted where they occur. Data on steel, concrete and masonry were each compared to their associated Canadian Standard and to one another. A statistical analysis on each of the materials was then conducted which allowed a comparison between each material in the study, and to previously collected data found in Chapter 2.

Chapter 5 presents conclusions and recommendations.

Appendix A contains equations that apply throughout the paper. Appendices B, C, and D contain direct extracts from the Canadian Standards pertaining to steel, concrete, and masonry construction tolerances.

2. LITERATURE REVIEW

2.1 INTRODUCTION

The standard of accuracy thought to be attainable in building construction is often much higher than that actually found in practice. In addition, the problems associated with tolerances are often either neglected or not given much consideration during the design stage.

Tolerances are primarily material based, and therefore can vary substantially whenever different materials are used in conjunction with one another. For example, steel and masonry have maximum allowable vertical plumb tolerances of +75 mm, -50 mm and ±13 mm respectively. Steel and masonry also have significant plan tolerance variation. Steel components are permitted to vary 6 mm from the structures length if the structure is 12000 mm long, whereas masonry is allowed 20 mm of deviation. Not only do these tolerances affect constructability, but they can heavily influence the structural design and cost of the exterior wall assembly. On a case where a shelf angle is cantilevered 100 mm off of a steel beam, simply moving the brick veneer 10 mm further away from the structure on the shelf angle will increase the bending moment at the support by 10%.

This chapter begins by looking at the frequency and associated cost of facade failures. Next, a review of data regarding problems associated with exterior walls is summarized, followed by the compilation and comparison of the current construction tolerance standards used by Canada and the United States. An example using the Canadian concrete and masonry standards is used to illustrate how tolerance problems can arise in practice, and finally, previously collected data on plumbness of columns and walls is looked at to determine the validity and quality of this paper's research.

2.2 FREQUENCY AND ASSOCIATED COST OF FACADE FAILURES

Building envelope failures are far more widespread and serious than most engineers and architects suspect (Brand, 1990). Many of these problems can be linked to poor design and construction methods which do not address tolerances adequately.

The following data is based on studies that were conducted in Canada. These studies were summarized and documented by Brand (1990).

- Claims for "facade failures" have increased from 15% of all claims in 1960 to 33% of all claims in 1980. Although this data is 20 years old, the trend has not changed. Considering the recent failures in British Columbia, it is not unreasonable to estimate that the claims are now more than 50%.

- Major parking garage problems have been experienced by nearly two-thirds of high rise condominium buildings with water infiltration being the largest problem, followed by concrete deterioration. One corporation spent $850,000 on garage repairs.

- Roof leakage presents a problem with one quarter of all high-rise condominiums. The cost of each incident has averaged $45,000. Accountants reporting on cost and frequency say, "those twenty year roofs should really be called convertible six year roofs." The report also states that 40% of townhouse roofs have needed repairs costing on average $24,000.

- Water leakage through walls is experienced by 75% of high-rise condos and 65% of townhouses.
- Repair costs varied between $4,000 and $150,000. Of the individuals and corporations suffering these difficulties, half have taken, or are taking the developer to court to recover costs.

Although the frequency of lawsuits is increasing, they are fewer than might be expected, given the extent of the failures.

2.3 CLADDING FAILURE, CAUSES, AND PREVENTATIVE DESIGN METHODS

Building failures are often not catastrophic. Usually they involve parts of facilities that do not perform as intended by the owner, designer, or builder. A number of cladding distress cases have been investigated by researchers (refer to items 2 to 8 in the List of References). Other similar cases were summarized in an unpublished paper titled, "Construction Tolerances and Their Effects on Cladding Systems," by Hatzinikolas of the Canadian Masonry Research Institute, where many of the following points originated. The investigations involved buildings varying from low to high-rise structures with the components of these buildings consisting of different types of structural frames, back-up and veneer systems.

Distress reported in these structures are categorized in the following groups:

- Buckling/bulging of veneer
- Cracking of veneer
- Local spalling
- Crushing of bricks or blocks
- Complete collapse of sections of veneer

Other finishing systems are just as susceptible.

In all of these investigations, it was concluded that differential movement is the main cause of veneer distress. The movements are mainly the results of:

- Frame shortening due to shrinkage, creep, and elastic deformation
- Brick veneer expansion due to moisture
- Sagging of supports
- Movement of foundations
- Excessive deflection of some back-up systems, such as metal studs
- Thermally induced movements

The following recommendations were made in the studies (items 2 to 8 in List of References), in order to provide for safe and stable designs of such systems:

- Understanding the behaviour of such systems
- Providing shrinkage and control joints to permit movements in two directions
- Proper design of shelf angles

- Including flexural stiffness of the veneer in the design and the use of more stringent deflection limits
- Proper detailing of waterproofing geometry and anchoring
- Understanding the behaviour of ties
- Understanding the physical properties of veneer material
- More stringent inspection and quality control

While most of the investigations conducted by these six researchers have indicated the involvement of tolerance variations in veneer distress, very few have focussed on tolerance as being the underlying cause of distress. Among the work done on tolerances is a study by Borchelt (1985), which was summarized by Hatzinikolas of the Canadian Masonry Research Institute. The paper analyses tolerance related problems in brick veneer structures. The main concern is that the allowable tolerances for structural frames is greater than the acceptable tolerances for exposed brickwork, and design details usually do not have sufficient dimensional latitude to account for these differences. As a result, the masonry contractor is often required to make field adjustments to try to alleviate the problem. A review of the tolerance requirements as set by United States Codes showed that the tolerance values for each building material have been developed independently of those for other materials. A set of suggestions for improvement were presented for the U.S. Standards, among them are the following:

- Construction tolerances of cladding systems should be established which are both achievable and in line with those of other materials.

- Design details should be more flexible to allow for the variations in specified tolerances.

2.4 DESIGN STANDARDS

Current Canadian Design Standards; steel, concrete, and masonry are set out and plotted in Figures 2.1 to 2.3. U.S. Design Standards are plotted in Figures 2.4 to 2.6. Note that although this paper focuses primarily on vertical tolerances, level and plan tolerances have been included for interests sake.

2.4.1 Canadian Design Codes

Figures 2.1 to 2.3 give a graphical interpretation of the allowable tolerances set by the Canadian Codes cited in Appendices B, C, and D. These figures compare allowable deviations of plumbness, plan, and elevation. From the figures, one can determine that there is essentially no co-ordination between any of the design codes. For example, maximum level tolerance variations of concrete are ±40 mm whereas masonry are ±13 mm. They also point out that masonry veneer, being the last material to be constructed in a steel or concrete framed structure, may require a larger than allowable deviation from plumb, plan, and elevation. These deviations, whether large or small can result in stress re-distribution in the veneer/back-up assembly.

2.4.2 United States Design Standards

To examine how the American construction practice addresses tolerances, the Handbook of Construction Tolerances was referenced and the following were reviewed:

- Code of Standard Practice for Steel Buildings and Bridges, 1992
- Standard Tolerances for Concrete Construction and Materials (ACI 117-90) (which applies to cast-in-place, and precast concrete, along with concrete unit masonry and brick)
- Dimension Stone Design Manual IV, 1991 (granite and marble installation)

The tolerances for steel, concrete and masonry are plotted on Figures 2.4 to 2.6. The data was converted to metric to allow for easier comparison to Canadian data.

2.4.3 Analysis and Comparison of Design Standards

From Figures 2.1 to 2.3 it is apparent that the current design tolerances for steel, concrete and masonry vary substantially. This is most evident when vertical plumb tolerances are contrasted. Masonry has by far the most stringent tolerances with limits maximizing at ±13 mm for a 12000 mm high structure. The steel code initially follows a similar rate of increase in deviation with respect to length of member to that of masonry, but continues to expand out to -50 mm and 75 mm at 96000 mm. The latter value is considerably larger than any of the other codes. As expected, due to the nature of its material and construction the two concrete codes have very large allowances of ±50mm at heights of 9500 mm (Clause 10.5.1), and ±40 mm at 15000 mm (Clause 10.3). Examining the data presented for allowable tolerances in levelling, in Figure 2.2, we observe that steel and masonry limits are very comparable, whereas concrete construction tolerances are considerably greater. When comparing tolerances in plan locations of the elements, it becomes evident that no coordination had been established between the codes at the time they were developed.

To examine similarities and or differences between the Canadian and U.S. code standards we find that steel construction tolerance on plumbness in both the Canadian and American codes are essentially identical at heights above 48000 mm, and also follow similar profiles below 48000 mm (Figure 2.7). However, concrete construction tolerance on plumbness is different in the two practices (Figure 2.8). Only the American standard has a clause that gives values for plumbness of unexposed concrete. These numbers are double the ±75 mm allowance of exposed concrete, which is still 25 mm more than Canadian concrete standards largest permissible deviation in plumbness. In comparing the masonry codes in Figure 2.9, one finds that both countries follow a very similar profile.

Examining the allowable tolerance on levelling (Figures 2.2 and 2.5) shows that some variation is present. The difference between Figures 2.2 and 2.5 is that the Canadian code dealing with concrete has a much higher allowance of ±40 mm compared to the ±19 mm permitted in the United States. Here the Canadian standard is less restrictive.

Finally in reviewing Figures 2.4 and 2.6 we observe that the American practice permits an additional ±13 mm in steel codes for tolerances on plan locations of elements. The concrete plots are substantially different for small plans, but both peak out in the 25 to 30 mm range. A comparison of masonry tolerances on plan locations reveals that Canadian practice permits more deviation.

From the above one concludes that both the Canadian and American code standards allow concrete construction the most variation, masonry the least, and leave steel construction somewhere in between.

Although most of the Canadian Standards have clauses pertaining to the interaction of masonry with other materials, it is necessary to examine the consequences of accidentally overlooking such interaction.

2.4.4 Vertical Tolerance Example Using Canadian Standards

This section examines some of the problems that occur when different building materials are used in conjunction with each other in the building of exterior walls, while using the Canadian Standards code. Difficulties associated with vertical tolerances are focussed on as this is where most of the problems are found.

Since masonry is used as a veneer, and because of its more stringent tolerance restrictions (Figure 2.1), it is the most likely to experience construction problems. Figure 2.10 illustrates the following example: A 30000 mm concrete framed building using masonry veneer, where both walls were built to their respective tolerances. The concrete at foundation has been properly placed. However, because of the tolerance variation between the codes, the masonry cannot follow the same profile of the concrete. The illustration shows a concrete frame with an exterior wall assembly consisting of 80 mm of rigid insulation and a 25 mm airspace. At the foundation the concrete wall is positioned exactly on its building line. The wall however, leans away from its proper vertical position as it is constructed, but still remains within its boundaries of 40 mm at 30000 mm of height. Since the masons realized this when laying their first course of bricks, they moved them 6 mm away from the building line in order to try and compensate for the sloping of the concrete. Unfortunately, the wall still experiences problems at the top of the structure.

To deal with the problem illustrated in Figure 2.10, the masonry contractor has little choice but to employ one of a number of practices that are not sanctioned by the code. Because there is no air space left within the wall and the masonry is encroaching into the insulation, a contractor will either reduce the depth of the bricks by cutting or splitting, or will shave off some of the insulation. Changing the dimensions of the brick can be hazardous because it reduces its bearing strength and may lead to stress failures. If the contractor opts to reduce the insulation, there can be significant heat loss through these sections of the wall causing increased freeze-thaw cycles in the brick, and this in turn results in failure of the veneer. Another result of tolerance incompatibility is that the wall cavity size of 25 mm has been reduced to almost zero. It is possible that bricks can "pop-off," as a result of moisture buildup developing behind the brick during freezing.

In addition to the wall cavity problem, the masons may experience a second problem illustrated in Figure 2.10; the proper placing of bricks on the shelf angles of the building. Because these angles are usually installed by a different contractor (miscellaneous iron), they tend to follow the established profile of the vertical concrete wall. As a result, elements of the angle and its location in conjunction with the veneer is not coordinated. In order for the masons to seat the bricks, they need to split the bricks as they did earlier, but to an even greater degree.

An easy, but not recommended solution to some of these problems is for the masons to do away with their tolerances, follow the contour of the wall and do away with the required wall cavity. This would not only raise a question of aesthetics, but likely objections from the owner. In a different example, the wall cavity can get too large and not permit the proper tying back of brick to the rest of the structure, resulting in a structurally unsafe wall. Similar examples could have been generated using steel with brick veneer.

2.5 REVIEW OF PREVIOUS COLUMN AND WALL RESEARCH

Since little previous attention has been focussed on construction tolerances, it is not surprising that there is little information on this subject. However, one paper published by Beaulieu and Adams (1977), does provide some very useful vertical plumbness data. The data includes original testing conducted by Beaulieu and Adams, as well as a compilation of data on other structures that was carried out in Sweden and Great Britain. The values from this paper regarding measured tolerances are found in Tables 2.1 to 2.4. Table 2.1 contains the measurements of three structures taken by Beaulieu and Adams. Structures A and B are high-rise buildings, while C is a warehouse. All the numbers in these tables contain mean and standard deviation data on columns and walls, and are recorded in radians to facilitate the comparison of plumbness readings taken over different heights. These values provide a good basis for comparison to those which have been collected by the author for the purposes of this study discussed in Chapter 4.

	BUILDING	TYPE	SAMPLE DIMENSION n	MEAN	STANDARD DEVIATION ($x10^{-2}$ Rad)	SKEWNESS	KURTOSIS
ALGEBRAIC VALUES	A	x Axis	458	-0.004	0.164	0.27	5.1
		y Axis	458	-0.005	0.160	0.00	4.7
		Total	916	-0.004	0.162	0.14	4.9
	B	x Axis	880	-0.009	0.167	-0.13	3.8
		y Axis	880	0.012	0.178	0.17	4.2
		Total	1760	0.002	0.173	0.05	4.1
	A + B	Total	2676	-0.001	0.170	0.09	4.5
	C	Total	561	0.015	0.160	0.05	4.7
ABSOLUTE VALUES	A	x Axis	458	0.119	0.113	1.74	7.5
		y Axis	458	0.115	0.112	1.51	6.1
		Total	916	0.117	0.112	1.62	6.8
	B	x Axis	880	0.126	0.110	1.24	5.2
		y Axis	880	0.134	0.119	1.43	6.1
		Total	1760	0.130	0.114	1.35	5.8
	A + B	Total	2676	0.125	0.115	1.50	6.4
	C	Total	561	0.118	0.108	1.68	6.9

Table 2.1 Statistical characteristics of steel column out-of-plumbs (from Beaulieu and Adams, 1977).

References	Type of Columns and Locations	Number of Measurements	Arithmetic* Mean		Standard* Deviation	
Jacobson and Widmark (Sweden)	Rectangular Columns					
	Ground Storey	20	0.12	[1.2]	0.14	[1.4]
	First Storey	18	0.22	[2.0]	0.15	[1.4]
Van den Berg (Sweden)	Circular Columns					
	Beam Direction	377	-0.02	[0.1]	0.23	[1.9]
	Facade Direction	349	-0.01	[0.1]	0.17	[1.5]
Holmberg, Berner et al. (Sweden)	Rectangular Facade	34	–	[0.1]**	–	[0.6]
	Columns	36	–	[4.2]**	–	[2.7]
	Rect. Interior Col.	15	–	[1.2]**	–	[3.3]
Klingberg (Sweden)	Square Interior Col.					
	N-S Direction	12	–	[0.2]	–	[2.3]
	E-W Direction	13	–	[2.3]	–	[1.9]
Hardwick and Milner (Britain)	Rectangular Columns					
	Ground Storey	30	–	–	0.24	–
	First Storey	49	–	–	0.28	–

* All values are given in inches except those in brackets which are given in Rad. $x10^{-3}$.

** Not reported whether absolute or algebraic values were used.

Table 2.2 Out-of-plumbs measured on precast concrete columns (from Beaulieu and Adams, 1977).

References	Type of Walls and Locations	Number of Measurements	Arithmetic* Mean	Standard* Deviation
Suu** (Sweden)	h = 100"	117	– –	0.25 [2.5]
Van den Berg (Sweden)	Facade Element (2 Measurements per Element) h = 104"	670	0.04 [0.4]	0.14 [1.3]
Klingberg	Apartment Bldg.	–	– –	– [1.6]
(Sweden)	Hospital	–	– –	– [1.5]
	Cross Wall Elements h = 96"			
	Block S			
	Ground Storey	24	0.00 [0.0]	0.11 [1.1]
	First Storey	24	0.02 [0.2]	0.15 [1.7]
	Second Storey	24	0.02 [0.2]	0.14 [1.5]
	Third Storey	24	0.04 [0.4]	0.09 [1.0]
	Block T			
	Ground Storey	24	0.02 [0.2]	0.19 [2.0]
	First Storey	24	-0.03 [0.3]	0.19 [2.0]
	Second Storey	24	0.02 [0.2]	0.21 [2.3]
Butler	Third Storey	24	0.03 [0.3]	0.12 [1.3]
(Britain)	*Longitudinal Wall Elements* h = 98"			
	Block P			
	Ground Storey	24	0.04 [0.4]	0.13 [1.4]
	First Storey	23	0.04 [0.5]	0.14 [1.5]
	Second Storey	24	0.01 [0.1]	0.22 [2.3]
	Third Storey	24	0.09 [0.9]	0.18 [1.9]
	External Wall Element h = 96"			
	First Storey			
	Second Storey	19	0.03 [0.3]	0.11 [1.2]
	Third Storey	15	0.08 [0.8]	0.21 [2.2]
	Fourth Storey	20	-0.07 [0.7]	0.17 [1.8]
		15	-0.04 [0.4]	0.13 [1.3]

* All values are given in inches except those in brackets which are given in Rad. $x10^{-3}$.
** Absolute values.

Table 2.3 Out-of-plumbs measured on precast concrete walls (from Beaulieu and Adams, 1977).

Building No.	Number of Measurements	Mean* (Rad.)	Standard Deviation* (Rad.)
I	104	0.00274	0.00277
II	36	0.00216	0.001
II	106	0.00233	0.00152

* Absolute values

Table 2.4 Out-of-plumbs measured on reinforced concrete columns (from Beaulieu and Adams, 1977).

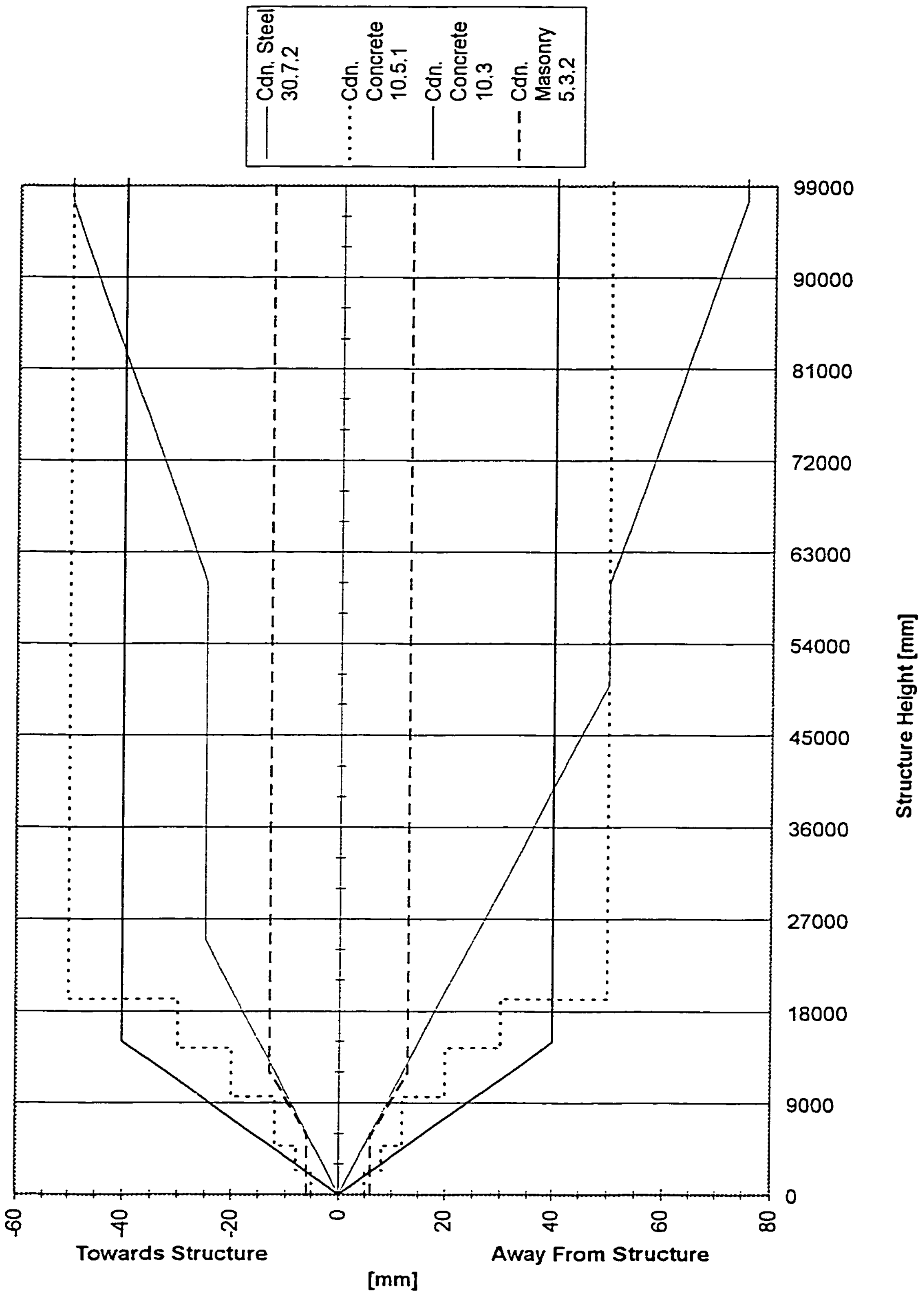


Figure 2.1 Allowable vertical plumb tolerances from Canadian Standards.

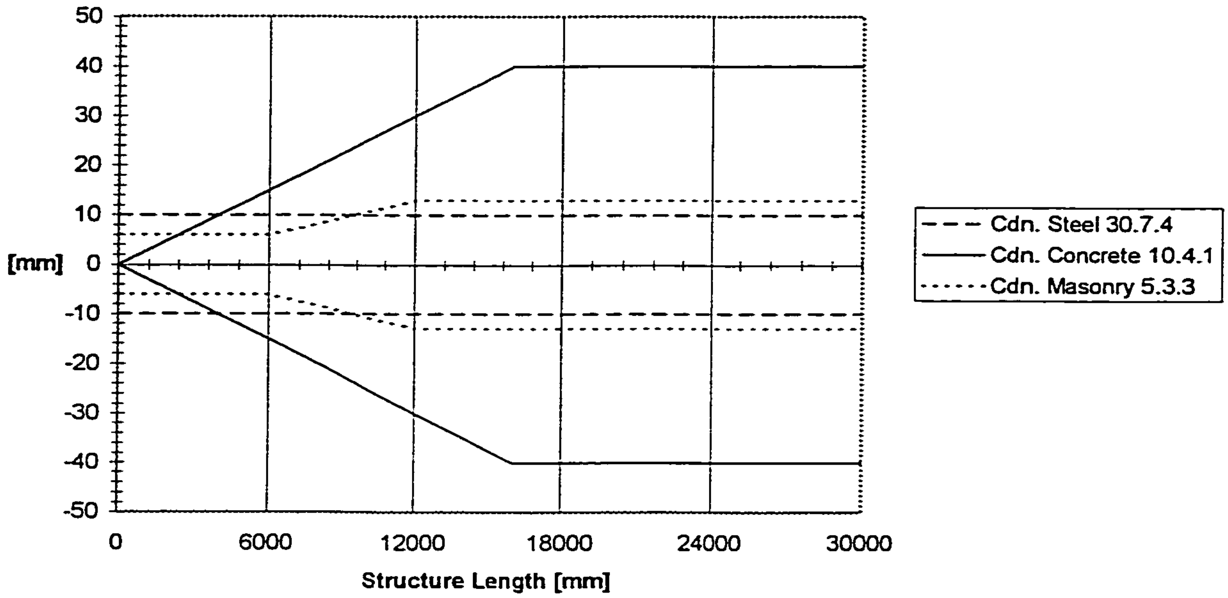


Figure 2.2 Allowable level tolerances from Canadian Standards.

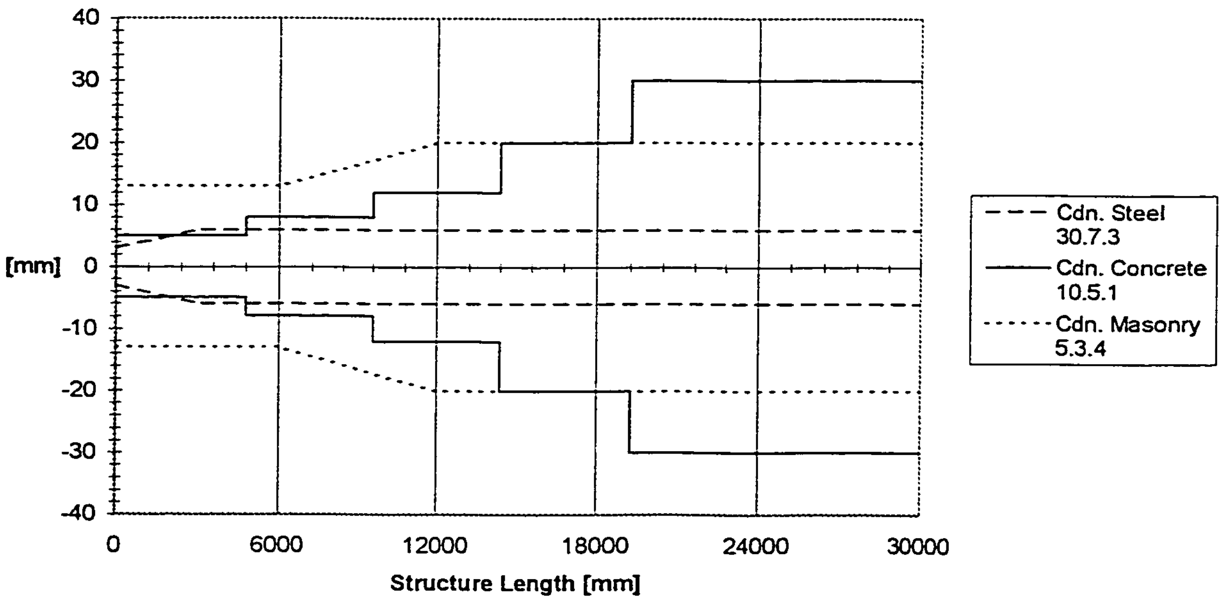


Figure 2.3 Allowable plan tolerances from Canadian Standards.

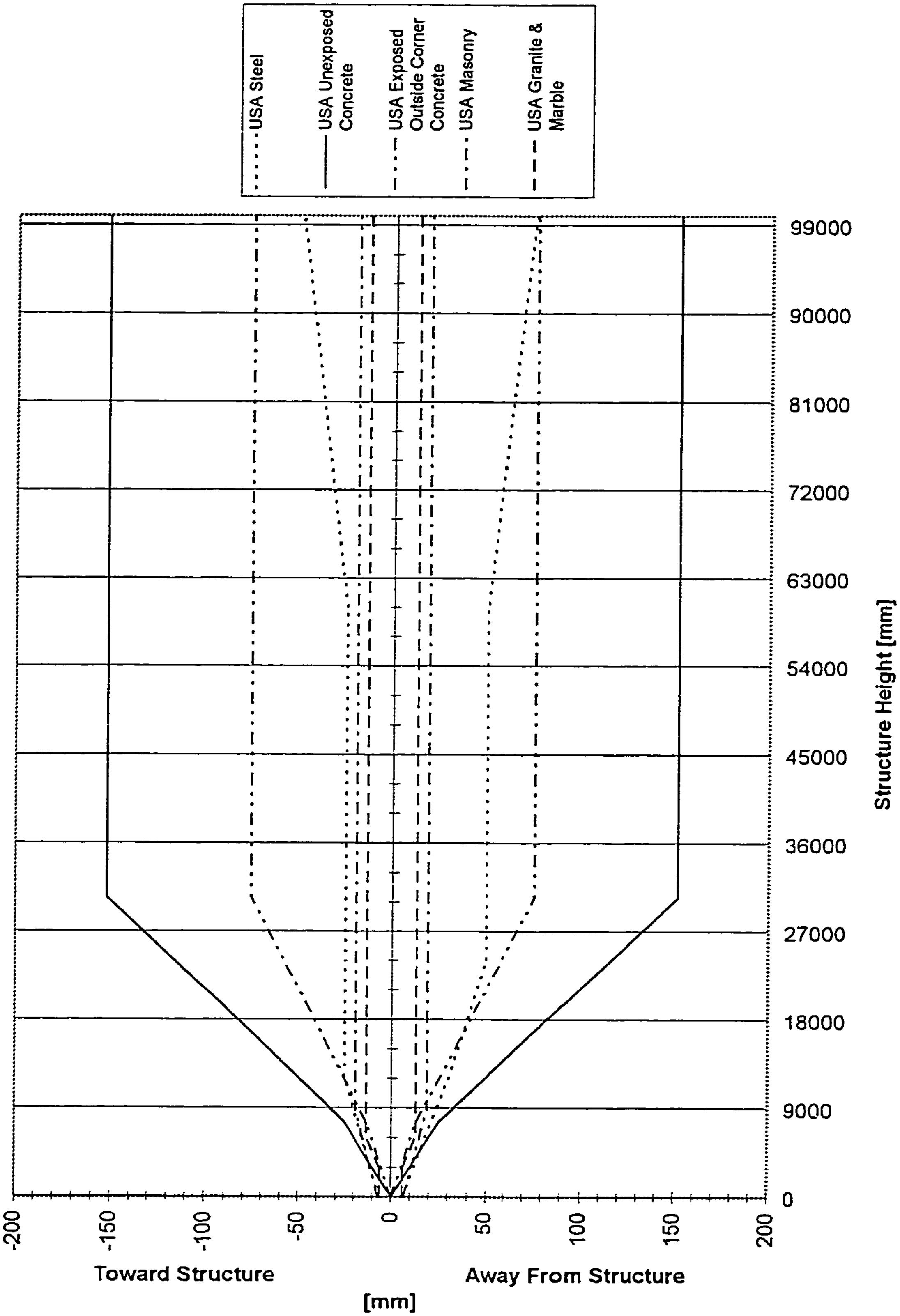


Figure 2.4 Allowable vertical plumb tolerances from U.S. Standards.

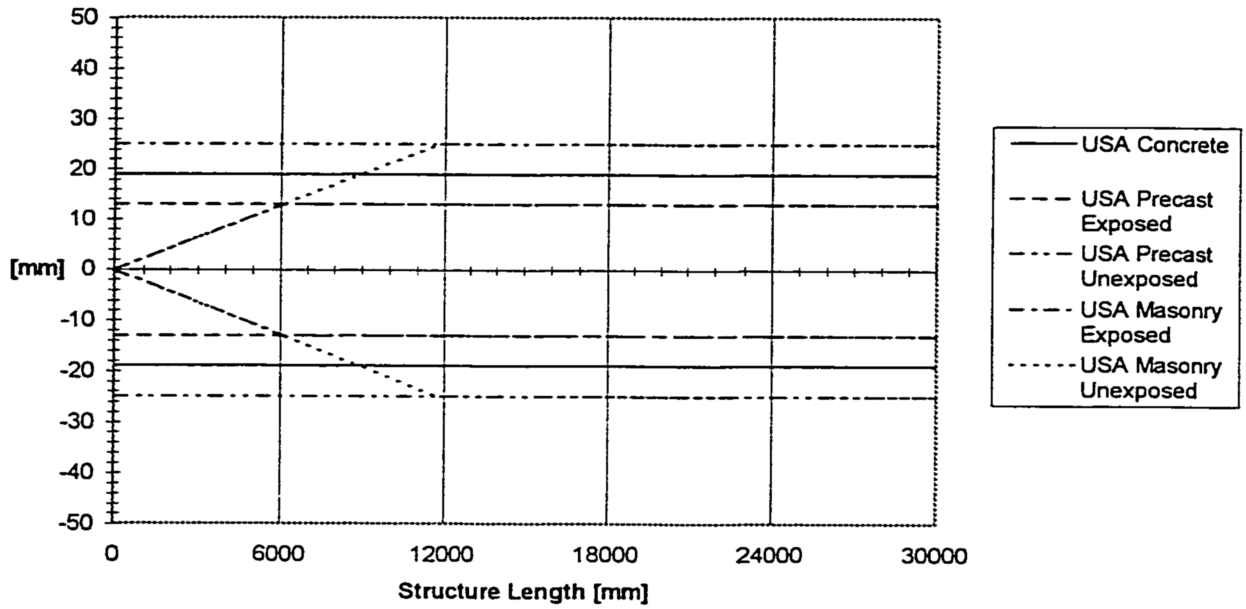


Figure 2.5 Allowable level tolerances from U.S. Standards.

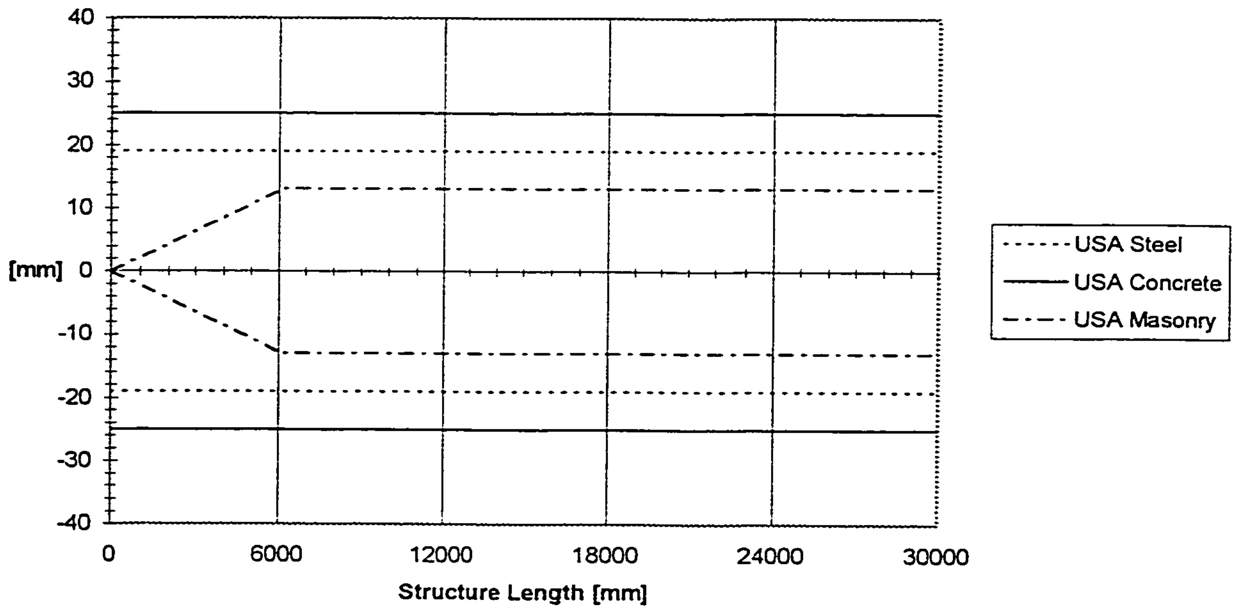


Figure 2.6 Allowable plan tolerances from U.S. Standards.

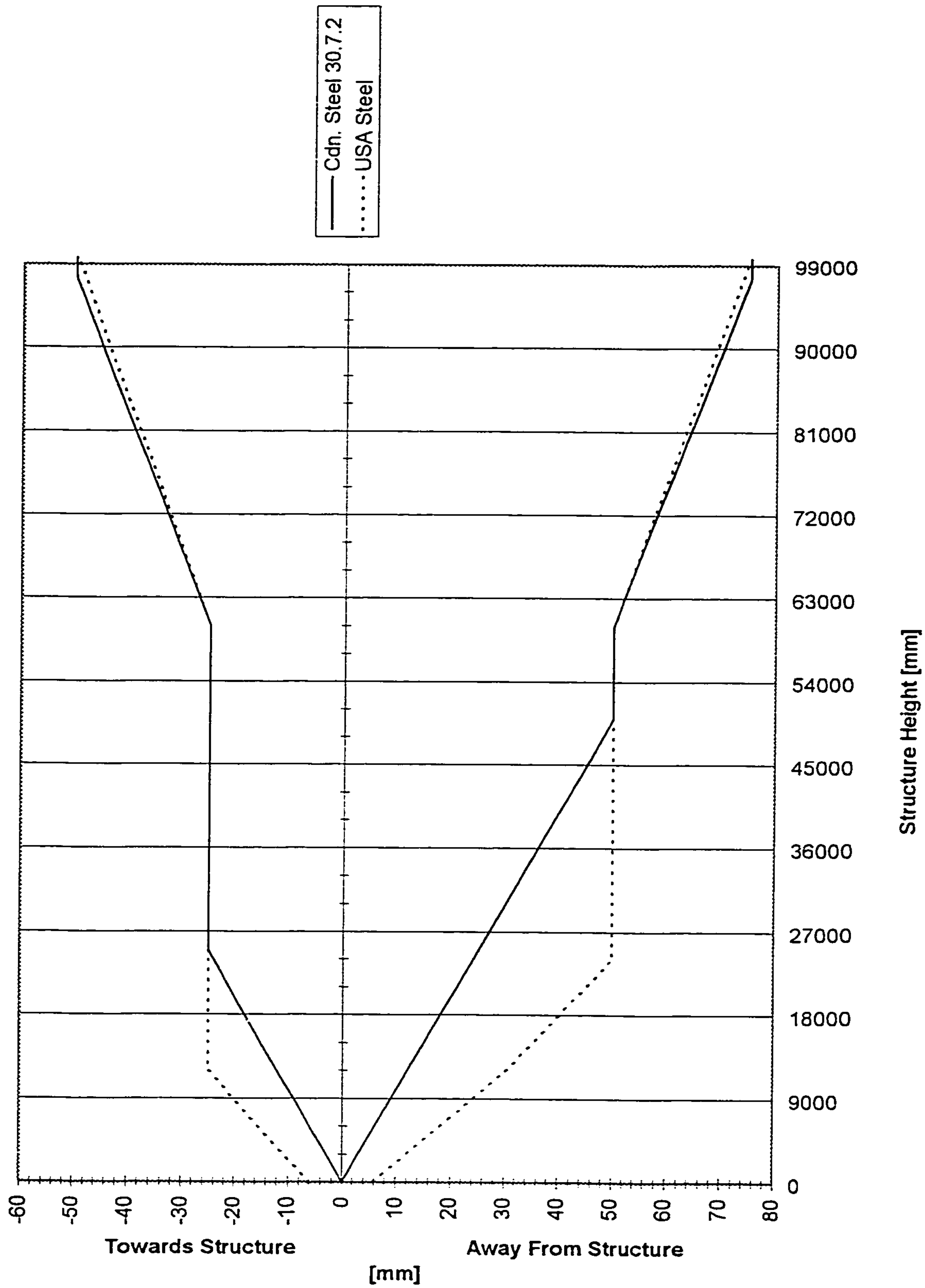


Figure 2.7 Canadian versus U.S. vertical steel plumb tolerances.

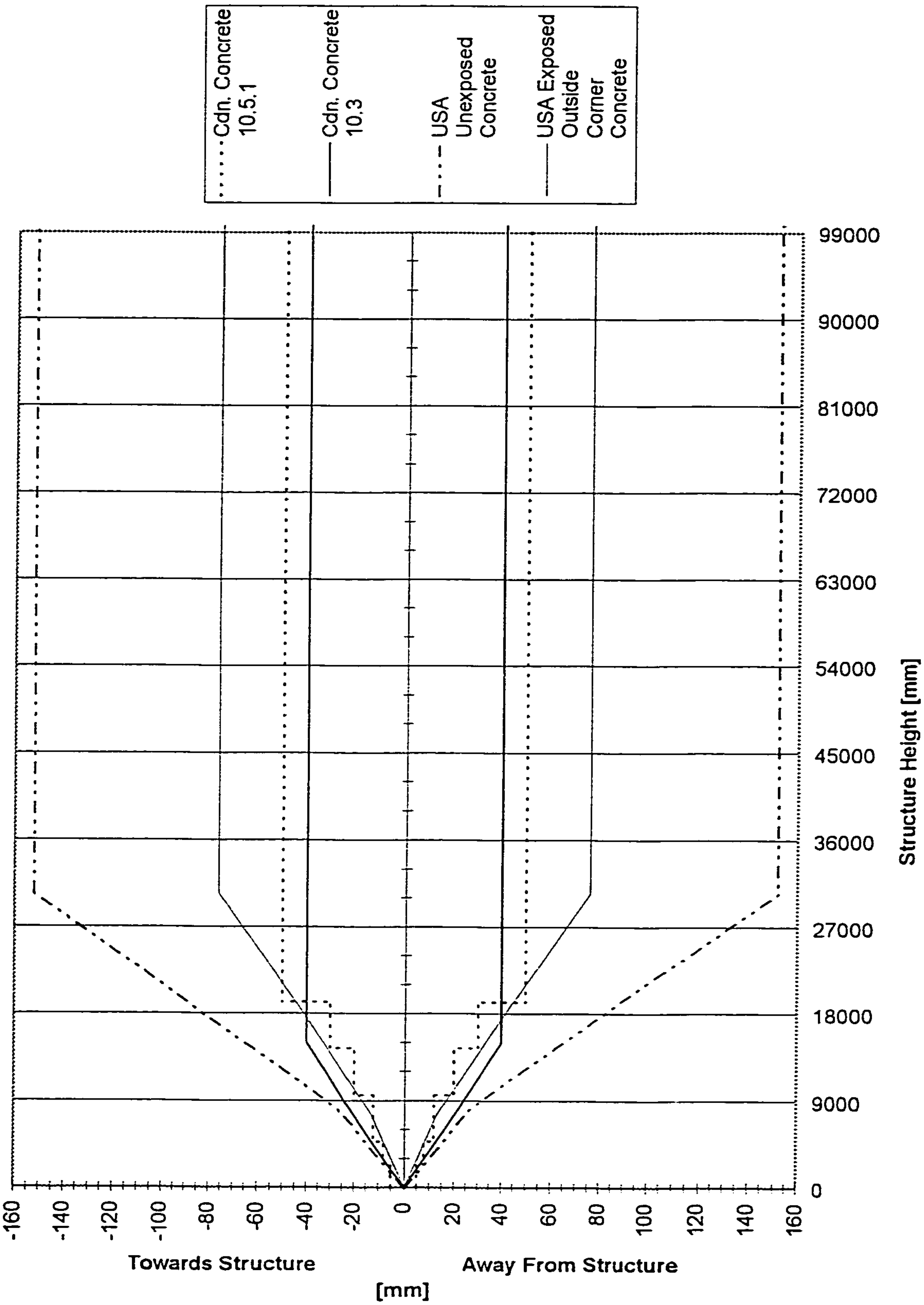


Figure 2.8 Canadian versus U.S. vertical concrete plumb tolerances.

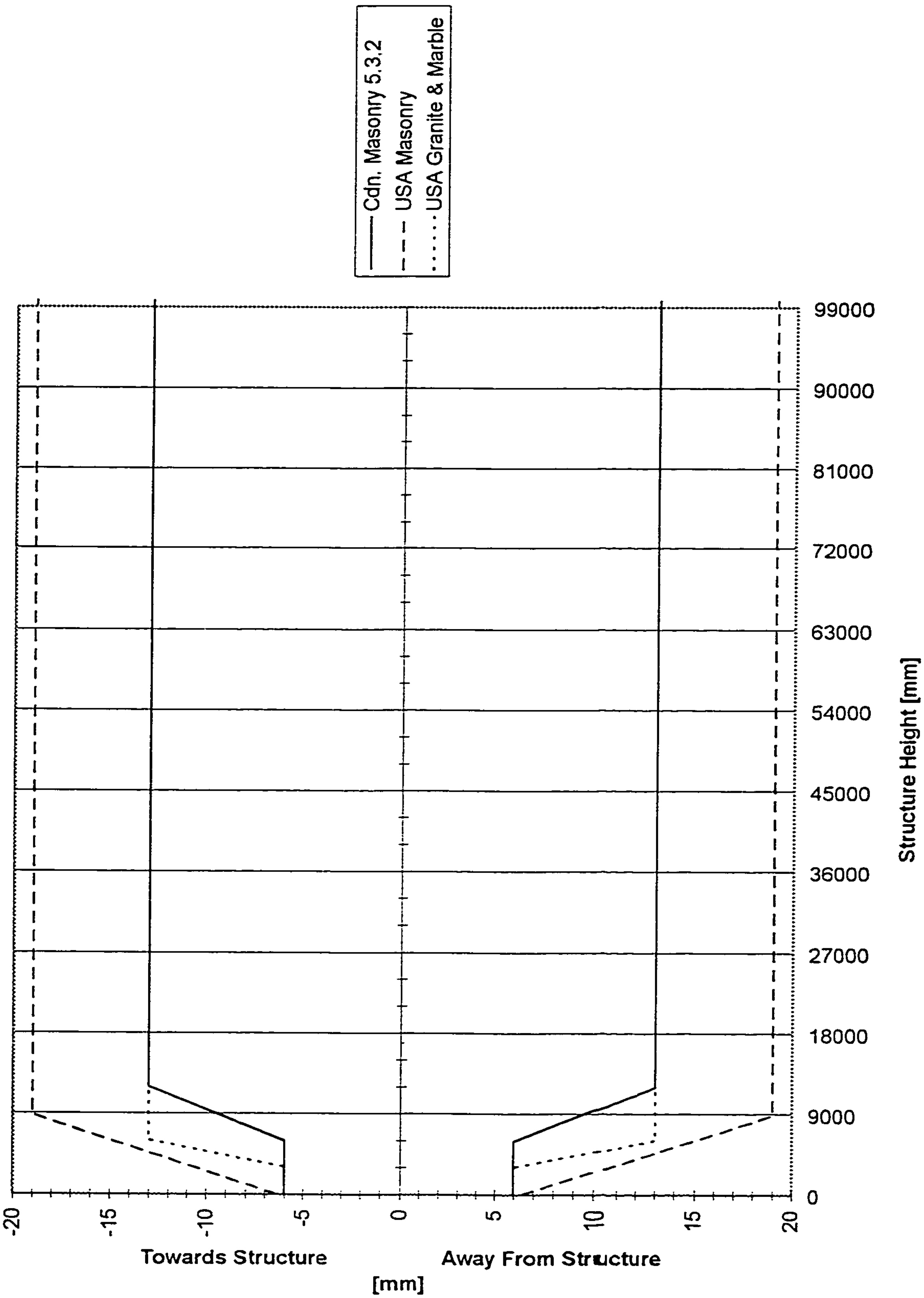


Figure 2.9 Canadian versus U.S. vertical masonry plumb tolerances.

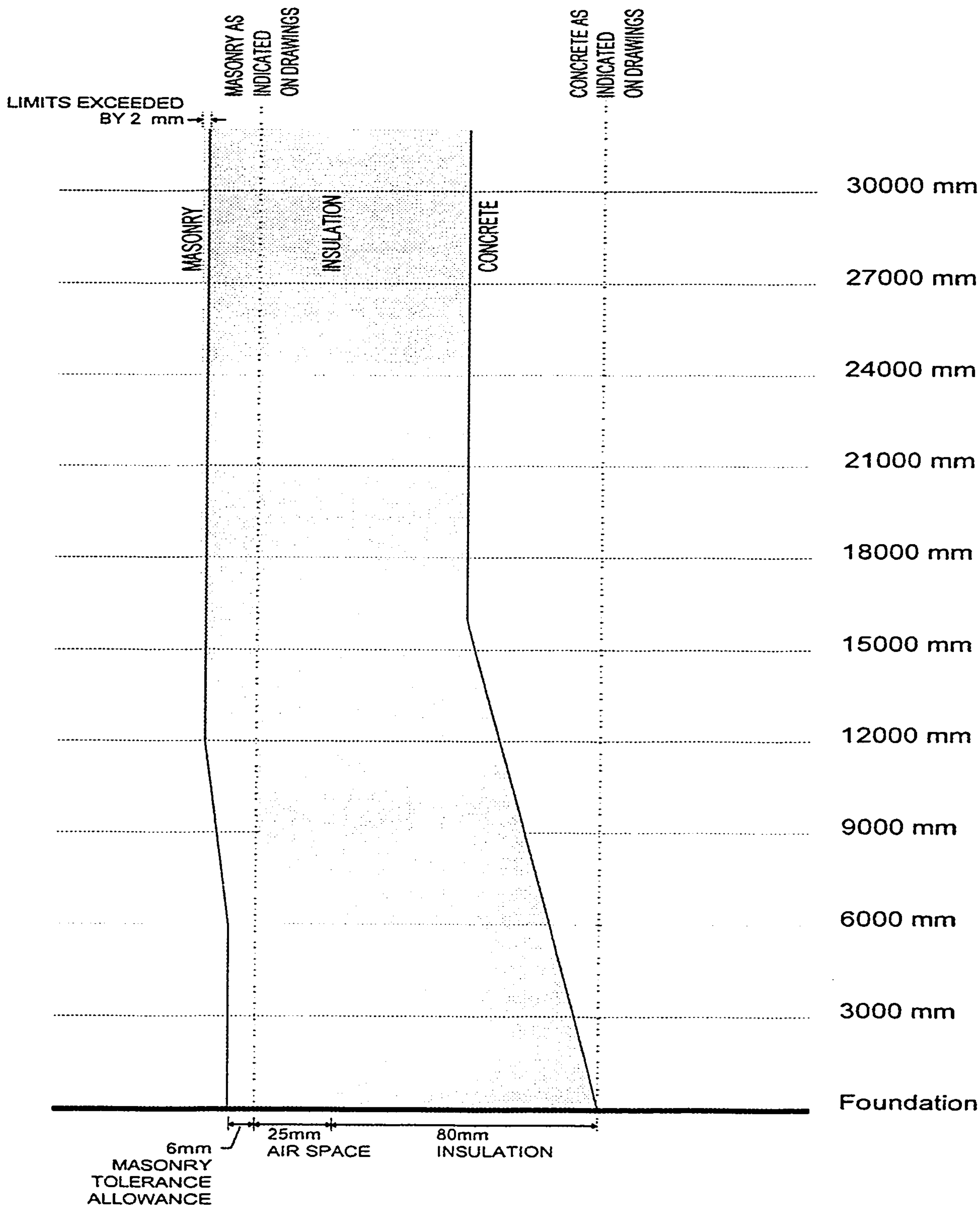


Figure 2.10 Masonry and concrete vertical tolerance example.

3. CASE STUDIES

3.1 INTRODUCTION

This section of the report reviews three case study buildings dubbed A, B and C in order to determine the effects of construction tolerances on different exterior wall systems. In the first part of this chapter, each of the three structures is independently discussed, including a brief description of the plans, construction assessments and any other observations. The second part details the kind of measuring instruments used in collecting the data, the methods employed, and the accuracy of these devices.

3.2 BUILDINGS INVESTIGATED

To learn how construction tolerances affect different exterior wall systems, three different types of buildings were investigated. Building A is a commercial structure consisting of a steel frame with brick veneer. Building B, a condominium, uses a concrete frame, and Building C, a recreational facility, is enclosed with large concrete unit masonry walls.

3.2.1 Building A - Steel with Brick Veneer

This steel framed structure is three storeys high (14.24 metres including parapet) having a ground level of approximately 1600 in area. The second floor is similar in size to ground level, while the third level is slightly smaller at 1300 m^2 (this is due to an open core above the second floor). The building plan dimensions are about 46 m long by 36 m wide.

The steel exterior columns are 12.6 m long HSS152x152x6.4 and HSS152x152x8 sections, and rest on the foundation walls of the basement. These columns rise to the full height of the structure and are not spliced. The interior columns are W250x89 sections and are framed into footings in the basement. Around the perimeter of the structure are beams which range in size from W410x39 to W410x85. Figure 3.1 shows the building plan.

The concrete floors consist of 125 mm of concrete topping on 38 mm composite steel decking. This floor in turn is held up by open web steel joists. Because a brick veneer was to be used to finish the outside walls of the building, shelf angles were required. To accomplish this, L100x100x10 angles are welded to the bottom flanges or webs of the W410 beams. Some details of this can be found in Figure 3.2.

The exterior wall system that was used is shown in Figure 3.3. Moving from the outside of the wall inward, it is composed of 90 mm face brick c/w ties, a 35 mm airspace followed by 75 mm of semi-rigid insulation. Behind the insulation is an air/vapour barrier membrane, 12.5 exterior grade gypsum board, 152 mm steel studs spaced at 400 mm on centre, and lastly 16 mm type “X” gypsum board. The top of the metal stud wall is detailed with a 50 mm deflection track filled with fire stop insulation. The brick wall was specified to have weepholes at 600 mm on centre in the masonry course resting on the shelf angle. Details also show proper butyl membrane coverage of the shelf angle assembly.

3.2.2 Building B - Concrete

Building B is a unique concrete condominium high-rise. The structure is 12 storeys high. What makes this structure interesting is the novel approach the designers took to minimize dead load. Because each condominium unit is two storeys high, concrete slabs were only poured every second floor, to ensure that requirements of noise abatement between units are met. The remaining intermediate floor assemblies were made of steel beams and joists, overlaid with steel decking and then concrete topping.

Figure 3.4 shows a plan view of the structure. This figure, shows that the building is about 37 m long, 8 m wide at its narrowest side, and 21 m wide at its deepest side. Exterior columns are 5.461 m tall, as are the metal stud walls that form the back-up wall between them. Figure 3.5 shows a typical cross section of an exterior wall. Not much attention was paid to the wall exterior because it was almost impossible to take measurements due to line of site limitations.

3.2.3 Building C - Concrete Unit Masonry Walls

The third structure is a very large recreational facility. It is primarily made from structural steel, but also has substantial sections of concrete unit masonry walls. Four exterior walls were examined. These walls were chosen because of their size, accessibility, and simplicity. All walls are constructed of standard 200x200x400 mm concrete masonry units, and appear to be designed not to carry vertical loads. That was the purpose of the structural steel. Three of the walls are 9.4 m high, with varying lengths of 33.9 m, 15.6 m, and 21.8 m. The last wall is about 5 m tall with a length of 21.1 m. Figure 3.6 shows the relative locations of the walls. All masonry walls sit on below grade short concrete walls, which in turn rest on a strip footing. The finish of the masonry unit wall can only be guessed at because the architectural drawings were unavailable. Embedded in the walls are shear connectors intended to tie into a brick veneer. These ties are located every second concrete block, both vertically and horizontally, resulting in a 400x800 mm spacing. The ties in the vertical direction however, stopped when five rows had been placed. From examining other sections of the building, it can only be assumed that some sort of metal cladding was to be installed above the brick wall.

3.3 METHOD OF MEASUREMENT

To determine how construction tolerances affect various exterior wall components, some simple, yet very accurate measuring devices were required. These instruments were chosen to be able to take more than one type of reading.

3.3.1 Instruments Used

Primarily three different instruments were used to gather data; a Pacific Laser Systems PLS-5, a Leica Disto Memo, and an ordinary metric ruler. These devices are shown in Figure 3.7. In addition to these, another measuring device was built in order to obtain measurements from hard to reach places.

The PLS-5 is a laser plumb-level-square system, for this study it was used primarily for plumbing. The laser is self-levelling, and has an accuracy of <3 mm at 30 metres of height. Because it is a laser, it is unaffected by wind. This laser was always used in conjunction with a metric ruler. Usually two people were required to operate it. For example, if a two storey column was being plumbed, one person would go to the top of the column with a transparent ruler, and the other person would stay at ground level with the laser and an additional ruler. The laser device would then be activated, shooting upwards alongside the column. Each person measured a distance from the face of the column to the centre of the laser beam. Knowing the height of the column and having these two measurements, the plumbness of the column was then determined.

In areas where one could not get to the top of a column or wall to take a reading, the device shown in Figure 3.8 was used in conjunction with binoculars. This measuring tool incorporated a ruler which was mounted to the end of a long pole by means of a wooden bracket assembly, allowing the ruler to remain square with the measured surface.

The other instrument used was the Disto Memo hand-held distance metre. This device, like the PLS-5, was also laser based. It had a range of approximately 0.3 m to 100 m, with a typical measuring accuracy of ±3 mm, and a maximal measuring accuracy of ±5 mm. Using the Disto Memo was quite easy, one simply butted the back of the unit to one of the endpoints which was being measured, and then pointed the laser at the object to where the measured distance was required. Because holding the laser steady on target could be difficult at times, a minimum of three readings were taken and then averaged to arrive at the recorded value.

3.3.2 Building A Measurements

Of the three buildings studied, gathering data from the steel structure was the easiest and most convenient, and because of this more information on tolerances was collected. Due to the nature of the study, and the fact that it took place on a busy and ever changing construction site, readings were gathered over a number of months.

The first set of data collected from the steel structure was the plumbness of the columns. This was done when all the concrete had been placed on the floors so that sufficient dead load was on the frame of the building. All values were taken on the outside face of the column, to see whether they were leaning towards or away from the building. These readings were acquired using the laser plumb. Data was gathered from the west and southern faces of the structure at each floor level. The next set of readings taken were to determine the location of the shelf angles relative to the vertical plane of the wall. These values were also collected from the west and south faces of the building.

Once the exterior drywall was fastened to the steel studs, plumbness values were taken. Following the air/vapour membrane and insulation installation, the size of the wall cavity was measured as the bricks were being laid. These readings were taken with a ruler. After completion of the brick wall, it was measured for plumbness. Lastly, an overall visual inspection was made of the components of the exterior wall assembly, to see if components of the wall assembly varied from the drawings.

3.3.3 Building B Measurements

The next building studied was the concrete condominium. Because of the height of the structure, the laser plumb could not be accurately viewed when used on the outer face of the building. Therefore, plumbing took place from the inside on three different columns shown in Figure 3.4. This was done under the assumption that the column had the same cross-section throughout its floor-to-ceiling height and, therefore, would still indicate whether or not it was leaning towards or away from the vertical plane of the wall. Due to the height of the columns, the device shown in Figure 3.8 had to be used in conjunction with the PLS-5 and small binoculars.

Other readings taken were the plumbness of steel stud walls and the floor-to-ceiling heights of these walls. Once again, the plumbness values were collected with the laser plumb, with two locations being measured on each wall. Floor-to-ceiling heights were gathered using the laser distance metre. All of these readings were taken on levels one through nine wherever it was possible. As with the other structures, a visual inspection was also made of the building.

3.3.4 Building C Measurements

The last set of data was collected on the large concrete unit masonry walls in Figure 3.6. Due to their simplicity, only plumbness was measured. Readings were taken about every 4.5 m along the wall.

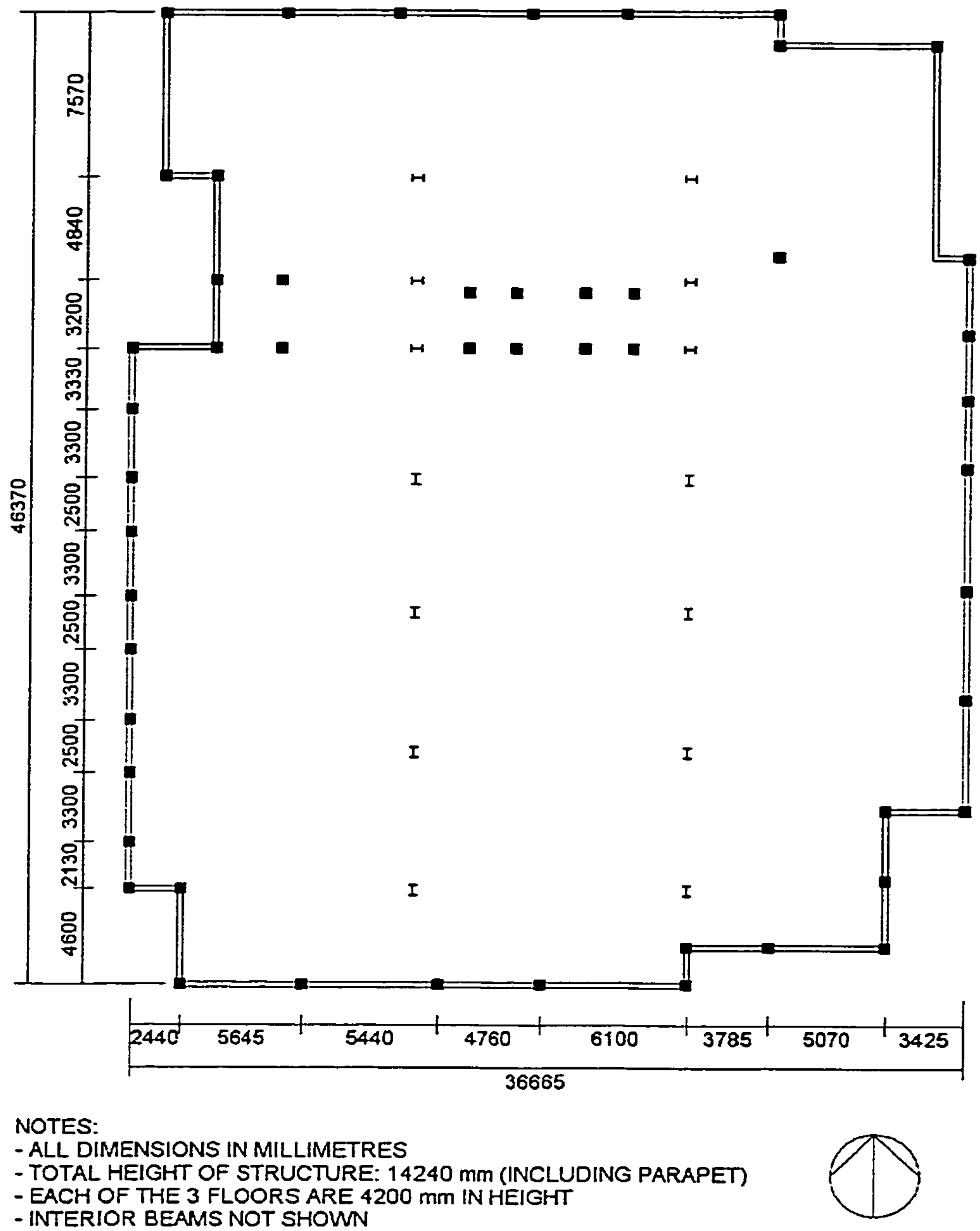


Figure 3.1 Plan view of Building A.

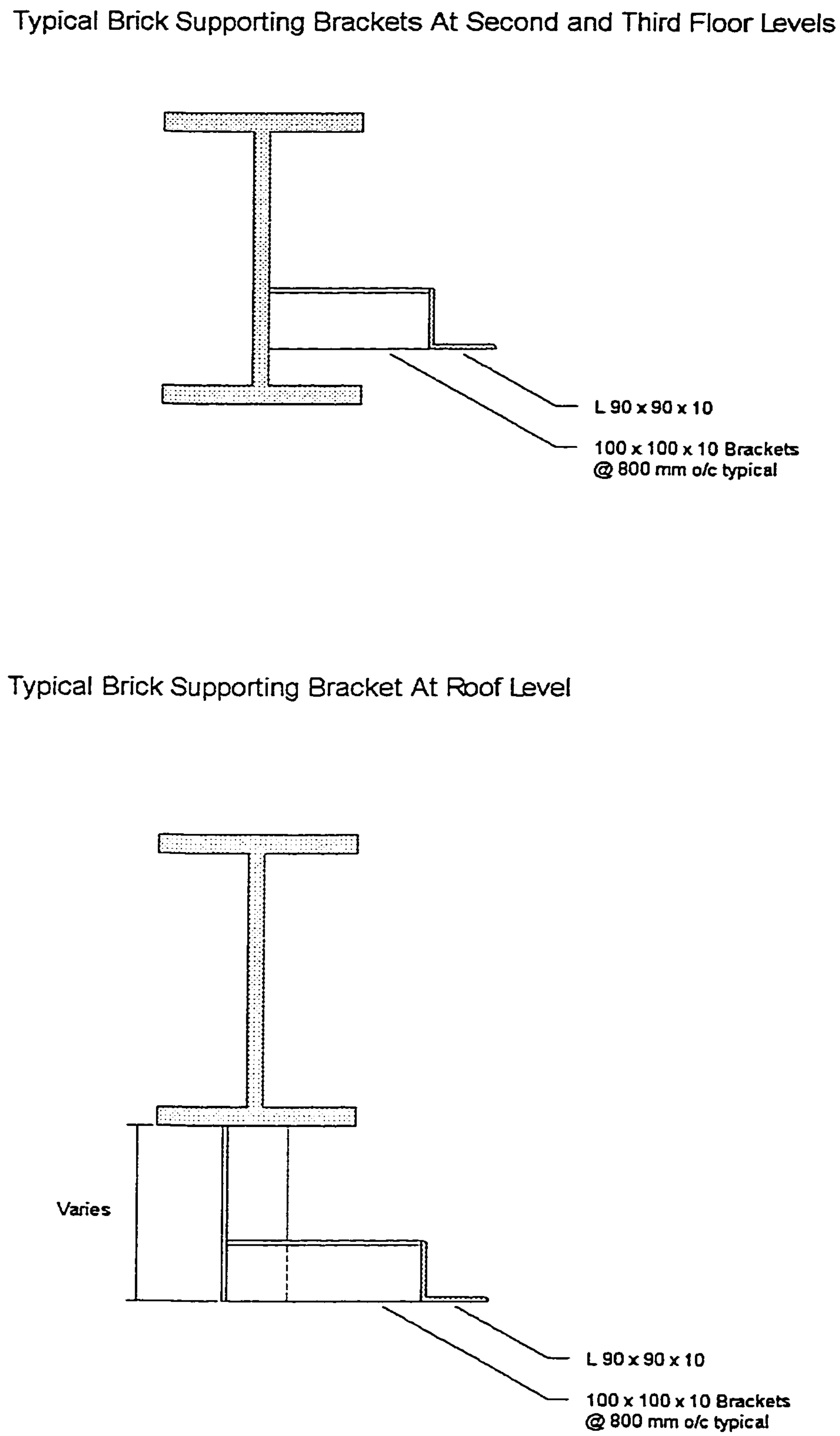


Figure 3.2 Building A shelf angle details.

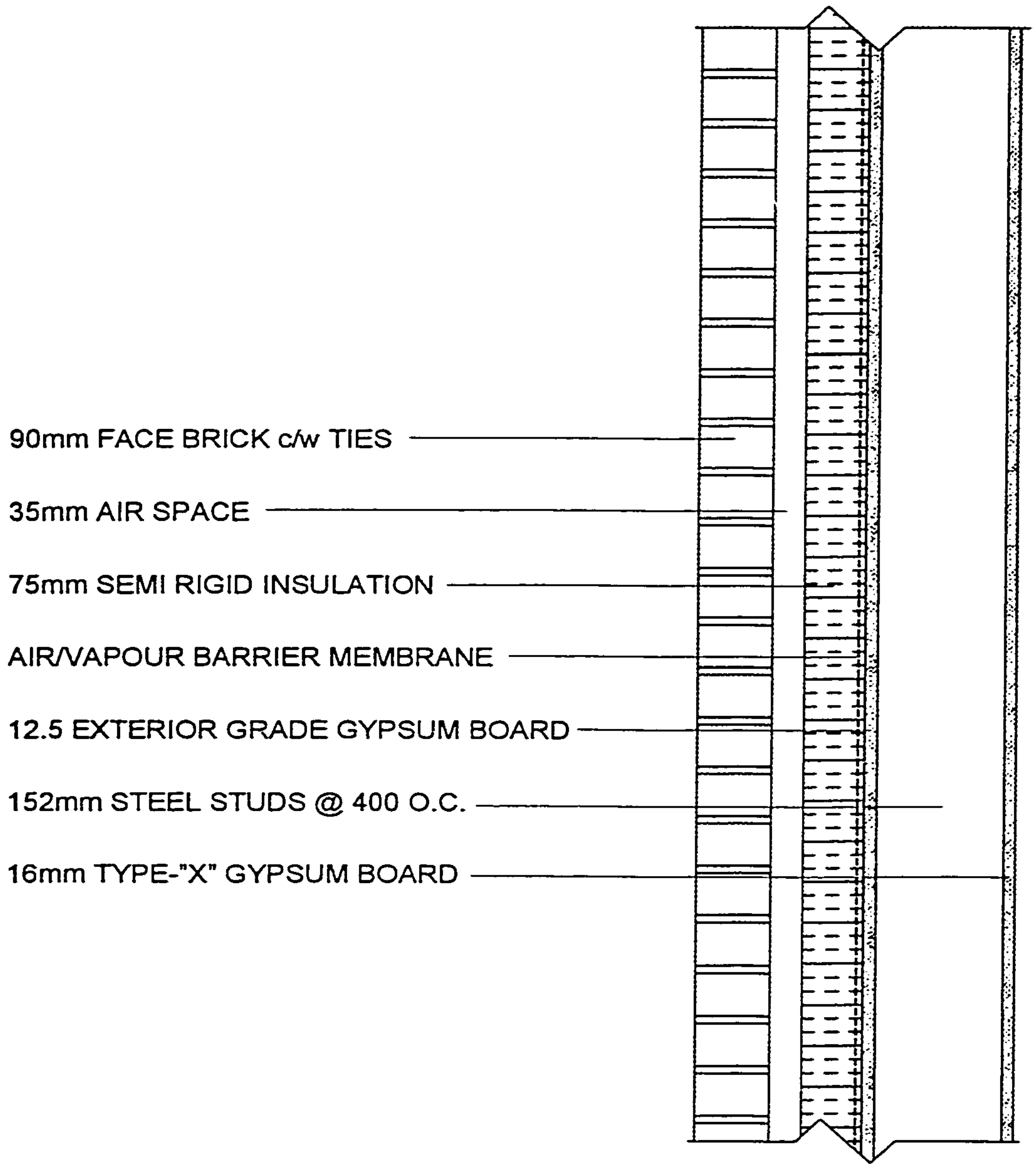


Figure 3.3 Typical exterior wall section Building A.

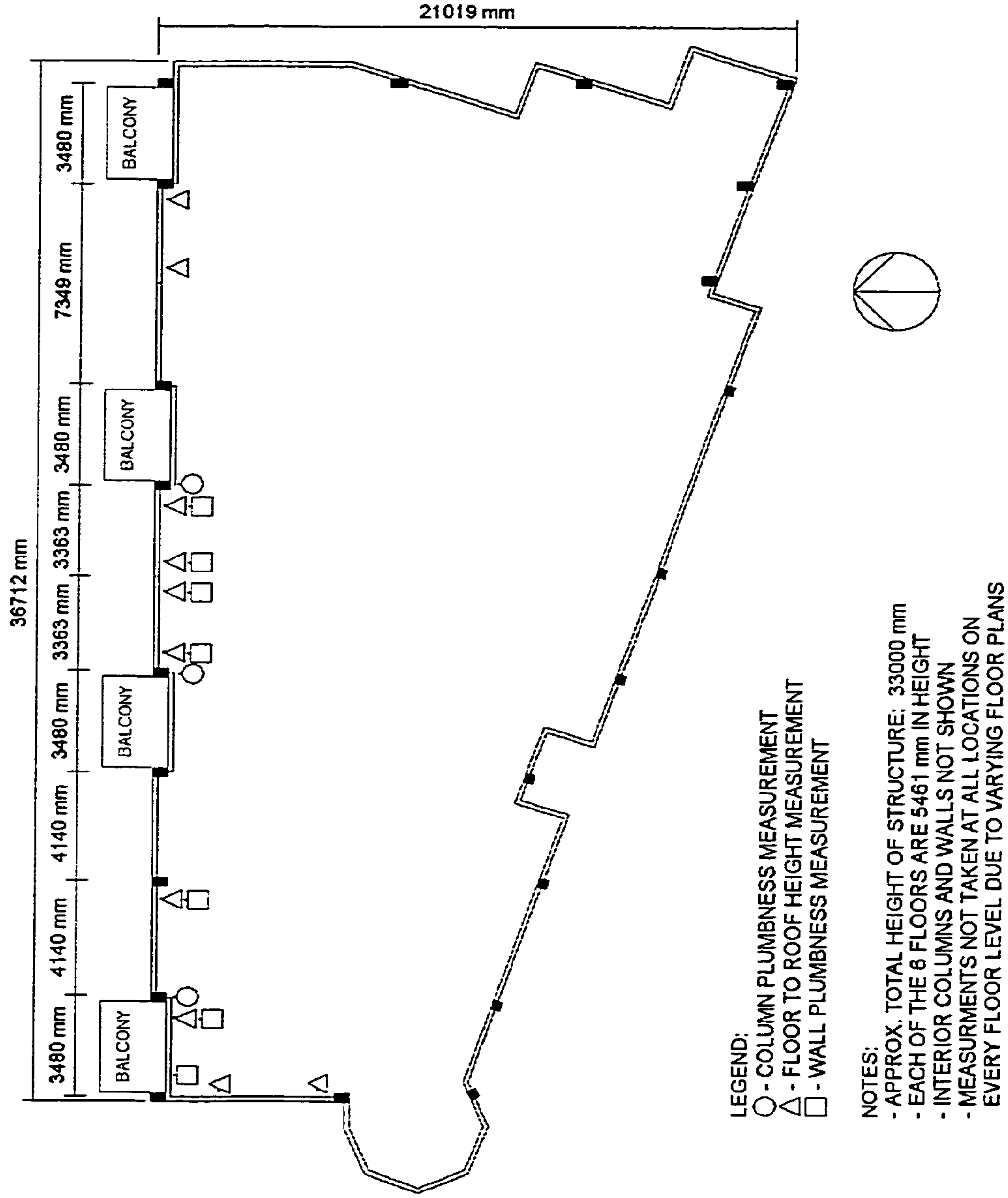


Figure 3.4 Plan view of Building B.

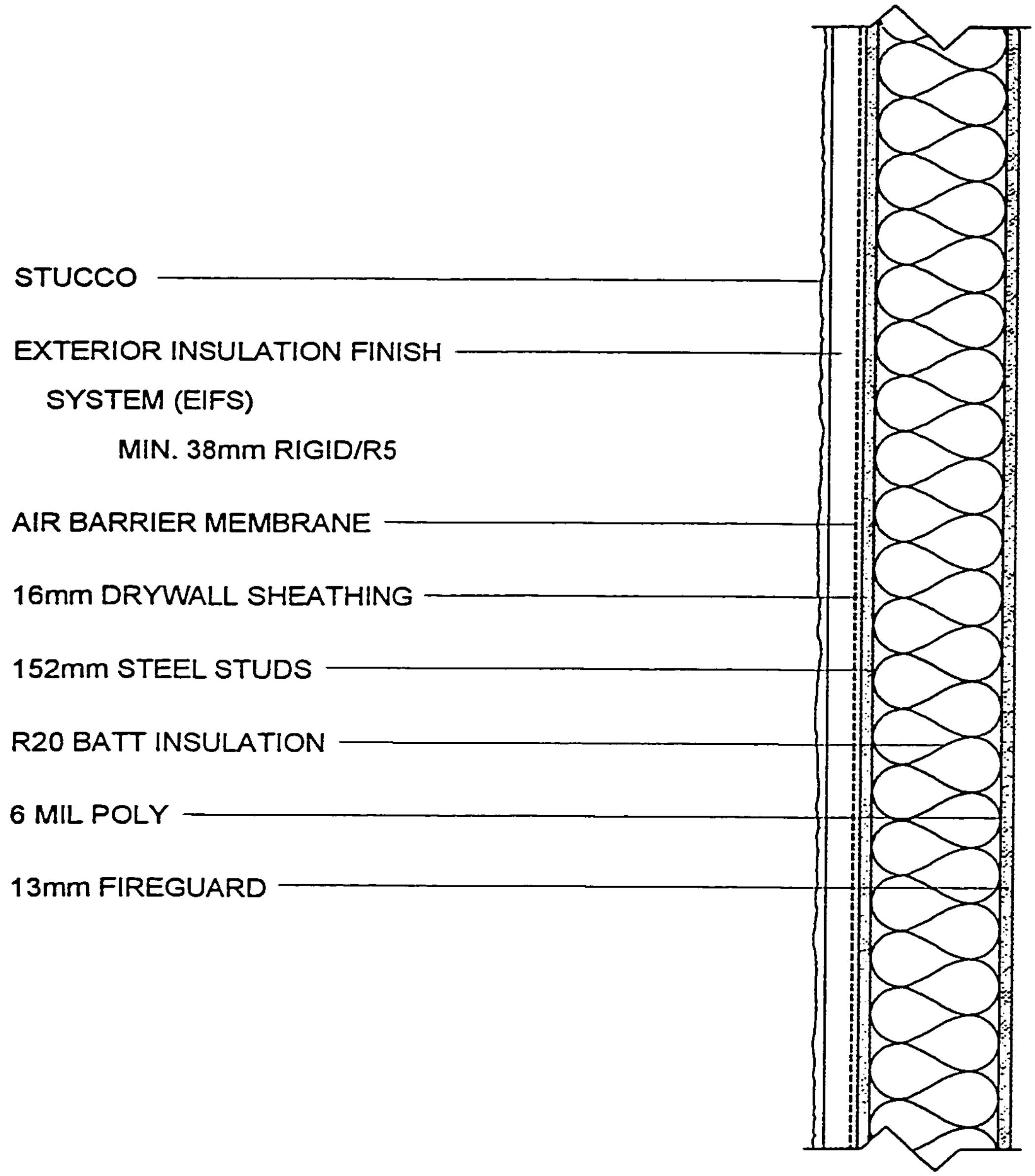


Figure 3.5 Typical exterior wall section Building B.

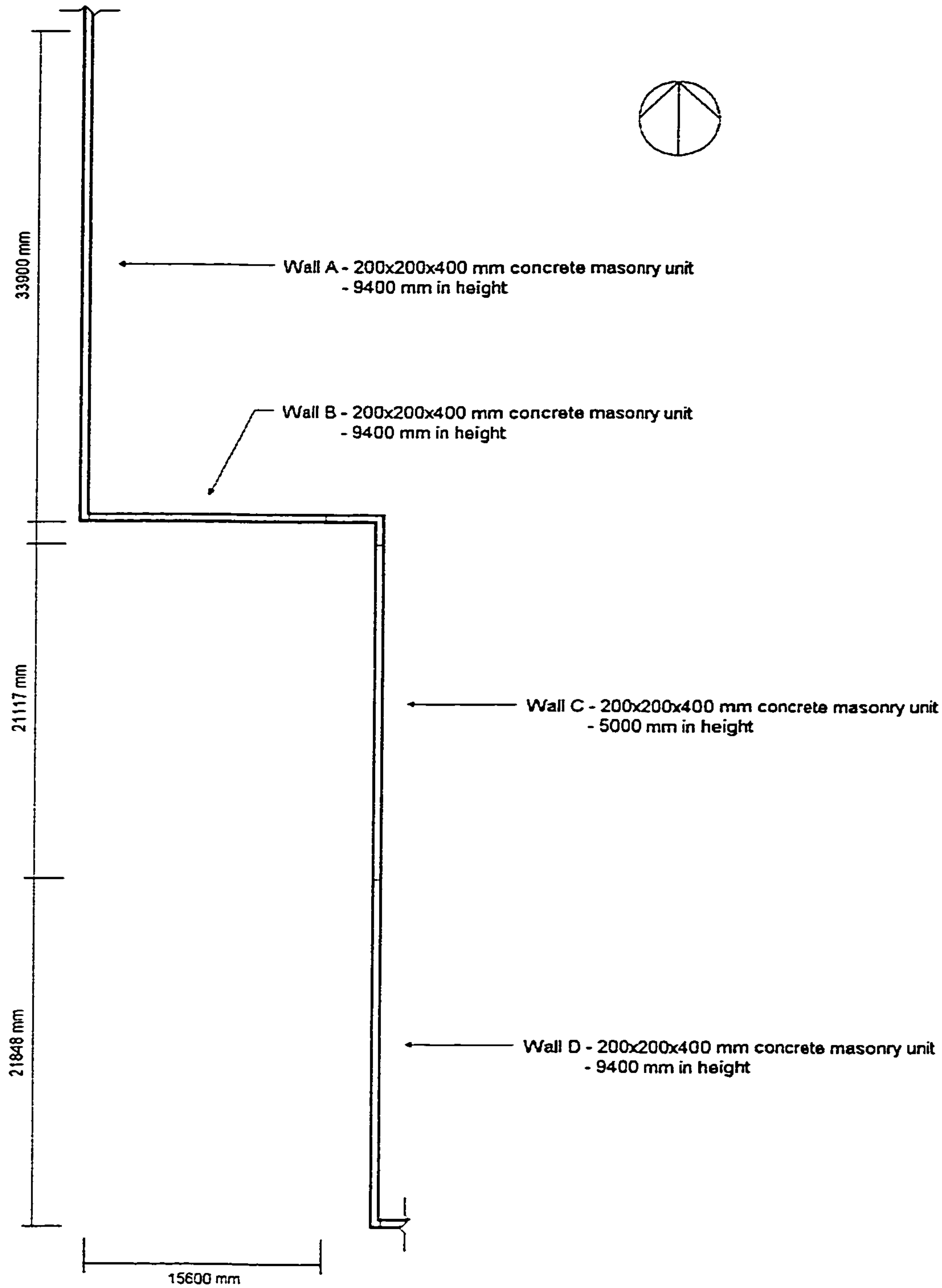


Figure 3.6 Partial plan of Building C.

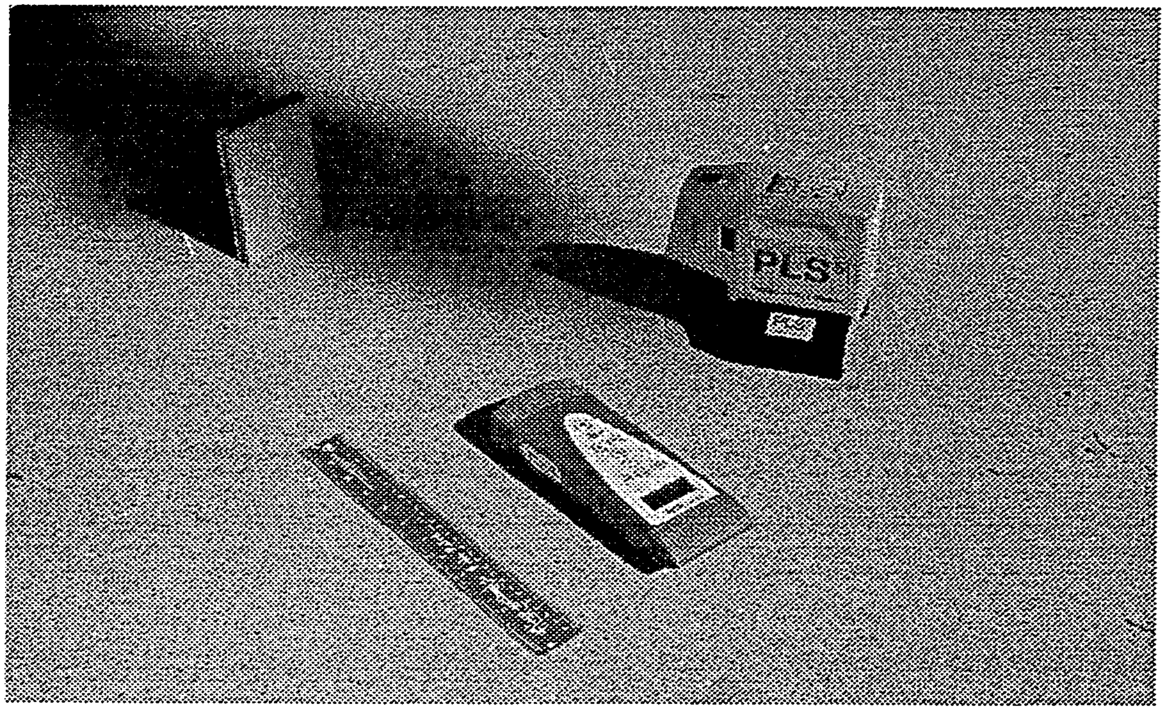


Figure 3.7 Measuring tools.

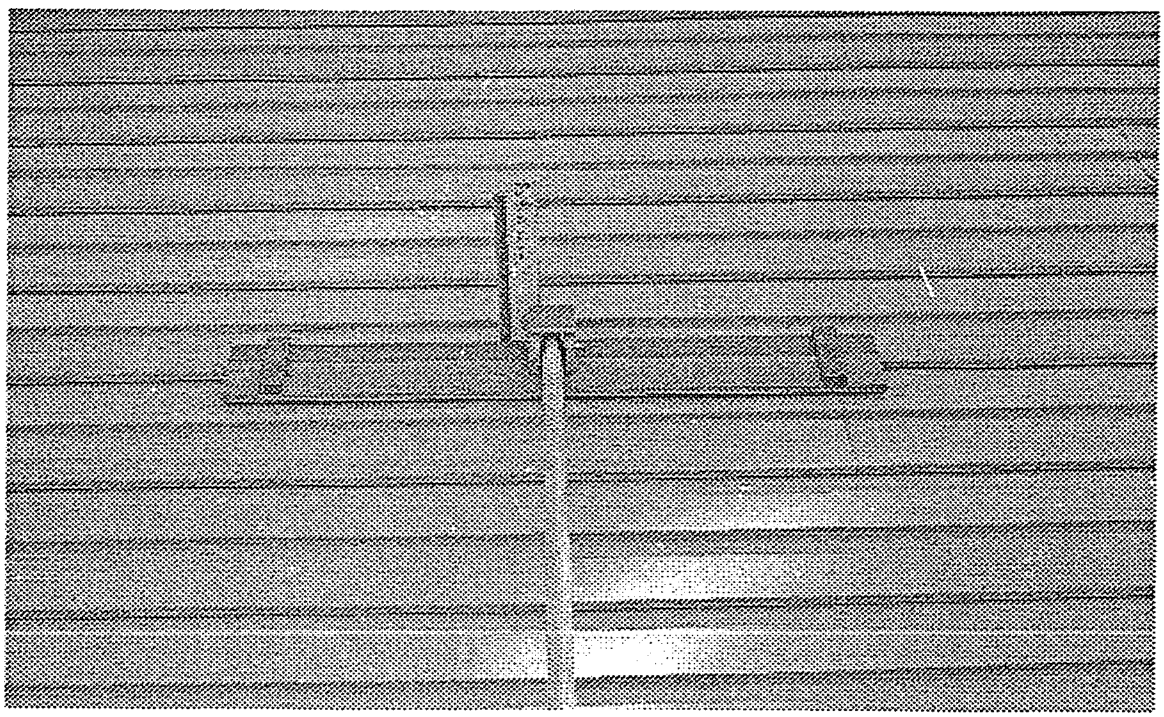


Figure 3.8 Laser plumb measuring aid.

4. TEST RESULTS

4.1 INTRODUCTION

Figures 4.1 to 4.3 summarize the results of the plumbness data collected on the three buildings, and compare it to the current applicable Canadian Design Codes. Note that the values plotted are average values. Tables 4.1 to 4.3 contain the data that was plotted, along with the associated sample size, standard deviation, maximum and minimum values, the corresponding Canadian Design Code allowances, and the percentage of readings that were outside of the allowances.

Figures 4.4 to 4.22 are algebraic and absolute value statistical plots of the data gathered, measured in radians. This was done so that measurements of different heights could be compared. Similar to Figures 4.1 to 4.3, sample size, mean, and standard deviation values are included. Table 4.4 summarizes some of the data found in Figures 4.4 through 4.20.

Figures 4.23 to 4.32 are photographs of the structures and show various areas of interest found on them.

These figures and tables will be discussed in detail in the following sections, and then a comparison of the buildings to each other will follow.

4.2 BUILDING A

Building A, is constructed of steel (See Figure 4.23 for photo). Measurements collected from it were vertical plumbness of the exterior steel columns, masonry shelf angles, exterior drywall, and brick veneer. In addition to these, the size of the air space in the wall cavity from the back face of the brick to the insulation was collected, as well as some other miscellaneous observations about the wall system. These include the placement of the shelf angles, the placement of the bricks, and the expansion tracks of the exterior stud wall.

4.2.1 Steel Column Plumbness

The values for the plumbness of the columns can be found in Table 4.1, with the associated plot in Figure 4.1. By examining the numbers, one can see that the columns are leaning towards the structure, and are not even close to the set tolerance limits. At 4200 mm they are already out by 6 mm, and at 8400 mm the problem progresses to 8 mm past the limits (note that roof level values were not taken due to site access limitations). The standard deviations of both sets of values are around the 10 mm range. Maximum and minimum values are about 2 mm and -35 mm respectively (a negative value indicates leaning towards the structure off the centre line).

If one views the histogram in Figure 4.4 , the mean plumbness value is -1.998×10^{-3} Rad., with a standard deviation of 1.967×10^{-3} Rad. By comparing this data to the data gathered by Beaulieu and Adams (Table 2.1), one can see if the size of the deviation is above or below their findings. Their mean and standard deviation values were found to be -0.044×10^{-3} Rad. and 1.62×10^{-3} Rad. for two of the steel buildings that were 27 and 34 storeys in height. This indicates that the columns from their structures had less deviation from vertical, and the entire sample was less spread out.

Table 4.1 shows that 68% of the values at 4200 mm and 83% at 8400 mm are outside of the set tolerances. Note that the Canadian concrete code recommends that 90%of the construction should fall within the tolerance limits. The remaining 10% is only conditionally acceptable, but may be used in the final structure if the defects are remedied to the degree that the completed job will comply with the tolerance of the finished project. It is obvious that the steel erectors did not do a sufficient job in erecting the columns, and considering that this building is only three storeys high, it is worrisome to think what might happen if the structure were taller.

4.2.2 Shelf Angle Plumbness

Since the shelf angles did not have adjustable connections they cannot be compared to Part 30.7.5(c) of the CAN/CSA-S16.1-94 design code. If they are compared to the rest of the steel code, the first set of data at 3467 mm has an average out of plumb value of -3.2 mm, which is essentially at the limit of the allowable tolerance of -3.5 mm. Unfortunately, as one moves up the structure, the quality of craftsmanship appears to decline, for at 7667 mm the shelf angles are on average 11 mm outside of the prescribed code limits. This results in just under a 5% increase in bending moment on the shelf angle and beam assembly because the bricks are not following the same profile as the shelf angles.

Examining Figure 4.6 and comparing it to Figure 4.4 one observes that the average Radian value for the shelf angles are a little larger than those of the columns. The standard deviation on the other hand is substantially larger with a value of 3.788×10^{-3} Rad. meaning there is far more variance in the data. This is also represented in Figure 4.7 where the plot has a fairly level and spread out appearance.

Once again Table 4.1 indicates that the shelf angles have been poorly placed, with some leaning too far, but many more leaning too close to the structure.

4.2.3 Exterior Drywall Plumbness

The exterior grade drywall was mounted on 152 mm steel studs that were installed around the perimeter of the building between the steel columns and between the concrete floor and steel beams. A photo of this is seen in Figure 4.23. The gypsum board was screwed into place on small vertical metal tracks that were now present around the outer corners of the columns. The remainder of the drywall was fastened directly to the steel studs. Since the wallboard plumbness originated primarily from the stud wall and not the columns, one would expect a more vertical wall.

Figure 4.1 indicates that the exterior drywall is more plumb than the steel columns, but still has an average deviation of -12.8 mm from vertical at 12600 mm, pushing it just outside of the steel code limits.

Figures 4.8 and 4.9 values are also a little more promising with average and standard deviations being only half of those of the columns.

4.2.4 Wall Cavity Air Space Size Variation

The results of the measurements of wall cavity air space size are recorded in Table 4.1 with the associated histogram Figures 4.10, 4.11, 4.12 and 4.13. Data was simply collected by measuring with a ruler from the back face of the brick to the insulation (see wall section Figure 3.3), and since the insulation and brick locations could move from place to place, a high degree of accuracy was not thought to be present. Although these measurements are not an accurate means of determining plumbness, they can be used to get an idea of what is going on inside the wall, and how well it is being constructed.

The wall was specified to have an airspace behind the brick of 35 mm, a value which is a little larger than used in standard practice. Data plotted in Figure 4.10 is for all measurements that were taken on the entire height of the first storey. They have an average deviation of -8.3 mm resulting in a wall cavity size of 26.7 mm. Storeys two and three had less variation with averages of -0.9 mm and -1.7 mm respectively. Figure 4.13 is a compilation of all three storeys indicating an average air space of 31.1 mm.

In summary, it appears that the average wall cavity was kept quite close to its specified value of 35 mm. One must remember that this airspace not only serves as a means to keep moisture away from the rest of the wall assembly, but it is also there to accommodate construction errors, primarily vertical tolerances of the different components. In this case however, the shelf angles were non-adjustable, and therefore the masons could not use the cavity to their maximum advantage.

4.2.5 Brick Veneer Plumbness

The placements of the brick veneer relies heavily on the location of the shelf angles, particularly in this case, where the shelf angles are welded into place, hence making them non-adjustable. Unlike the other trades that use transits (steel erectors), or spirit levels (stud walls), masons use plumb lines that are tied into place to help them while they build. This method could quite easily have been incorporated for the shelf angle installation.

The plot of the veneer data indicates what was suspected; the shelf angle was incorrectly placed relative to the desired locations leading to the bricks being out of plumb. Unfortunately, since plumbness values for the bricks were not taken at the same height as that of the shelf angles, one cannot be entirely sure, but it would appear that looking at the -3 mm and the -17 mm areas as shown in Figure 4.1, that the data line up. Following this further, it would suggest that the upper most shelf angle (unable to be measured) falls in line with the one located at 7667 mm. The data also shows that the masons were able to erect the wall within the masonry code tolerances, but were unable to do so at the the higher elevations where they were out by just over 3mm. Percentage values exceeding allowable limits also improved to 31% at 5300 mm and 60% at 12600 mm, however, with the latter only five measurements were taken.

If we move to Figure 4.12 we see that the average and standard deviation values are -0.673×10^{-3} Rad. and 1.173×10^{-3} Rad. Once again these values are better than the steel columns and shelf angle readings.

4.2.6 Miscellaneous

This part of the paper contains a collection of some miscellaneous observations that did not fit into other categories. This includes shelf angles being placed at wrong heights, soft-joint deficiencies, and incorrectly constructed expansion tracks.

4.2.6.1 Improper Shelf Angle Placement

While section 4.2.2 of this paper deals with the plumbness of the shelf angles, this section focuses on the placement of the angles at their proper elevation. Located at the southeast corner of the structure, 4600 mm from the southern wall (see Figure 3.1) the shelf angles changed height by 135 mm, rather than staying level as indicated in the drawings. A photo of this was taken and is shown in Figure 4.25. Not only does this complicate things for the brick layers, but it also makes it difficult to have a proper expansion joint right below the shelf angles.

4.2.6.2 Brick Placement

Although comments from contractors are open to bias, in this case they seemed to agree with observations found in the data. In some sections of the wall, particularly at the lower levels, the masons had to do away with the soft-joint below the shelf angle and place mortar in it because the bricks were not sitting at least half way on the angle. Figure 4.1 supports this, as it indicates that the shelf angles were installed closer to the structure as they increased in elevation.

The contractor also stated that the shelf angles were deflecting downward as more bricks were being placed, thus reducing the size of the expansion joint, and perhaps in some cases inducing stress onto the courses below. This is most likely the result of the design of the shelf angle assembly shown in Figure 3.4, which has been known to experience problems (Nicastro, 1997). The detailing indicates that the shelf angles are to be welded onto the bottom flange of the beam or on the lower half on the web. In both cases the beam has little strength to resist the twisting motion placed upon it.

4.2.6.3 Stud Wall Expansion Tracks

Figure 4.26 shows the final area of the exterior wall assembly that was shown to have problems. The expansion tracks located at the tops of the steel stud walls should not have been screwed together (indicated by arrows). This is most likely the result of the contractor failing to remove them after building the wall assembly. Not removing these screws prevents the walls from being able to move as freely as intended. Note, however, that some movement is still present because the screws are located on only one side of the track.

4.3 BUILDING B

Figure 4.28, 4.29 and 4.30 show outside and inside views of the 33000 mm condominium during construction. Referring back to Figure 3.4 in Chapter 3, the three visible measurement locations are the concrete column plumbness, the steel stud wall plumbness and the floor-to-ceiling height distance. Data regarding this structure is presented in Figures 4.2, 4.14 to 4.18 and Tables 4.2 and 4.4.

4.3.1 Concrete Column Plumbness

In Figure 4.2 a graphical representation of the data collected on Building B is compared to the two Canadian Concrete Codes. The average column values are shown to be well within both standards, with the various data points snaking back and forth across the vertical plane. It should be noted however, that the slope of some of the upper columns has exceeded the maximum permitted slope of 1:400. Moving to Table 4.2, the actual plotted values in millimetres are indicated.

To understand how this data compares to previous research, a statistical plot was generated in Figure 4.14 and 4.15. Even though the sample size is rather small with 8 readings, one still gets a good approximation of what is taking place. The average absolute values are 1.531 $\times 10^{-3}$ Rad. and the standard deviation was computed as 0.770 $\times 10^{-3}$ Rad. Comparing this data to that documented by Beaulieu and Adams (Table 2.4), one can see that Figure 4.15's absolute values are smaller and therefore better.

If we look at this data once again, but now from the perspective of Figure 4.14 and compare it to the precast concrete in Table 2.2, it appears that as a whole the precast's average values are a little higher, but the standard deviations are about the same.

4.3.2 Steel Stud Wall Plumbness

The stud wall plumbness data for Building B follows a similar shape to the columns, but are much more relaxed and within the concrete tolerance standards. However, if we were to compare the data point associated with the 5308 mm height, and that of the steel code, it would indicate that we are over the allowable limit of 5.3 mm by 2.7 mm. Once again, a larger sample size would be desirable, unfortunately due to the nature of the construction site, that was not possible.

The histogram in Figure 4.16 gives a better indication of the quality of construction present in the walls, because the data is all grouped together. When the average is compared to that of the concrete columns, it is higher with a value of 0.882×10^{-3} Rad., rather than -0.542×10^{-3} Rad. The reason for this is that all of the wall data leans away from the structure, whereas the columns would lean both towards and away, hence somewhat cancelling each other out. This is supported by the standard deviation data.

4.3.3 Floor-to-Ceiling Height Deviation

The small amount of data that was collected on the floor-to-ceiling distance deviation between the storeys of Building B is presented in Figure 4.18. The numbers indicate that on average the floor-to-floor distances were 36.75 mm short of their specified 5461 mm height. This is rather high considering section 10.4.1 of the concrete code states that total variation of the average slope of floors, beams and other horizontal units shall not be more than 40 mm for the total length of the structure. The author believes this large variation can be the result of the columns being spaced relatively close together, making it harder for the contractors to level the slab around the columns where the majority of data was collected, and also because of the rather tall height of the storey.

4.4 BUILDING C

Building C, contains four large concrete unit masonry walls that are of interest. Three walls measured 9400 mm and one 5000 mm (see Figures 3.6, 4.31, and 4.32). Only plumbness data was collected.

4.4.1 Concrete Unit Masonry Wall

Figure 4.3 shows the mean plumbness values for the walls. Due to the nature of the collected data, the three tall walls, A, B and D were grouped, leaving the short Wall C on its own. All of the data gathered lie within masonry tolerances. What is interesting is that Wall C leans toward the structure more than the taller walls. Perhaps less care was taken during its construction because of its smaller size. Plotted points are found in Table 4.5.

Looking at Figures 4.19 and 4.20 the average and standard deviation values are shown as lower than the plumbness values of the other structures. It would appear that these masonry contractors have a better handle on controlling tolerances than some of the other trades examined in the study.

4.5 SUMMARY OF BUILDINGS A, B AND C

From reading the earlier sections of this Chapter and from looking at the plots in Figures 4.1 to 4.3, it is easy to see how the following conclusions are derived. Building A was very poorly constructed in terms of tolerance. Almost all of the data was outside of the prescribed allowances, and the entire wall assembly leaned toward the building. All of these faults stem from poor placement of the steel frame, which fortunately does not appear to be a common problem. Site inspection of Buildings B and C, contractor feedback and data from Beaulieu and Adams' paper reinforce this conclusion.

Buildings B and C were nicely constructed. However, Building B's concrete columns exceeded their 1:400 slope restriction in one part of the structure.

It should be noted that Building A's steel and masonry problem is not the ideal for testing what occurs when different construction materials interact. One would have hoped that the steel would have been built to the limits of its tolerance envelope, and then see how the masonry accommodated this. What is also unfortunate is that Building A was not tall enough to represent what happens at higher elevations where serious deficiencies in the standards occur.

MEASUREMENT TYPE	SAMPLE SIZE n	HEIGHT [mm]	MEAN [mm]	STANDARD DEVIATION [mm]	MAX. VALUE [mm]	MIN. VALUE [mm]	ALLOWABLE CDN. CODE MAXIMUM [mm]	ALLOWABLE CDN. CODE MINIMUM [mm]	VALUES EXCEEDING MAX. ALLOWABLE [%]	VALUES EXCEEDING MIN. ALLOWABLE [%]	TOTAL EXCEEDING [%]
Steel Column Plumbness	19	4200	-10.211	9.754	2	-36	(steel) 4.2	(steel) -4.2	0	68	68
	18	8400	-16.861	10.597	2.5	-35	8.4	-8.4	0	83	83
Shelf Angle Plumbness	18	3467	-3.222	13.397	19	-31	(steel) 3.467	(steel) -3.467	28	44	72
	19	7667	-18.417	12.088	8	-35	7.667	-7.667	6	83	89
Exterior Drywall Plumbness	12	12600	-12.833	11.060	2	-40	--	--	--	--	--
Wall Cavity Size Variation (from 35mm)	33	2100	-8.333	8.399	4	-32	--	--	--	--	--
	26	6300	-0.923	4.741	5	-15					
	32	10500	-1.688	6.388	7	-20					
Brick Veneer Plumbness	26	5300	-2.932	5.986	7	-16	(masonry) 6	(masonry) -6	4	27	31
	5	12600	-16.400	16.667	7	-34	13	-13	0	60	60

* Positive values indicate leaning away from the structure as you increase in height, whereas negative indicates leaning towards.

Table 4.1 Summary of measured values from Building A in millimetres.

MEASUREMENT TYPE	SAMPLE SIZE n	HEIGHT [mm]	MEAN [mm]	STANDARD DEVIATION [mm]	MAX. VALUE [mm]	MIN. VALUE [mm]	ALLOWABLE CDN. CODE MAXIMUM [mm]		ALLOWABLE CDN. CODE MINIMUM [mm]		VALUES EXCEEDING MAX. ALLOWABLE [%]	VALUES EXCEEDING MIN. ALLOWABLE [%]	TOTAL EXCEEDING [%]
							Concrete		Concrete				
							(10.3)	(10.5.1)	(10.3)	(10.5.1)			
Concrete Column Plumbness	1	5308	5	0	5	5	14.2	8	-14.2	-8	0	0	0
	3	10616	-1.667	8.505	7	-10	28.3	20	-28.3	-20	0	0	0
	2	15924	-12.5	4.950	-9	-16	40	30	-40	-30	0	0	0
	1	21232	9	0	9	9	40	50	-40	-50	0	0	0
	1	26540	-7	0	-7	-7	40	50	-40	-50	0	0	0
Steel Stud Wall Plumbness	2	5308	8	15.556	19	-3	--		--		--	--	--
	5	10616	2.6	2.510	5	-1							
	4	15924	2.75	2.872	5	-1							
	4	21232	7.5	2.082	10	5							
	4	26540	4.75	5.679	11	-1							
Floor to Roof Height Deviation (from 5461mm)	24	--	-36.75	48.708	16	-118	--		--		--	--	--

* Positive values indicate leaning away from the structure as you increase in height, whereas negative indicates leaning towards.

Table 4.2 Summary of measured values from Building B in millimetres.

MEASUREMENT TYPE	SAMPLE SIZE n	HEIGHT [mm]	MEAN [mm]	STANDARD DEVIATION [mm]	MAX. VALUE [mm]	MIN. VALUE [mm]	ALLOWABLE CDN. CODE MAXIMUM [mm]	ALLOWABLE CDN. CODE MINIMUM [mm]	VALUES EXCEEDING MAX. ALLOWABLE [%]	VALUES EXCEEDING MIN. ALLOWABLE [%]	TOTAL EXCEEDING [%]
A, B, and D Concrete Unit Masonry Walls	25	9395	-2.76	3.551	5	-9	(masonry) 9.96	(masonry) -9.96	0	0	0
C Concrete Unit Masonry Wall	6	5000	-4.167	4.215	1	-9	(masonry) 6	(masonry) -6	0	33	33

* Positive values indicate leaning away from the structure as you increase in height, whereas negative indicates leaning towards.

Table 4.3 Summary of measured values from Building C in millimetres.

BUILDING	PLUMBNESS MEASUREMENT	SAMPLE SIZE	VALUE TYPE	MEAN [x10^{-3}Rad.]	STANDARD DEVIATION [x10^{-3}Rad.]
A	Steel Column	37	Algebraic Absolute	-1.998 2.159	1.967 1.784
A	Shelf Angle	36	Algebraic Absolute	-2.657 3.772	3.788 2.640
A	Exterior Drywall	12	Algebraic Absolute	-1.019 1.045	0.878 0.843
A	Brick Veneer	31	Algebraic Absolute	-0.673 1.037	1.173 0.855
B	Concrete Column	8	Algebraic Absolute	-0.542 1.531	1.713 0.770
B	Steel Stud Wall	19	Algebraic Absolute	0.882 1.001	0.985 0.857
C	Concrete Unit Masonry Wall	31	Algebraic Absolute	-0.398 0.500	0.529 0.431

Table 4.4 Out-of-plumbs data in Radians.

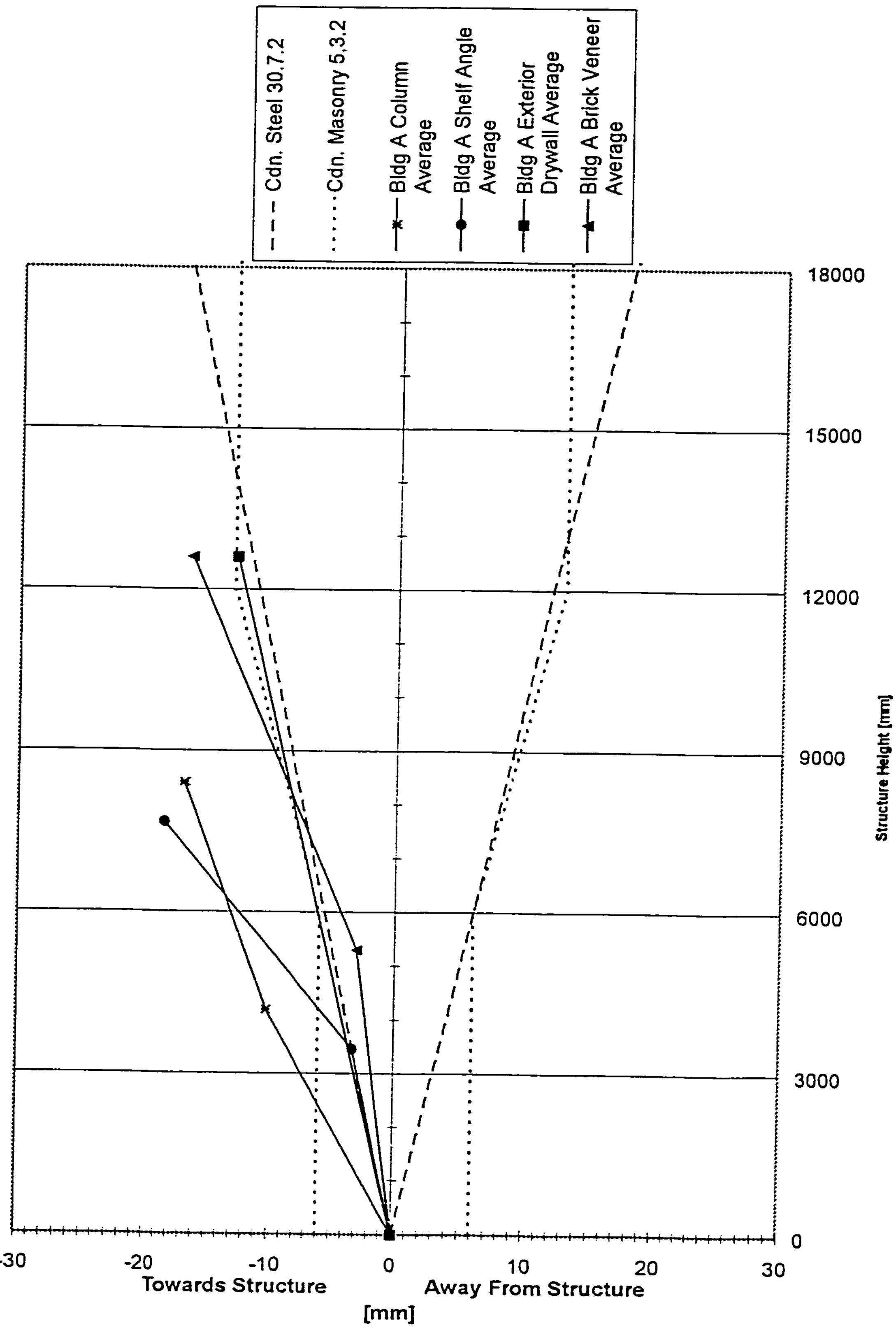


Figure 4.1 Out-of-plumb data for Building A.

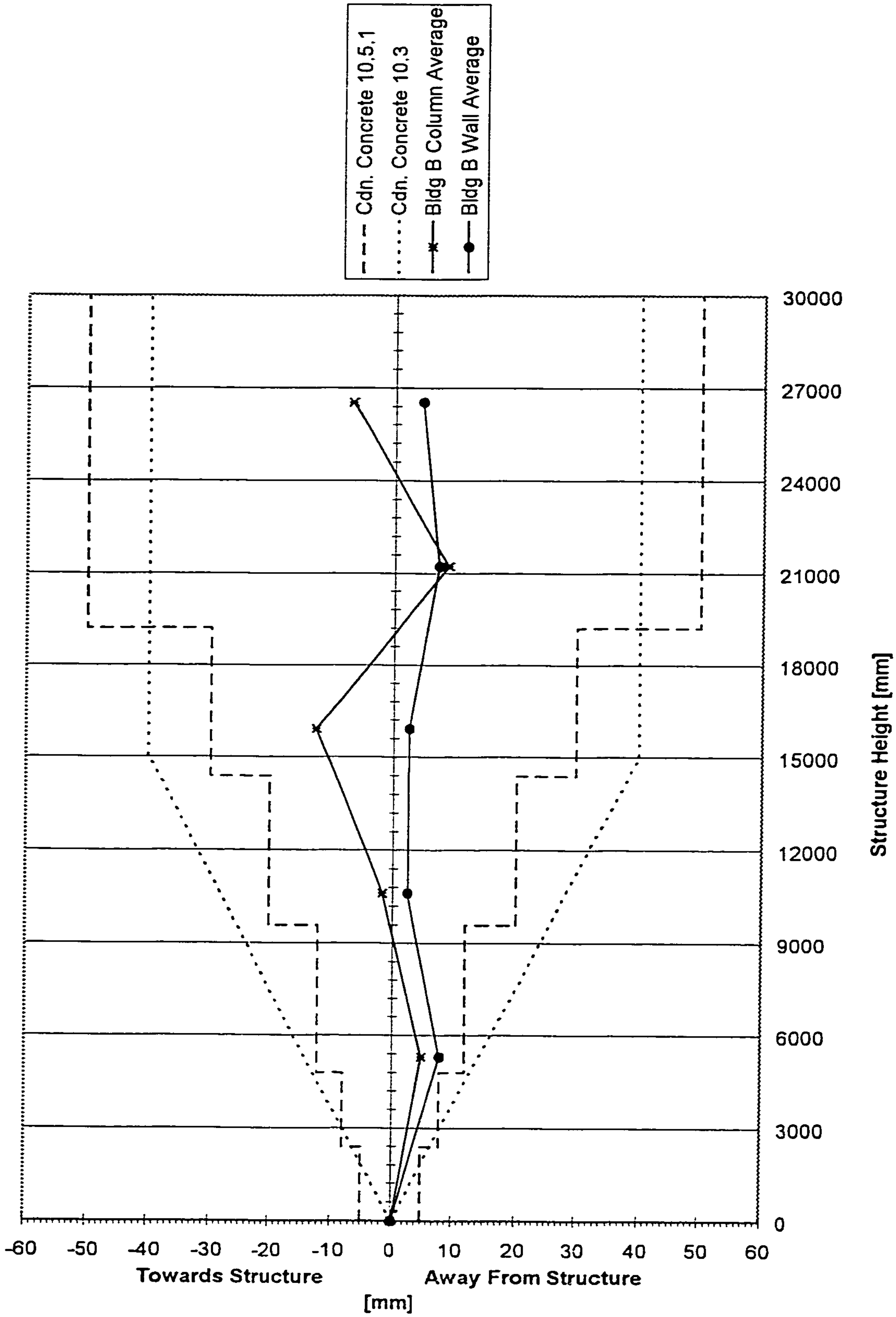


Figure 4.2 Out-of-plumb data for Building B.

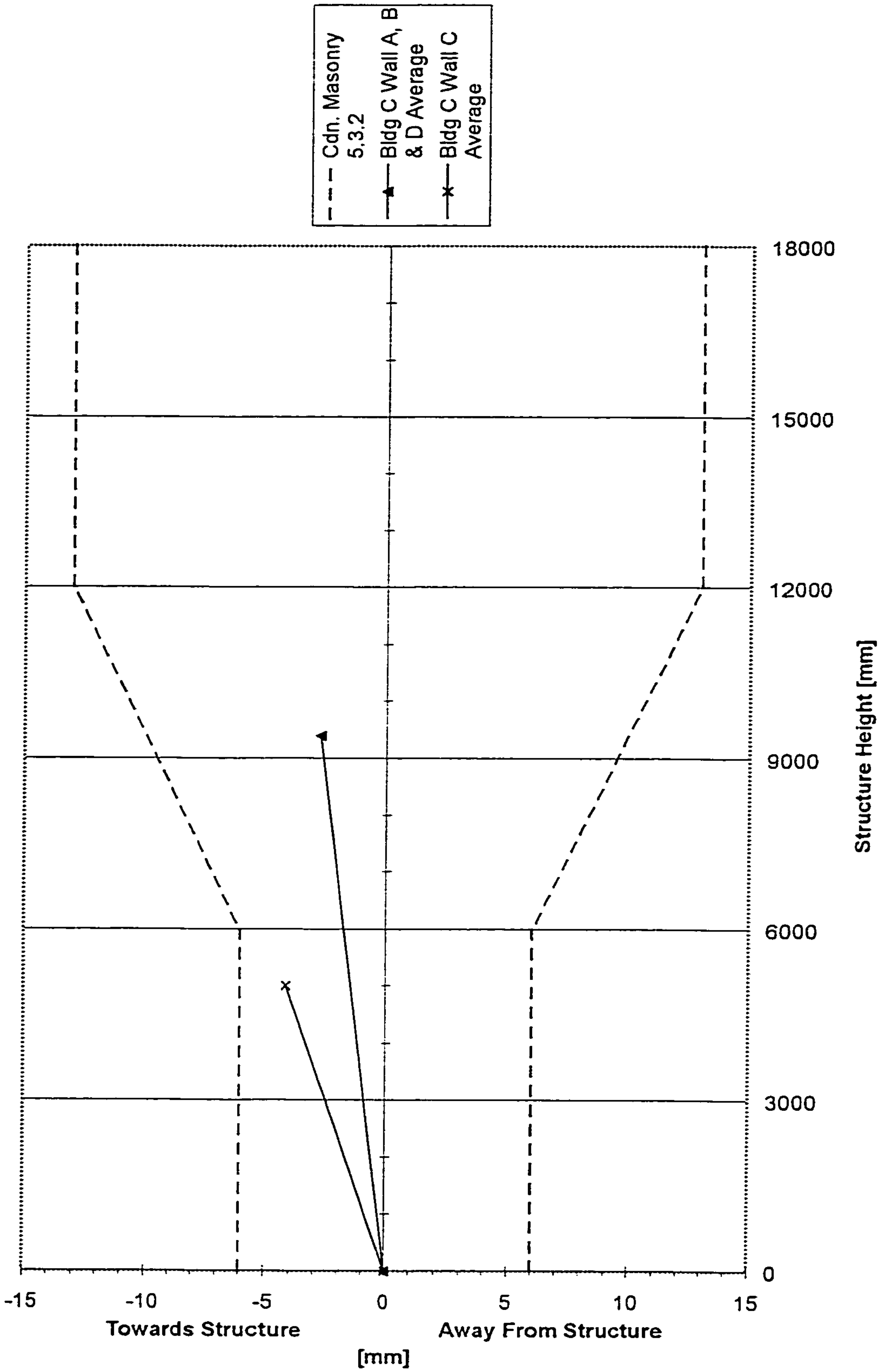
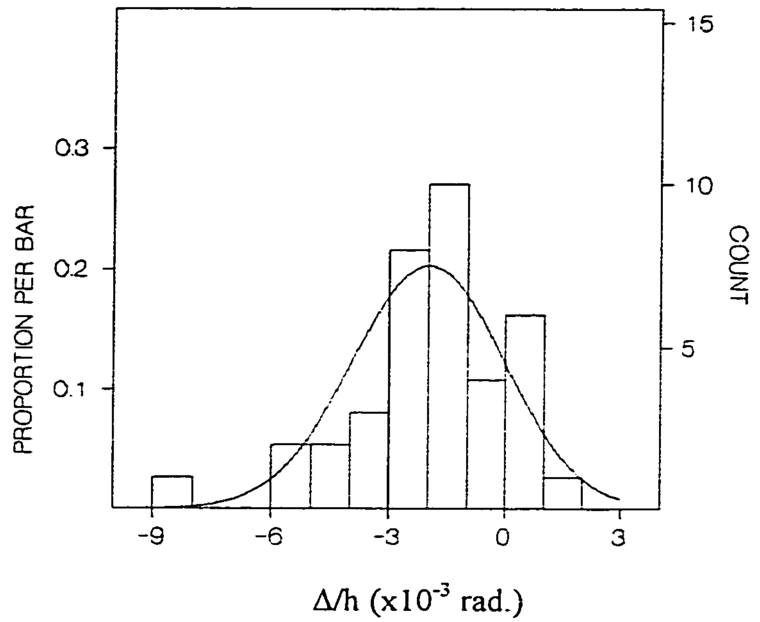


Figure 4.3 Out-of-plumb data for Building C.

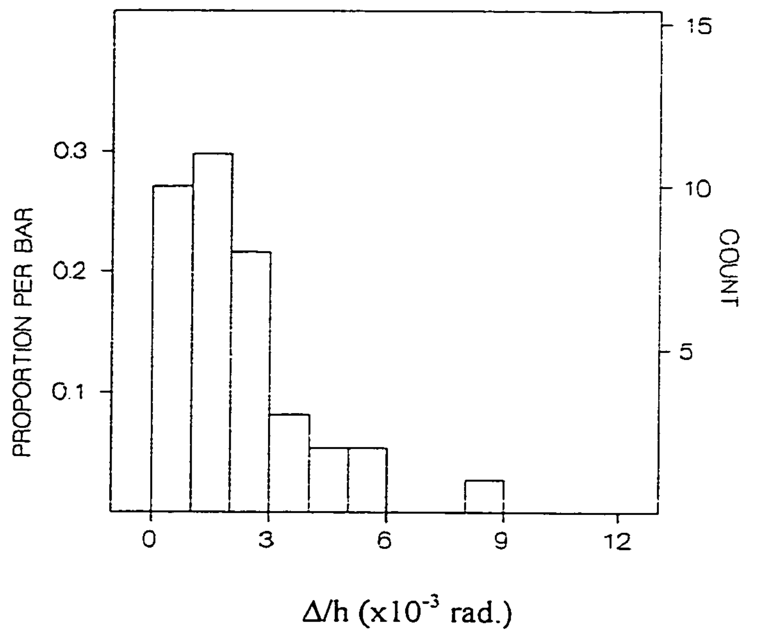


n = 37

Average = -1.998x10^{-3} rad.

Std. Dev. = 1.967x10^{-3} rad.

Figure 4.4 Steel column out-of-plumb distribution for Building A.



n = 37

Average = 2.159x10^{-3} rad.

Std. Dev. = 1.784x10^{-3} rad.

Figure 4.5 Distribution of absolute values of steel column out-of-plumbs for Building A.

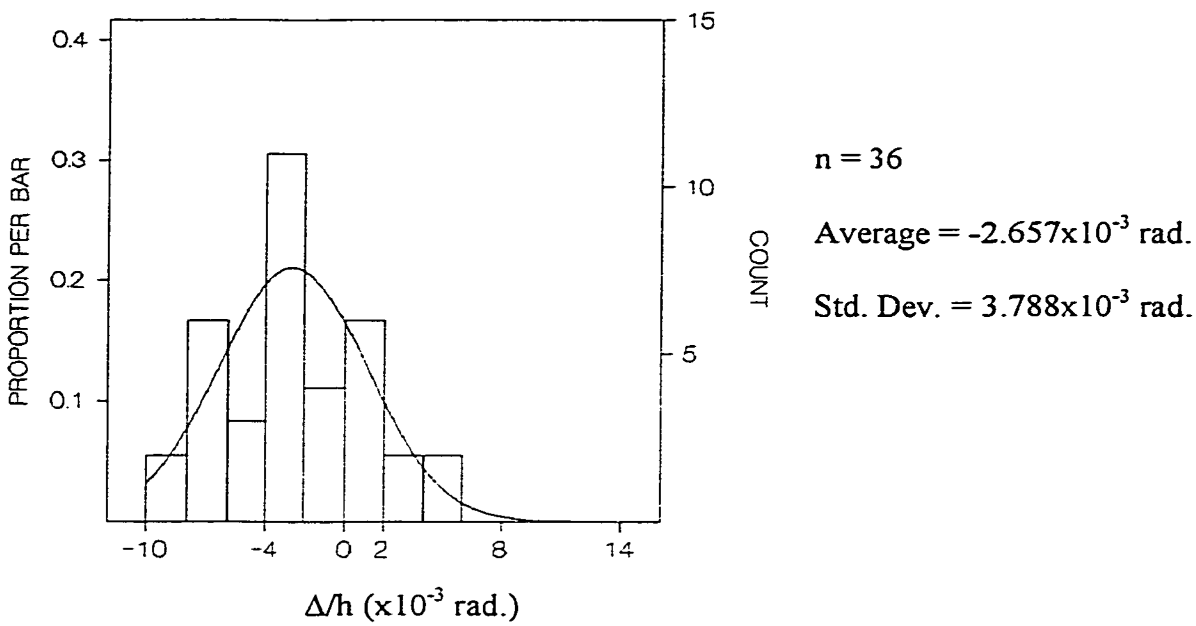


Figure 4.6 Shelf angle out-of-plumb distribution for Building A.

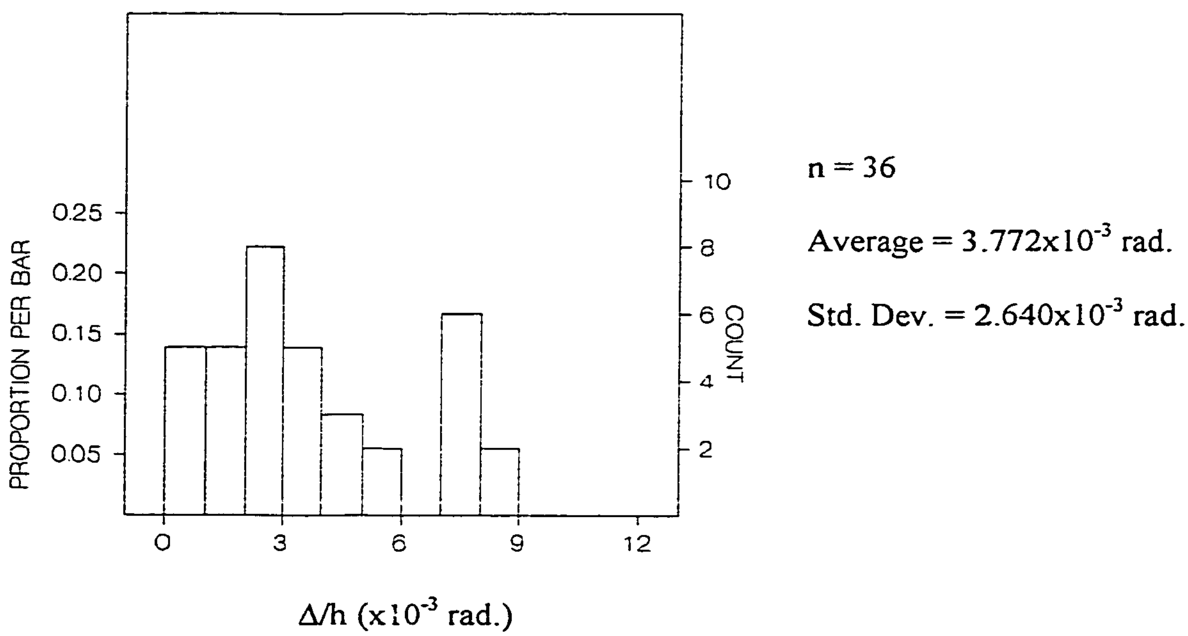
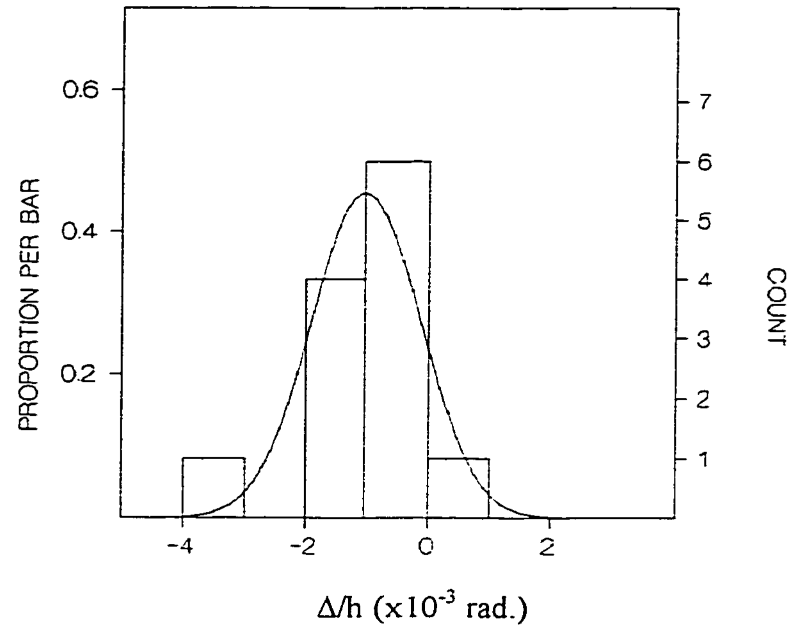


Figure 4.7 Distribution of absolute values of shelf angle out-of-plumbs for Building A.

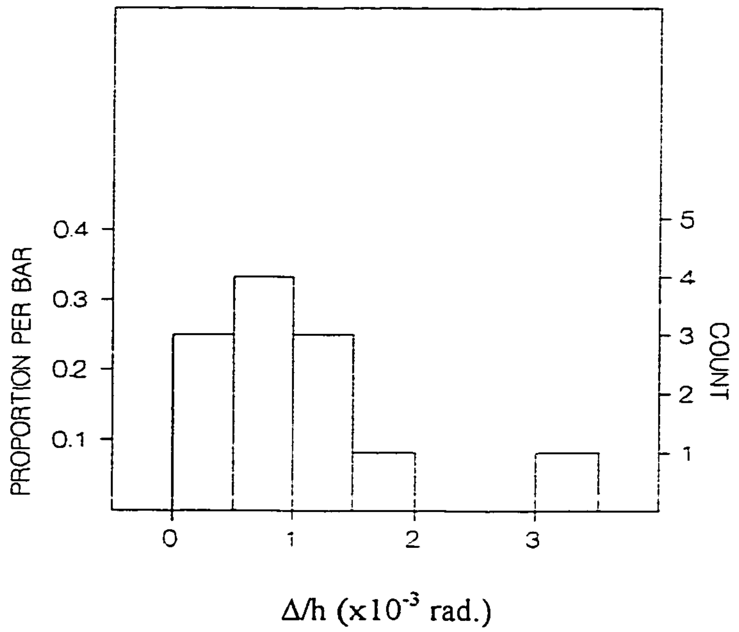


n = 12

Average = -1.019×10^{-3} rad.

Std. Dev. = 0.878×10^{-3} rad.

Figure 4.8 Exterior drywall out-of-plumb distribution for Building A.

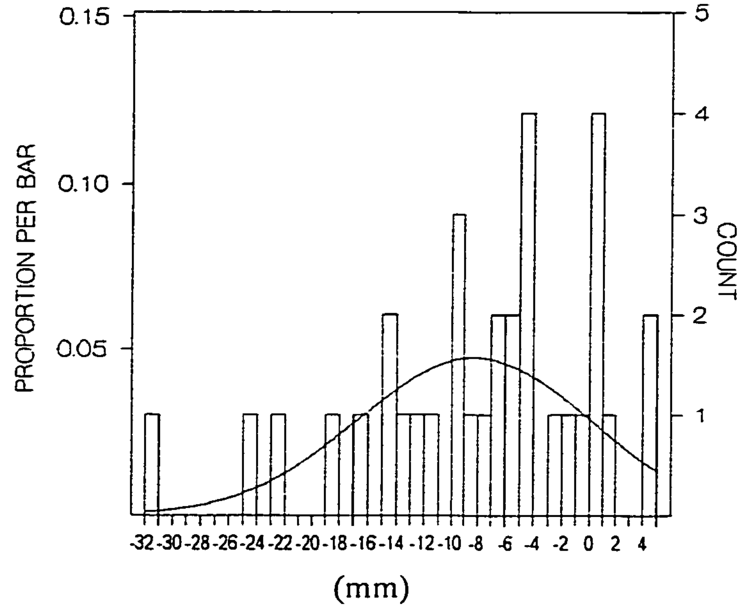


n = 12

Average = 1.045×10^{-3} rad.

Std. Dev. = 0.843×10^{-3} rad.

Figure 4.9 Distribution of absolute values of exterior drywall out-of-plumbs for Building A.

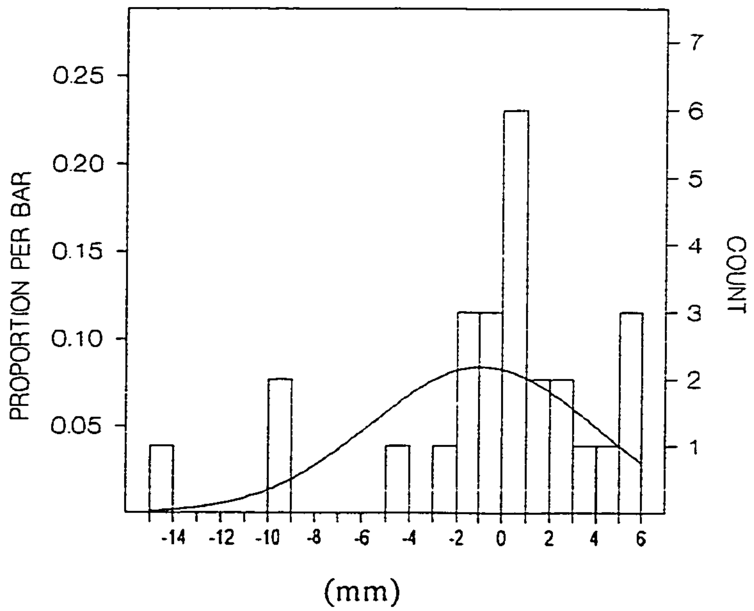


n = 33

Average = -8.333mm

Std. Dev. = 8.399mm

Figure 4.10 First storey wall cavity size deviation (from 35mm) distribution Building A.

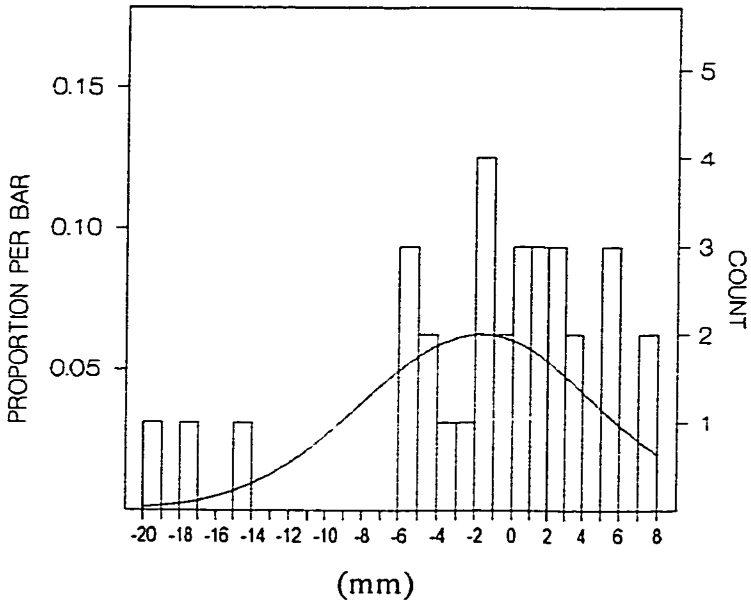


n = 26

Average = -0.923mm

Std. Dev. = 4.741mm

Figure 4.11 Second storey wall cavity size deviation (from 35mm) distribution Building A.

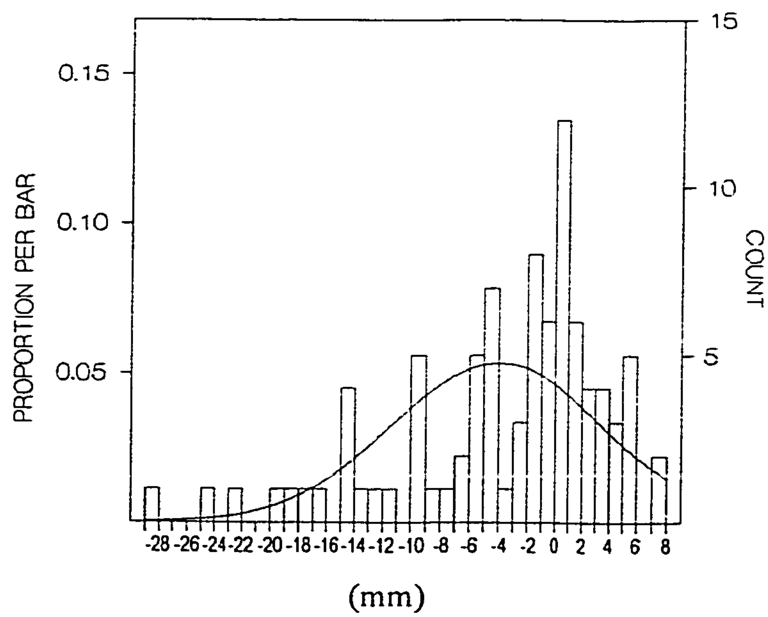


n = 32

Average = -1.688mm

Std. Dev. = 6.388mm

Figure 4.12 Third storey wall cavity size deviation (from 35mm) distribution Building A.



n = 91

Average = -3.879mm

Std. Dev. = 7.542mm

Figure 4.13 All storeys wall cavity size deviation (from 35mm) distribution Building A.

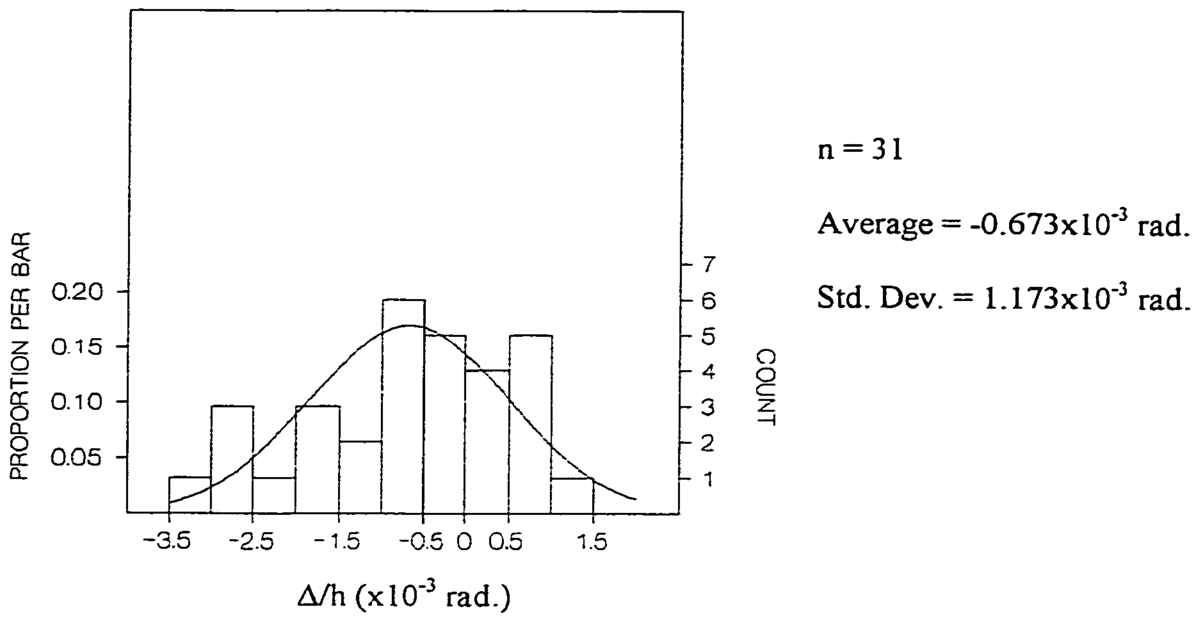


Figure 4.14 Brick veneer out-of-plumb distribution for Building B.

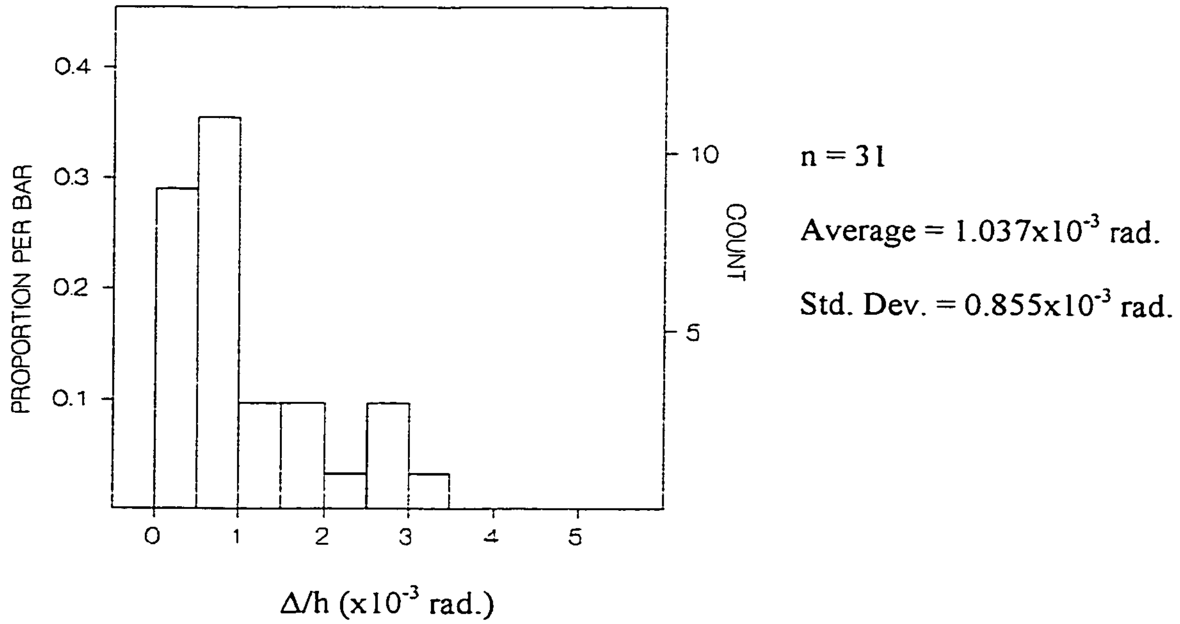
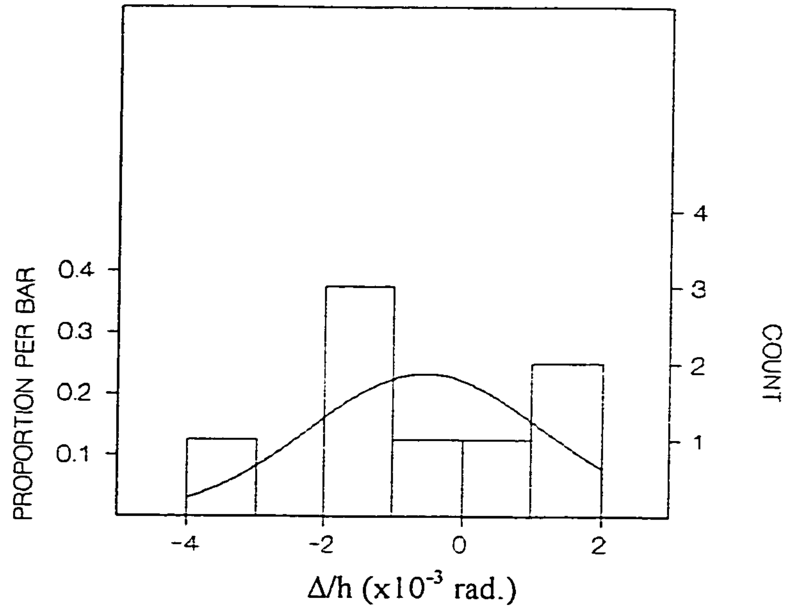


Figure 4.15 Distribution of absolute values of brick veneer out-of-plumbs for Building A.

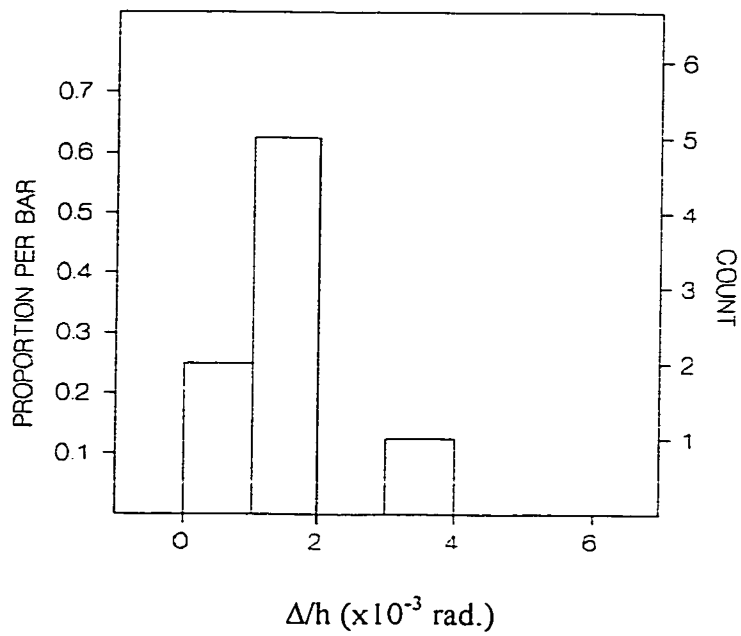


n = 8

Average = -0.542×10^{-3} rad.

Std. Dev. = 1.713×10^{-3} rad.

Figure 4.16 Concrete column out-of-plumb distribution for Building B.

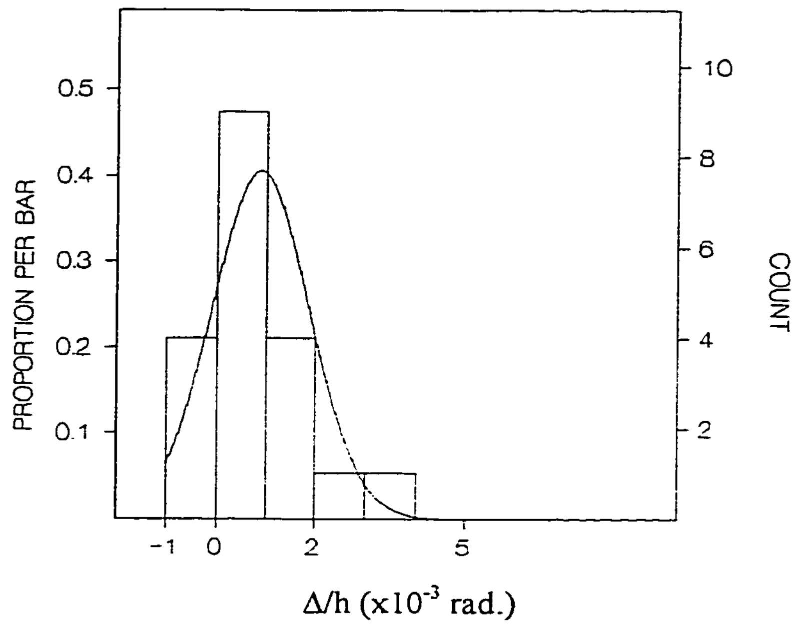


n = 8

Average = 1.531×10^{-3} rad.

Std. Dev. = 0.770×10^{-3} rad.

Figure 4.17 Distribution of absolute values of concrete column out-of-plumbs for Building B.

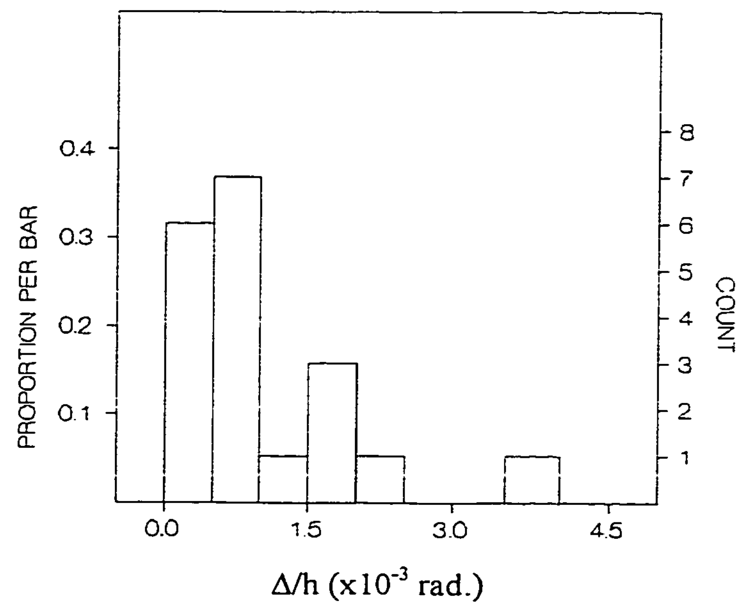


n = 19

Average = 0.882×10^{-3} rad.

Std. Dev. = 0.985×10^{-3} rad.

Figure 4.18 Steel stud wall out-of-plumb distribution for Building B.



n = 19

Average = 1.001×10^{-3} rad.

Std. Dev. = 0.857×10^{-3} rad.

Figure 4.19 Distribution of absolute values of steel stud wall out-of-plumbs for Building B.

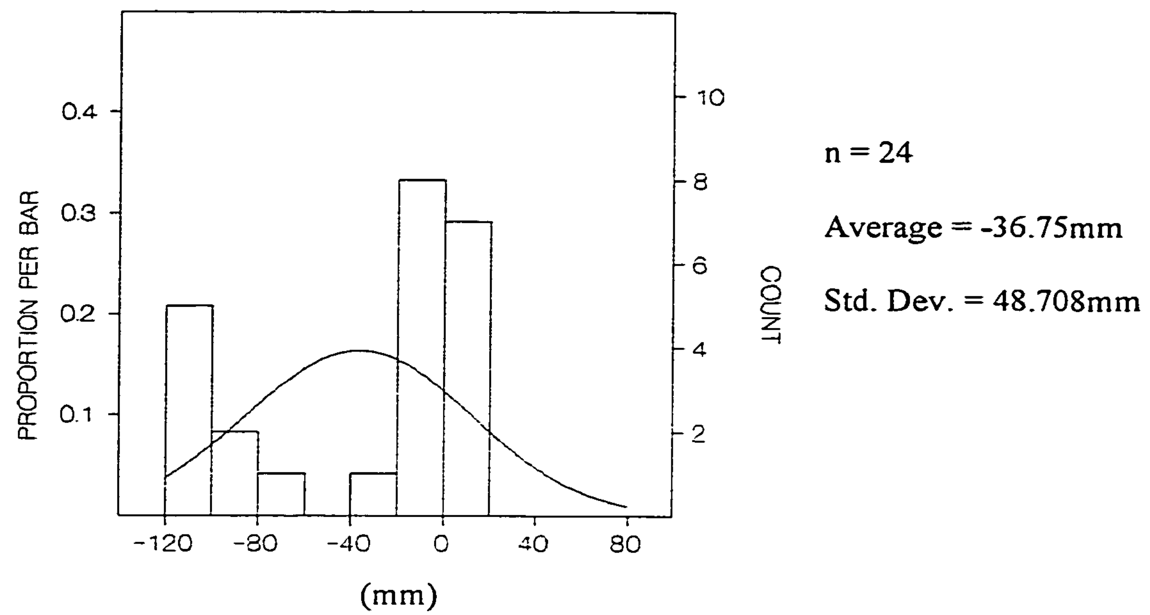


Figure 4.20 Floor-to-ceiling deviation distribution of Building B.

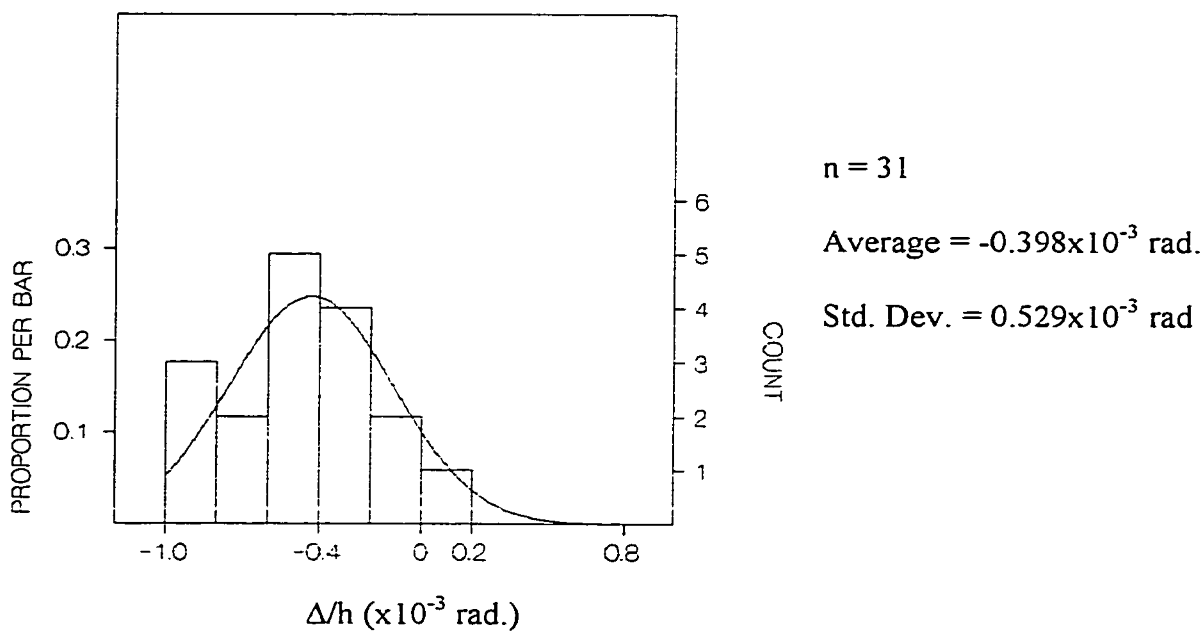


Figure 4.21 Concrete unit masonry wall out-of-plumb distribution for Building C.

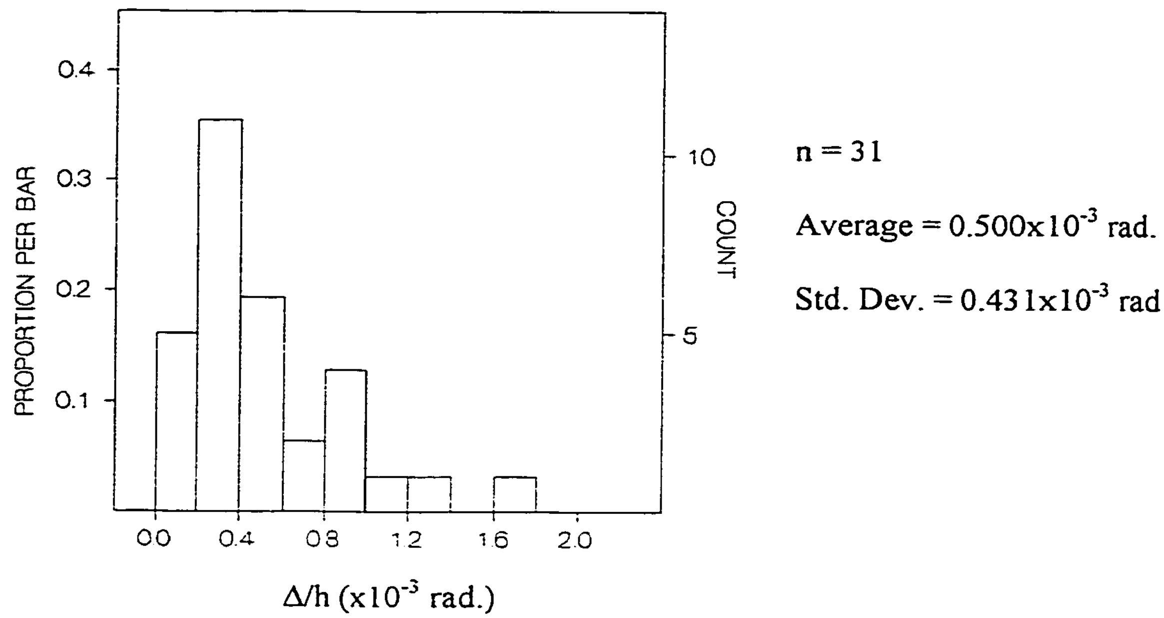


Figure 4.22 Distribution of absolute values of concrete unit masonry wall out-of-plumbs for Building C.

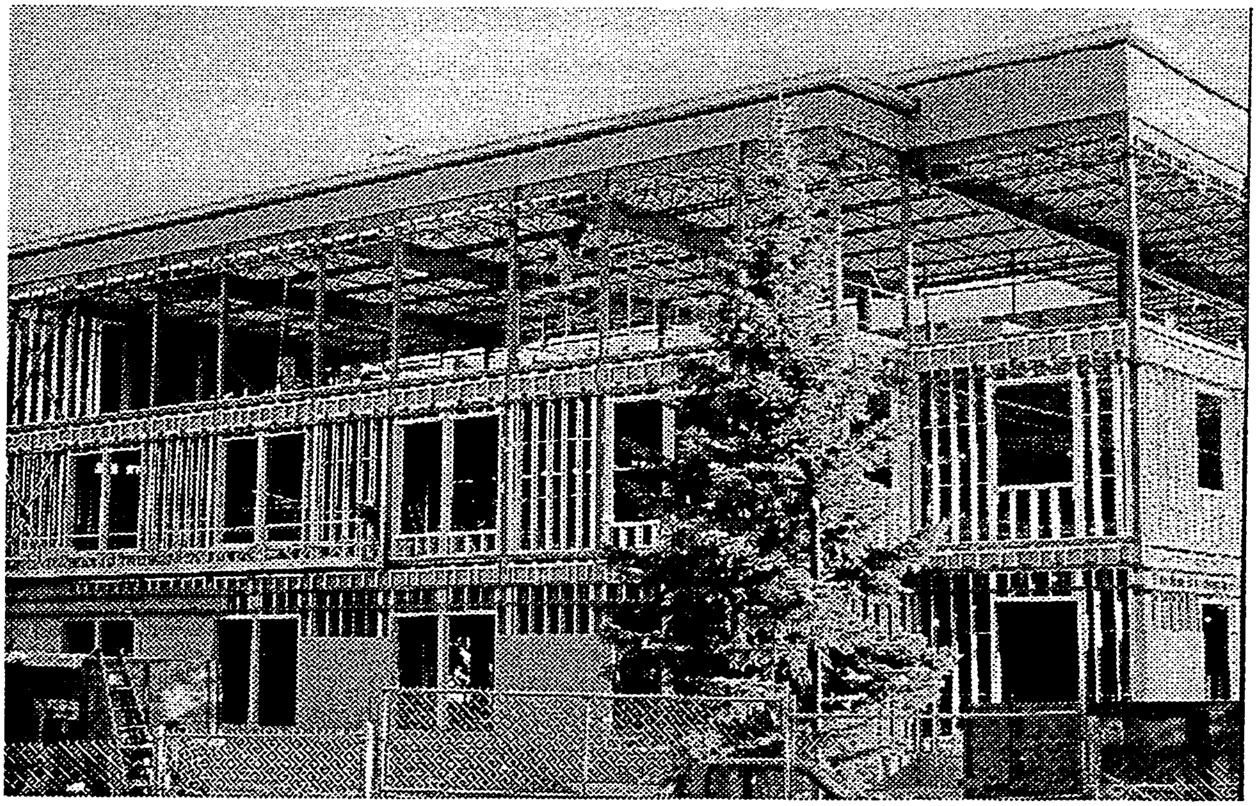


Figure 4.23 Building A under construction.

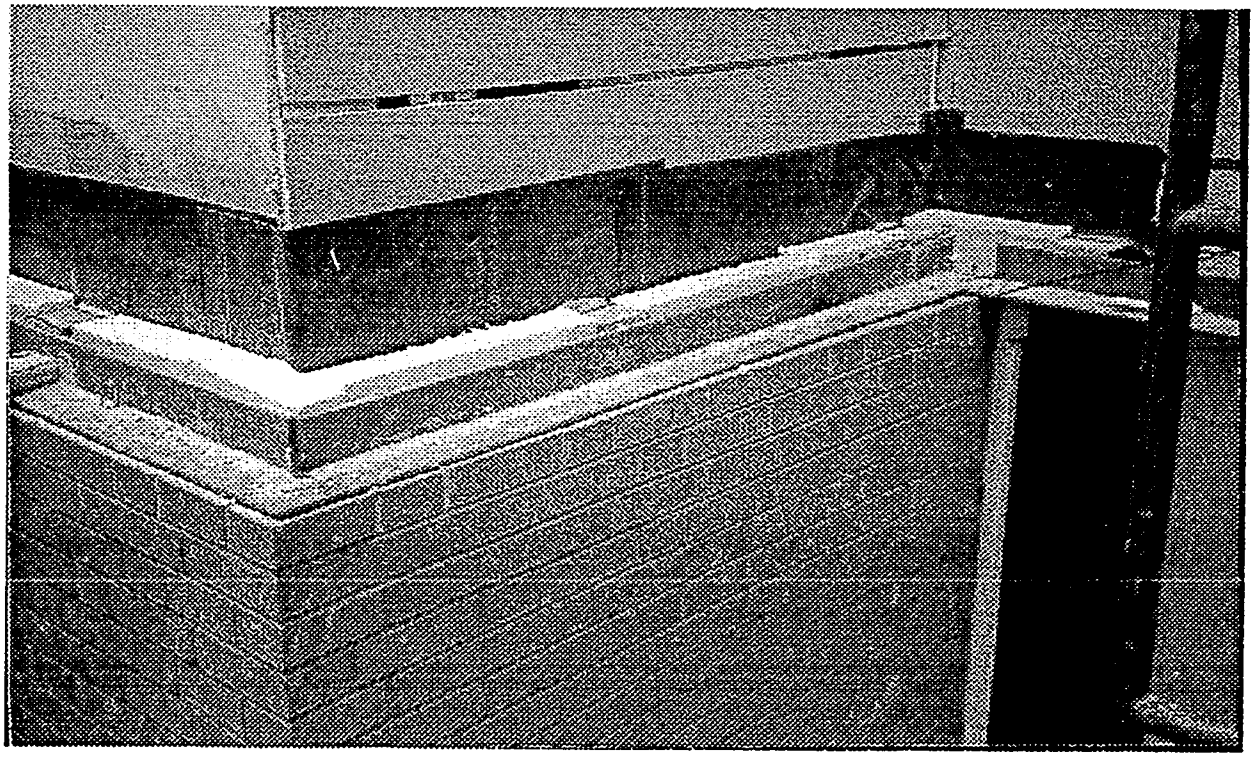


Figure 4.24 Typical wall of Building A during construction.

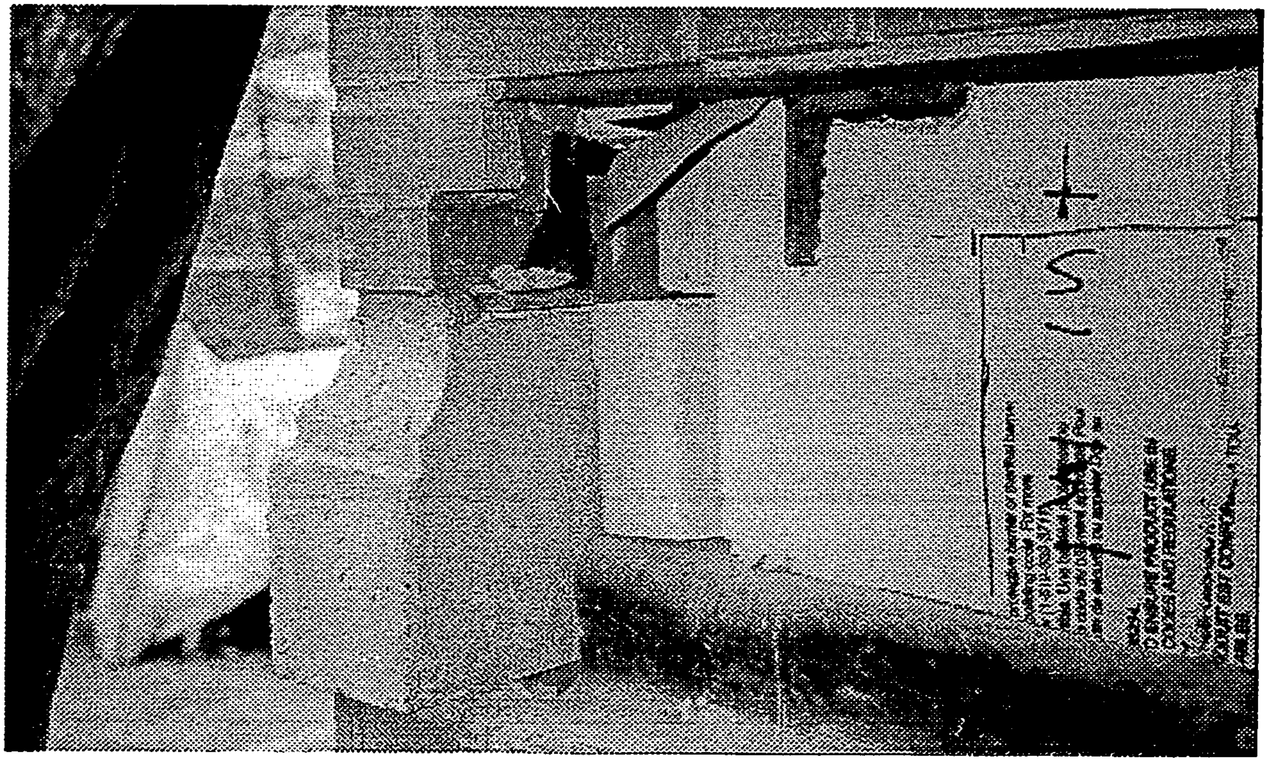


Figure 4.25 Shelf angles installed 135 mm higher on southern elevation of Building A.

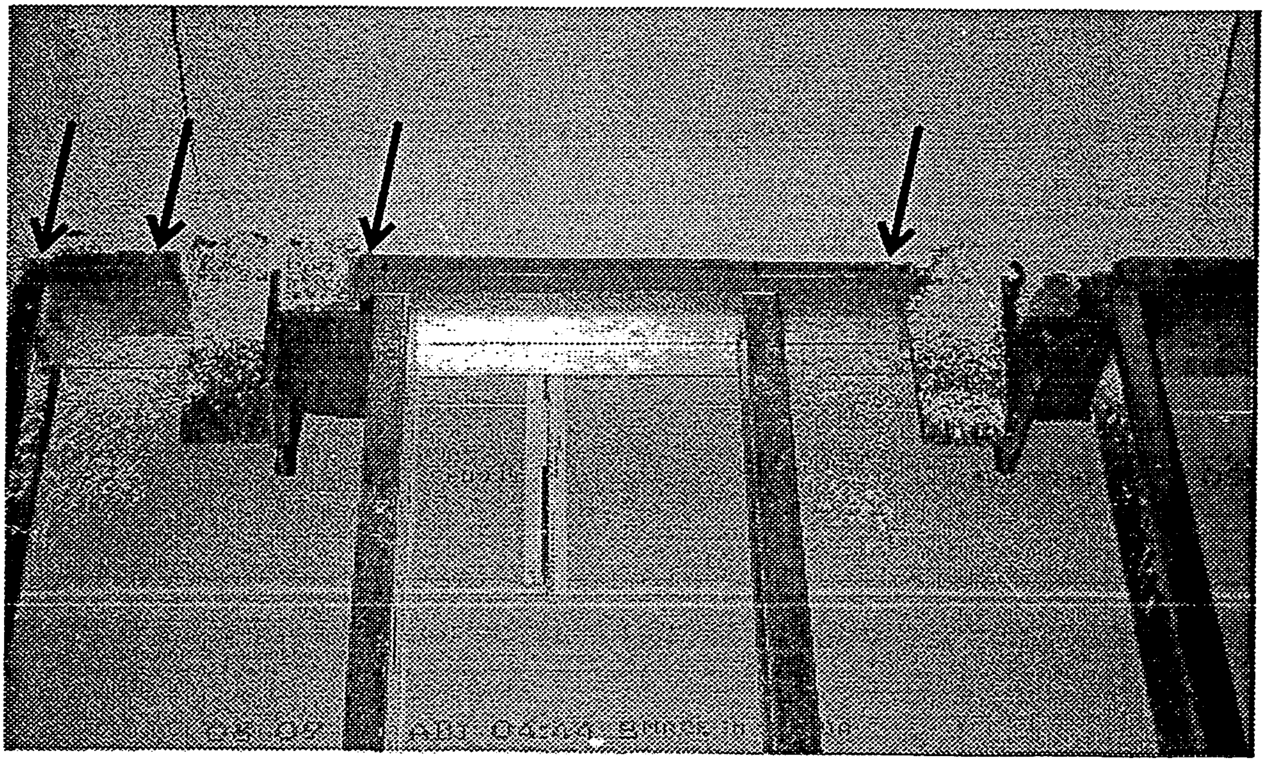


Figure 4.26 Screws installed in expansion tracks of Building A.

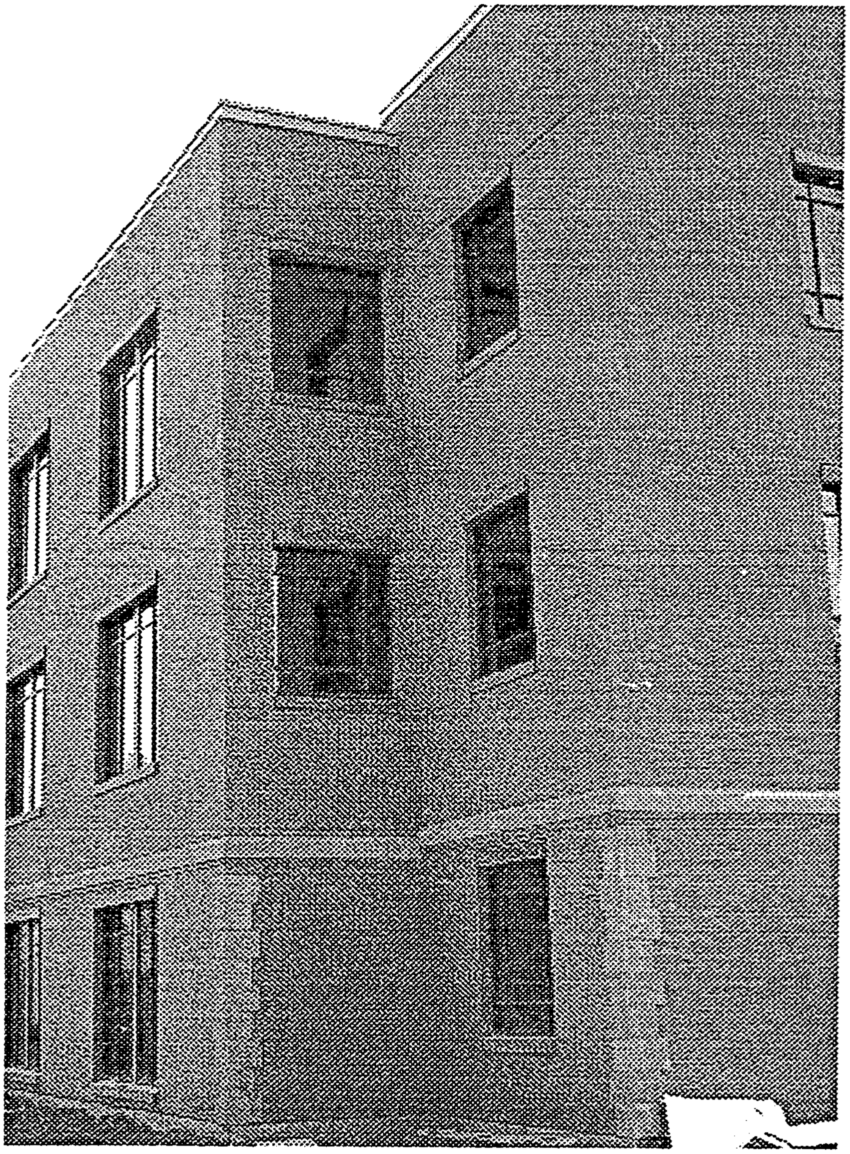


Figure 4.27 Building A nearing completion.

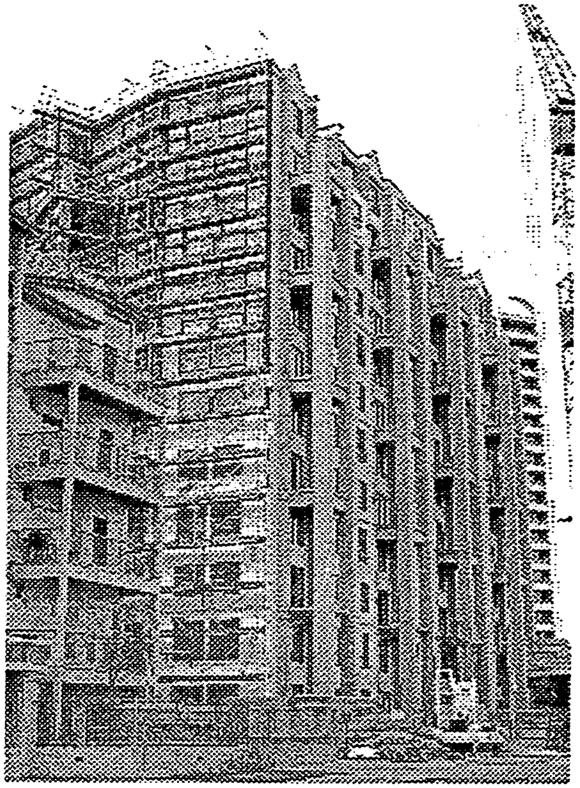


Figure 4.28 Exterior view of Building B.

Figure 4.29 Close-up of Building B.

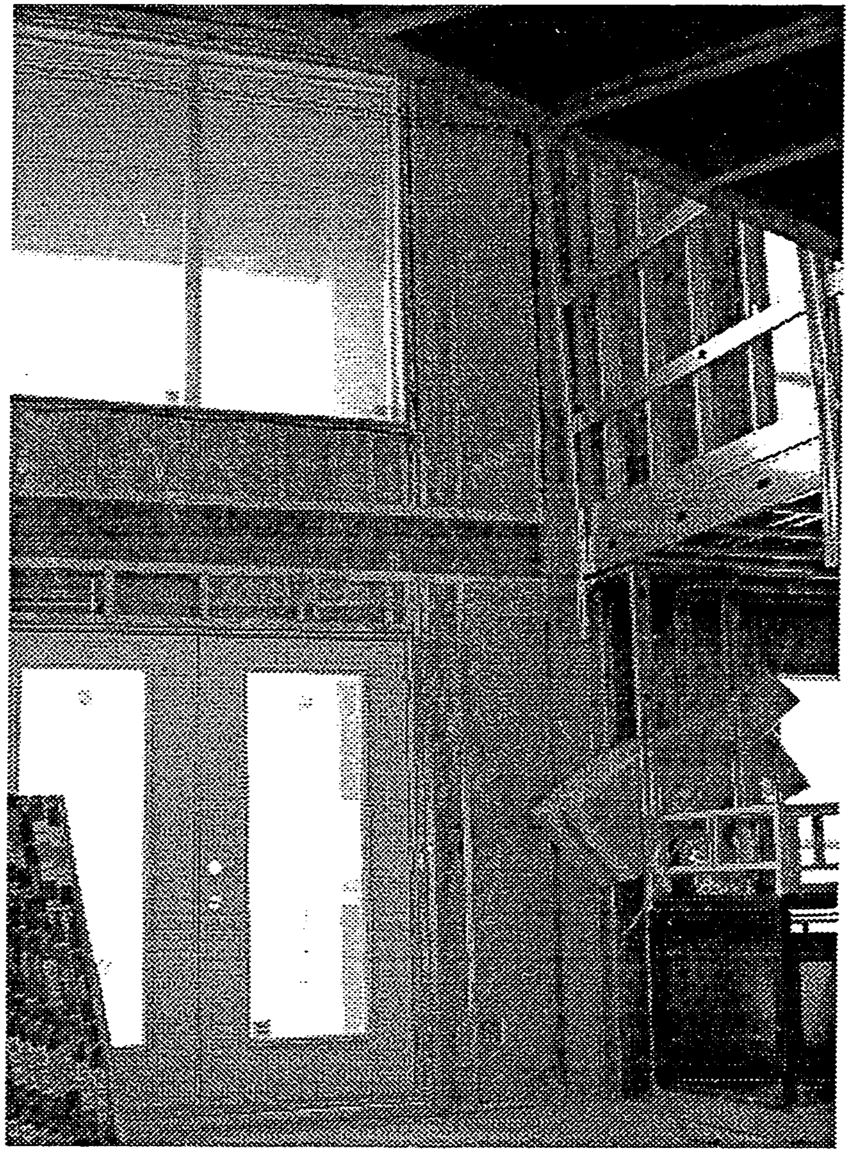


Figure 4.30 Typical interior view of Building B.

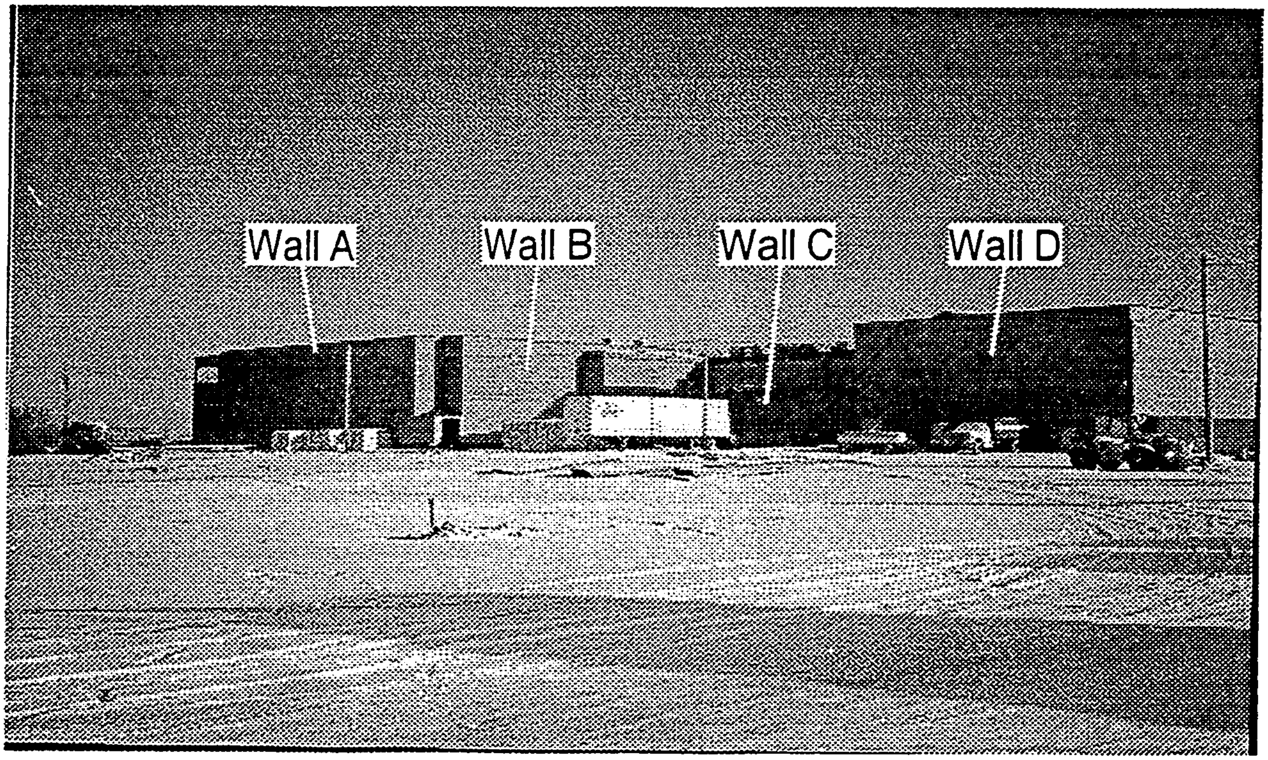


Figure 4.31 Building C elevation.

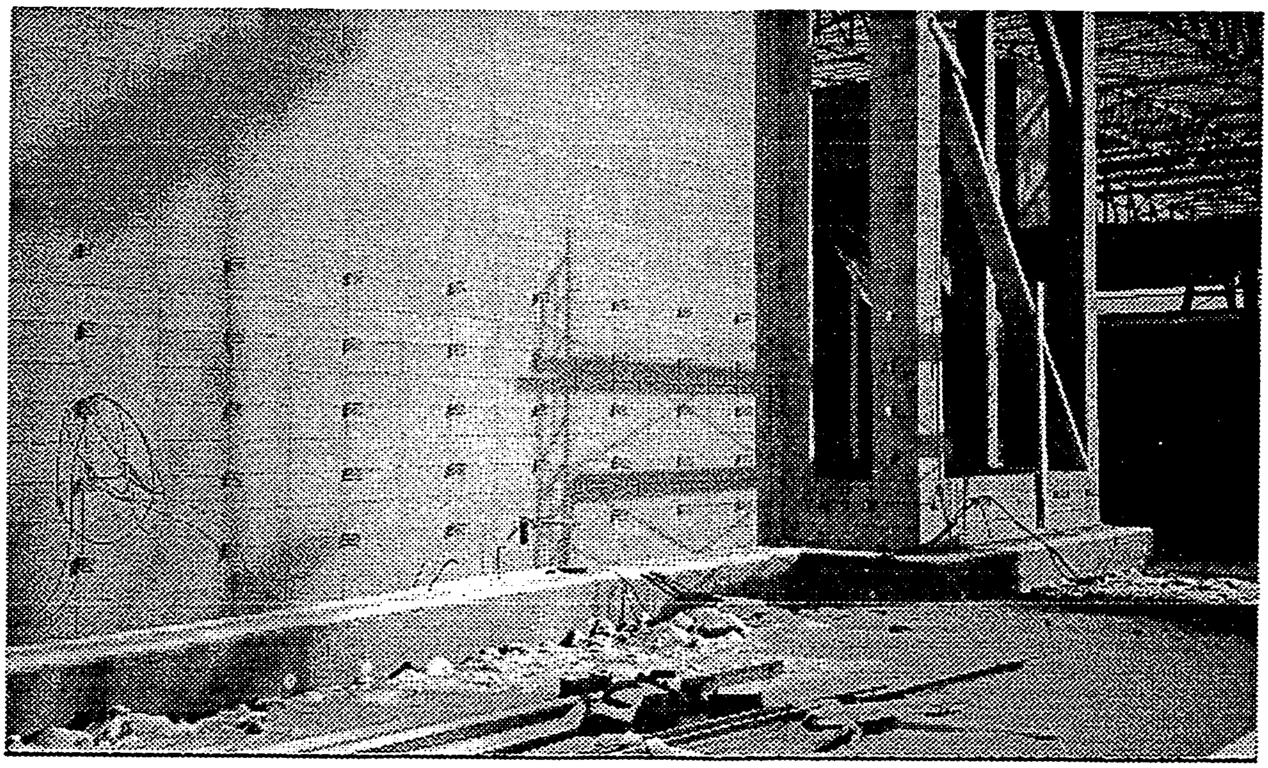


Figure 4.32 Wall close-up of Building C.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 OBSERVATIONS AND DISCUSSION

Based on the findings in Chapters 2 and 4, a need to revise tolerance limits currently found in the Canadian Standards is advisable.

The improper placement of structural elements in a building can have very serious effects on the stresses and deflections of these components. An example of this can be illustrated with masonry veneer resting on a 90x90x10 mm shelf angle which is bolted to the side of a concrete building. The shelf angle assembly was designed with the brick acting as a point load located 76 mm from the back of the angle. If the bricks are placed only 26 mm (1") closer to the edge of the angle, the moment induced on the assembly is increased substantially (35%), and the deflection increases by 142%. If we limit either of these to 10%, this results in an allowable deviation of 7.6 mm for the moment, and only 2.5 mm for deflection. Obviously these are very stringent restrictions, but they illustrate how significant the effects of tolerances have on building components.

In case study Building A, inherent flaws were shown to exist while using the present standards. See Figure 4.1 (Steel and Masonry). Primary structural elements (ie. steel frame) have less stringent vertical construction tolerances than secondary building materials (ie. masonry veneer). Secondary materials are usually harder to place and building problems occur since they rely heavily on the proper placement of the primary material.

The steel code vertical tolerances are not symmetric like other materials. The codes permit the steel to lean more away from the structure than towards it. This can lead to materials hanging off the building and to property line encroachment.

The 1994 Masonry Standard A371-94 was amended to incorporate deviations that may occur when masonry is combined with any other building material. The Concrete Standard A23.1-94 recognizes that difficulties may occur when combining masonry and concrete and makes reference to this new amendment in their Clause 10.5.1.1. The steel standard S16.1-94 however, has not documented that inconsistencies may occur between masonry and steel and this needs to be addressed. Although these clauses have been added to the codes they do nothing more than alert the designer that the codes do not mesh. No values are suggested to give assistance.

When comparing the Canadian and U.S. Codes, a number of differences between tolerance limits become evident. There is no apparent reason why Canadian and U.S. vertical tolerance limits should vary so much. This is an area that requires further study.

5.2 RECOMMENDATIONS

Recognizing that shortcomings exist with respect to tolerances, adopting the following suggestions is recommended:

1. Construction tolerances should be developed from a structural point of view by due consideration of the implications that these tolerances have on the expected behaviour of the assemblies.

2. Establish a standards committee with each of the building material trades being represented. This committee would be dedicated to creating an entirely new Canadian Standards book that would encompass all the building tolerance limits of each individual material, as well as set up new tolerance limits that would allow for the interaction of one or more materials.

3. To show this visually, vertical, level, and plan tolerance plots incorporating such materials as steel, concrete, and masonry would be established to allow for easier understanding on how materials interact.

4. A greater number of adjustable construction components should be incorporated into the design whenever possible. This would allow for greater flexibility during construction resulting in a higher likelihood that the structure be built and function as the designer intended. The design of these adjustable components should accommodate the full range of tolerances found in the structure. One such system entering the industry is an adjustable shelf angle bracket named Fero Angle Support Technology (FAST). It is field installed, and through the incorporation of different sized brackets and shims allows adjustments to maintain both vertical and level construction tolerances. Additional systems, such as FAST need to be developed and used more frequently.

5. Quality control inspection in the construction industry is lacking. This is perhaps the most important issue that needs addressing. Poor workmanship occurs much too often, and can compromise the safety of the structure, as well as reduce the effectiveness of the design. Maximum efficiency and cost effectiveness is lost when repairs are required to correct construction shortcomings.

6. The contract of each construction project should specify the responsible party for on site inspection. The engineer, architect or third party so named is then assumed ultimately responsible for the finished structure being built to its specifications.

5.3 CONCLUSIONS

Tolerance limits are a crucial factor in construction and significantly influence:

1. Structural integrity
2. Building envelopes
3. Constructability; and
4. Aesthetics

The current Canadian Standards tolerance limits for plumbness of elements appear to be adequate under the following conditions, provided strict quality control is maintained.

1. When only one building material is being used; and

2. When steel and masonry are used together at elevations up to but not exceeding 18000 mm.

Looking at the codes as they are written shows that mixing materials of different tolerance requirements present problems. This is because steel, concrete, and masonry requirements vary substantially.

From the author's data alone, it is difficult to draw hard conclusions about the interaction of the different building materials. This was due to the nature of the buildings examined and the measurements that were able to be taken.

Unfortunately, the structure that did have a mix of materials was not tall enough to enter the realm of the codes where the problems would become evident. Further studies on taller buildings that incorporate various wall materials should be conducted to confirm the findings of this study.

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13. CAN/CSA-S16.1-94. 1994. "Limits states design of steel structures." Canadian Standards Association, Rexdale, ON.

14. CAN/CSA-A23.1-94. 1994. "Concrete materials and methods of concrete construction." Canadian Standards Association, Rexdale, ON.

15. CAN/CSA-A371-94. 1994. "Masonry construction for buildings." Canadian Standards Association, Rexdale, ON.

APPENDIX A - Equations

Average (mean) $$\bar{x} = \frac{1}{n}\sum x$$

Standard Deviation $$s = \sqrt{\frac{1}{n-1}\sum (x - \bar{x})^2}$$

Radians $$= \frac{\Delta}{h}$$

where, n = number of measurements

x = actual measurement value

Δ = change

h = height

APPENDIX B - CSA-S16.1-94

The following excerpt from Limit States Design of Steel Structures (CAN/CSA-S16.1-94) sets out the erection tolerances for steel construction:

30.7.2 Plumbness of Columns

Unless otherwise specified, columns shall be considered plumb if their verticality does not exceed the following tolerances:

(A) for exterior columns of multi-storey buildings,
1 to 1000, but not more than 25mm toward or 50mm away from the building line in the first 20 storeys plus 2mm for each additional storey, up to a maximum of 50mm toward or 75mm away from the building line over the full height of the building.

(B) for columns adjacent to elevator shafts, 1 to 1000, but not more than 25mm in the first 20 storeys plus 1mm for each additional storey, up to a maximum of 50mm over the full height of the elevator shaft; and

(C) for all other columns, 1 to 500.

30.7.3 Horizontal Alignment of Members

Unless otherwise specified, spandrel beams shall be considered aligned when the offset of one end relative to the other from the alignment shown on the drawings does not exceed L/1000; however, the offset need not be less then 3mm and shall not exceed 6mm. For all other members, the corresponding offsets are L/500, 3mm and 12mm.

30.7.4 Elevations of Members

Elevations of the ends of members shall be within 10mm of the specified member elevation. Allowances shall be made for initial base elevation, column shortening, differential deflections, temperature effects, and other special conditions, but the maximum deviation from the specified slope shall not exceed L/500. The difference from the specified elevation between member ends that meet at a joint shall not exceed 6mm.

30.7.5 Members with Adjustable Connections

Members specified to have adjustable connections (such as shelf angles, sash angles, and lintels) shall be within tolerances when the following conditions are met:

(A) Each piece is level within L/1000; however, the difference in elevation of the ends need not be less than 3mm and shall not exceed 6mm.

(B) Adjoining ends of members are aligned vertically and horizontally within 2mm.

(C) The location of these members, both vertically and horizontally is within 10mm of the location established by the dimensions on the drawings.

APPENDIX C - CSA- A23.1-94

The tolerances for both cast-in-place and precast concrete are found in Concrete Materials and Methods of Concrete Construction (CAN/CSA-A23.1-94). These are cited as follows:

. . .

10.2 Cross-Sectional Dimensions and Tolerances

10.2.1

Allowable variations for cross-sections of girders, beams and columns and for the thickness of walls and slabs other than slabs on grade are as follows:

0.3m and less ± 8mm;

Greater than 0.3m but less than 1m ± 12mm;

1m and greater ± 20mm.

. . .

10.3 Plumbness

Plumbness of columns and walls shall be within 1:400 measured at any one surface but total variation shall be not more than 40mm for the total height of the structure. For special conditions, such as elevator columns and external columns, the tolerance shall be specified by the Owner, if closer tolerances are required.

Note: *Depending on elevator requirements and wall cladding details, it may be necessary to specify closer tolerances for the columns involved, although it may not be practical to specify less than half of the deviations permitted.*

10.4 Average Slope

10.4.1

The average slope of floors, beams, and other horizontal units shall be within 1:400, but total variation shall be not more than 40mm for the total length of the structure.

. . .

The tolerances below apply to precast and cast-in-place concrete.

10.5 Variations from a Reference System and General Dimensions

10.5.1

The actual dimensions to a vertical and horizontal reference grid system shall not vary from the dimensions on the drawings beyond the tolerances provided in Table 4.

Note: *Wherever possible the nearest building lines should be designed a minimum of 30mm from property lines. For practical reasons it is recommended that this allowance be increased wherever possible.*

10.5.1.1

When unit masonry cladding is to be incorporated into the structure, tolerances shall be coordinated with the requirements for masonry construction tolerances in CSA Standard A371.

Table 4 Dimensional Tolerances

For dimensions equal to or above, m	But below, m	Allowable variation, m
	2.4	±5
2.4	4.8	±8
4.8	9.6	±12
9.6	14.4	±20
14.4	19.2	±30
19.2	57.6	±50
57.6		As specified by the designer

. . .

APPENDIX D - CSA-A371-94

The tolerances for masonry construction are found in Masonry Construction for Buildings (CAN/CSA-A371-94) and are cited as follows:

5.3 Construction Tolerances

5.3.1 General

5.3.1.1

Unless otherwise specified, the tolerances for unit masonry as built, and for actual dimensions to a vertical and horizontal reference grid system, shall conform to the requirements of Clause 5.3.

Notes:

1. If the deviations of other adjoining or supporting structural components vary from those stated in Clause 5.3, approval to incorporate such deviations should be obtained from the designer before commencement of masonry construction.

2. For tolerance definitions, commentary and illustrative design drawings, see Appendix F.

3. Tolerances should not extend the structure beyond legal boundaries.

4. Whenever possible, the nearest building lines should be designed to be located a minimum of 30 mm from property lines. For practical reasons it is recommended that this allowance be increased wherever possible.

5.3.1.2

Tolerances shall not be cumulative, and the most restrictive tolerances shall control.

5.3.2 Standard Tolerances

5.3.2.1 Vertical Alignment

In surface of wall ±20 mm

In alignment of ±13mm

5.3.2.2 Lateral Alignment

Vertical members ±13mm

5.3.2.3 Level Alignment

In bed joints and top of wall exposed ±13mm

Not exposed ±25mm

Top of wall used for a bearing surface ±13mm

Top of wall other than a bearing surface ±20mm

5.3.2.4 Cross Sectional Dimensions

Multiwythed walls +13mm

-6mm

Other members +13mm

-6mm

Head and bed joint thickness ±13mm

5.3.2.5 Relative Alignment

Masonry surfaces may slope with respect to the specified plane at a rate not to exceed the following amounts in 3 m.

Wall and columns ±6mm

Bed joints, head joints ±6mm

Top of wall ±6mm

1. The tolerance in mortar joint thickness is intended to compensate for tolerances in dimensions between individual masonry limits and construction tolerances.

2. Where desired for architectural purposes, the designer should indicate which face of the units should be in true alignment.

3. Plus(+) tolerance increases the amount or dimension to which it applies, or raises a level alignment.

Minus(-) tolerance decreases the amount or dimension to which it applies, or lowers a level alignment.