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Thick Reinforced Concrete Walls Subjected To Non-Uniform Restrained Shrinkage

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Thick reinforced concrete walls subjected to non-uniform restrained shrinkage

by

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Thick reinforced concrete walls subjected to non-uniform restrained shrinkage

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Abstract

Several researchers have studied the behavior of reinforced concrete walls under restraint shrinkage, which demonstrate the variation of the degree of restraint with different Length/Height ratios. In general, concrete standards and codes of practice recommend a minimum amount of reinforcement for shrinkage effects.

This research investigates the response of thick reinforced concrete walls subjected to restraint shrinkage. The parameters studied are the thickness of reinforced concrete walls, and non-uniform distribution of shrinkage along the Length/Height and through the thickness of the wall.

This study uses the non-linear finite element method to simulate the cracking behavior of the concrete and to predict tensile stresses in the reinforcement in the vicinity of Cracks. Moreover, this study investigates the influence of reinforcement ratio and compares the results with well-known concrete standards and codes of practice. It is concluded that the non-uniform shrinkage through the thickness of the wall may have significant impact on the cracking behavior of thick concrete walls. In addition, as expected, higher reinforcement ratio results in lower tensile stresses in the reinforcement. The thesis also provides guidelines for minimum reinforcement ratio.

Acknowledgment

I would like to take this opportunity to thank my supervisor, Dr. Kianoush, for his generosity in financing me throughout my education at Ryerson University. I am also grateful for his patience and knowledge while providing me the room to work independently at my own pace.

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Lastly, I am indebted to my family for their unconditional love. This thesis and all other accomplishments I have ever achieved is a result of their initiative and constant motivation. It would, therefore, be an honor to dedicate this thesis to them.

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1 Introduction

Concrete is a construction material composed of coarse granular material, cement and a desired proportion of water. The cement used within the concrete mixture aids in filling the gaps between the coarse granular materials (aggregates) particles, thus forming a “glue” to bind the materials together. The word concrete comes from the Latin word "concretus", which means "hardened”, or "hard" (Mindess, Young, & Drawin, 2003).

There are many man-made materials; among which concrete is the world’s most widely used building material. Concrete structures provide uniform and comfortable indoor temperatures despite all types of climatic conditions. Therefore, it has been used in many civilizations (ACI Committee 122, 2002).

Concrete is the predominate material used in construction. It competes directly with all other major construction materials (timber, steel, asphalt, stone, etc.) because of its versatility in applications. The major advantages of concrete are listed as follows:

1- Ability to be cast, concrete can be cast to any desired shape and configuration such as soaring arches and columns, complex hyperbolic shells, or into massive, monolithic sections used in dams, piers, and abutments.

2- Economical, the main components for making concrete are relatively inexpensive, for instance Cement costs only about 62-88 US $/ton (2001) and aggregates less than 17.62 US $/ton.

3- Durable, good quality concrete is a very durable material and should remain maintenance free for many years when it has been properly designed for the service conditions and properly placed.

4- Fire resistance, concrete can be severely damaged by exposure to high temperatures, but it can maintain its structural integrity for a considerable period.

5- Energy efficient, in the first place, concrete requires less energy to produce than other construction materials. Second, energy requirements can be decreased for concrete by incorporating supplementary cementing materials, such as fly ash, silica fume, and blast furnace slag. Third, concrete buildings can be more energy efficient to operate because of the thermal properties of concrete.

6- Aesthetic properties, it has considerable aesthetic possibilities that can be expressed through the use of color, texture, shape, and so on (Mindess, Young, & Drawin, 2003).

Concrete does have weaknesses that may limit its use in certain applications. The major disadvantages of concrete are listed as follows:

1- Low tensile strength, concrete should generally not be loaded in tension (except for low bending stresses that maybe permitted in unreinforced slabs).
2- Low ductility, concrete lacks impact strength and toughness compared to metal.
3- Volume instability, concrete undergoes considerable irreversible shrinkage due to moisture loss at ambient temperatures and also creeps significantly under an applied load even under conditions of normal service.
4- Low strength to weight ratio, even in compression concrete has a relatively low strength to weight ratio, and a high load capacity requires comparatively large masses of concrete (Mindess, Young, & Drawin, 2003).

Concrete is a quasi-brittle material with a low capacity for deformation under tensile stress. The old-age axiom in concrete construction is that concrete cracks. While cracks may develop in concrete for a variety of causes, the underlying principle is the relatively low tensile strength of concrete. Visible cracking occurs when the tensile stresses exceed the tensile strength of the material. Visible cracking is frequently a concern since these cracks provide easy access for the infiltration of aggressive solutions into the concrete and reach the reinforcing steel or other components of the structure leading to deterioration.

Figure 1-1 provides a listing of some of the common types of cracks and distinguishes these cracks based upon when they appear in concrete, before hardening or after hardening (Transportation Research Circulare C107, 2006).

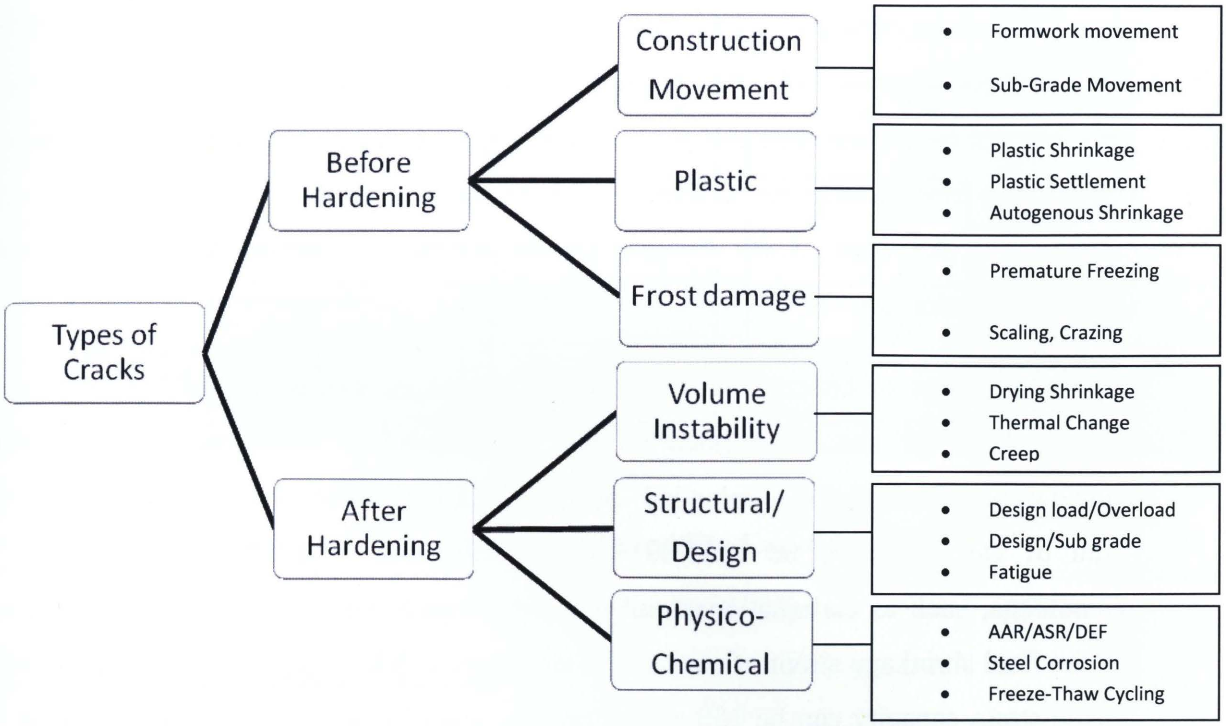


Figure 1-1Common cause for cracking in concrete structure

(Mindess, Young, Drawin, 2003)

While cracking is commonly observed in concrete structures, it is important to understand that all cracks may have different causes and different effects on long-term performance due to the confounding effects of design, traffic loads, and climatic conditions relevant to the structure. Cracking need not be alarming and can be addressed appropriately so that the life of the structure is not compromised.

1.1 Shrinkage of concrete

Shrinkage cracks occur when concrete members undergo restrained volumetric changes (shrinkage) as a result of drying, autogenous shrinkage or thermal effects. Restraint is provided either externally (i.e. supports, walls, and other boundary conditions) or internally (differential drying shrinkage, reinforcement). Once the tensile strength of the concrete is exceeded, a crack will develop. The number and width of shrinkage cracks that develop are influenced by the amount of shrinkage that occurs, the amount of restraint present and the amount and spacing of reinforcement provided.

Plastic-shrinkage cracks are immediately apparent, visible within 0 to 2 days of placement, while drying-shrinkage cracks develop over time. Autogenous shrinkage is not a new phenomenon but it has been assumed that it will only occur in concrete with very low w/c ratios, typically below about 0.4 (Pigeon et al., 2004). Historically no strain contribution from autogenous shrinkage has been included in the assessment of early-age cracking for the range of the strength classes commonly used in structural concrete (Bamfort, London 2007).

Drying shrinkage of concrete is the reduction in volume caused by the loss of water. Drying shrinkage can be defined as the time-dependent linear strain at constant temperature measured on an unloaded specimen that is allowed to dry. From a structural point of view, there is no need to separate drying shrinkage from other kinds of phenomena, such as carbonation shrinkage and Autogenous shrinkage. A typical value for the final shrinkage strain of concrete in structures is 600×10^{-6}. Because the concrete tensile-strain capacity can be 150×10^{-6} or less, cracking will result if the shrinkage is restrained in a concrete member (Mindess, Young, & Darwin, 2003). There is a high degree of uncertainty in predicting shrinkage of concrete structures, however, because this property varies considerably with many parameters, including concrete composition, source of aggregate, ambient relative humidity, specimen geometry, and more specifically, the ratio of the exposed surface to the volume of the structural element. Furthermore, the slow development of shrinkage over time makes it difficult to obtain an accurate prediction for a given concrete from short-term laboratory measurements. As a result, a coefficient variation of 20% or more can be expected in predicting long-term shrinkage (ACI Committee 224, 2001).

In practice, drying shrinkage and Viscoelastic phenomena usually take place simultaneously. Table 1-1 shows combination of restraining, and humidity conditions (Mehta & Monteiro, 2006).

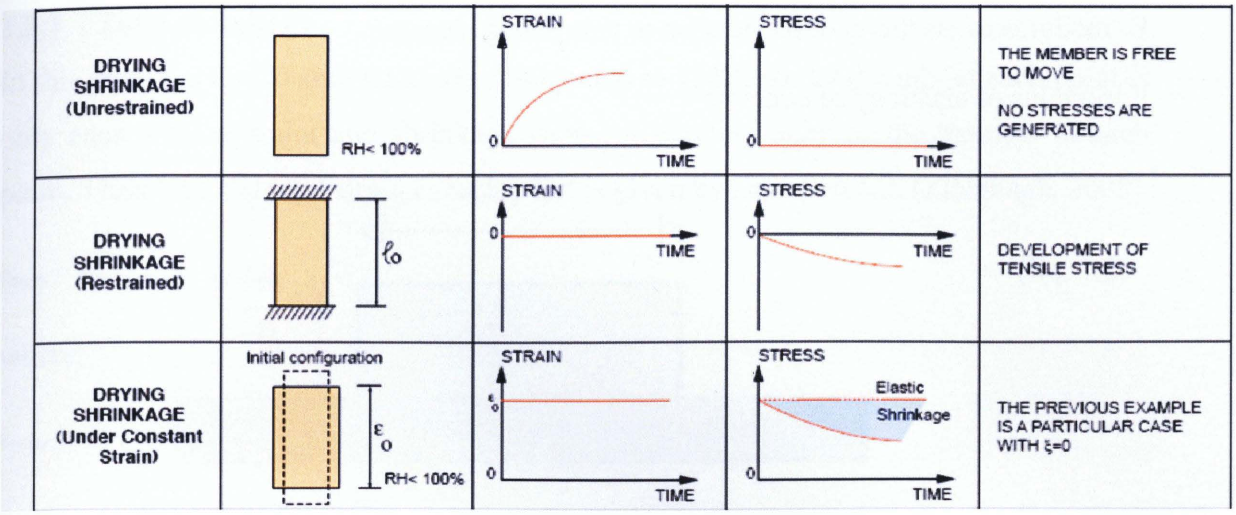


Table 1-1 Restraining and Humidity Conditions

(Mindess, Young, & Drawin, 2003)

1.2 Restraint shrinkage cracking

A concrete element, if free to move, would have no stress development associated with thermal deformation on cooling. However in practice, the concrete mass will be restrained either externally by the rock foundation or internally by differential deformations within different areas of concrete due to the presence of temperature gradients. For instance, assuming a rigid foundation, there will be full restraint at the concrete–rock interface (K_r=1.0). K_r is equal to zero if concrete elements free to move. However, as the distance from the interface increases, the restraint will decrease, as shown in Fig. 1-2 the same reasoning can be applied to determine the restraint between different concrete lifts. If the foundation is not rigid, the degree of restraint will decrease. When dealing with a non rigid foundation, ACI-207.2R recommends the following multipliers for K_r :(Mehta & Monteiro, 2006)

$$\text{Multiplier} = \frac{1}{1 + \frac{A_g + E}{A_f + E_f}} \qquad \text{(Eq.1.1)}$$

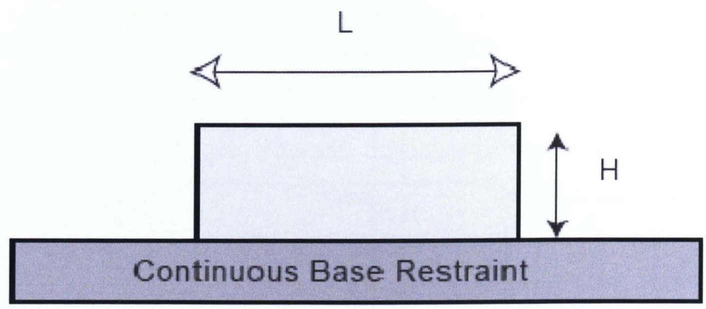
where,

A_g gross area of concrete cross section

A_f area of foundation or other restraining element

E_f modulus of elasticity of foundation or restraining element

E modulus of elasticity of concrete



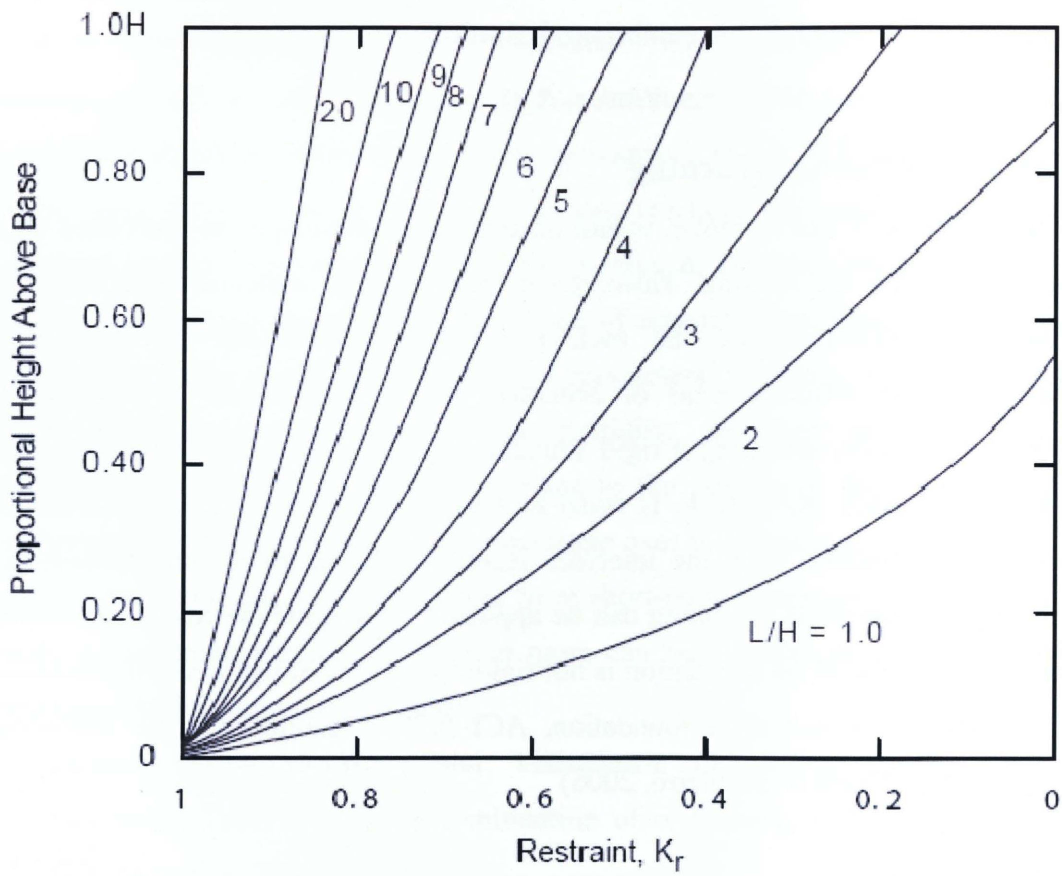


Figure 1-2 Degree of tensile restraint at center section

(Mindess, Young, & Drawin, 2003)

1.2.1 Total shrinkage

In this analysis, due to shrinkage strain subjected to walls, the total strain at each point is only caused by restraint and shrinkage from surrounding parts of the member at each point. Therefore, the total strain at each point is given by Equation 1.2. (Ziaolhagh, 2008)

$$\varepsilon_{total} = \varepsilon_{shrinkage} + \varepsilon_{restraint} \qquad \text{(Eq. 1.2)}$$

where,

ε_{total} is the total strain

$\varepsilon_{shrinkage}$ is the shrinkage strain

$\varepsilon_{restraint}$ is the restraint strain

According to (Gilbert, 1992) the shrinkage strain is $600X10^{-6}$ mm/mm for every point in the walls and deriving the total strain at each point on the center point of the walls, the restraint strain can be determined from Eq. 1.2.

1.2.2 Degree of restraint

The degree of restraint is the ratio of actual stress in concrete resulting from volume change to the stress that would result if concrete were completely restrained. Alternatively, that degree of restraint is the ratio of strain of concrete caused by restraint to the strain that would occur if concrete were not restrained. The degree of restraint can be expressed as (Ziaolhagh, 2008)

$$K_R = -\frac{\varepsilon_{restraint}}{\varepsilon_{shrinkage}} \qquad \text{(Eq. 1.3)}$$

where,

K_R is the degree of restraint

$\varepsilon_{restraint}$ is the restraint strain of the concrete

$\varepsilon_{shrinkage}$ is the shrinkage strain of the concrete

In this analysis, the restraint strain at each point is determined from Eq. 3.1 knowing the shrinkage strain is $600X10^{-6mm}/_{mm}$ at every point in the walls. Then, the degree of restraint at each point in the wall is determined from E.q. 1.3.

1.3 Objective of the thesis

This thesis studies the behavior of restraint thick reinforced concrete walls subjected to uniform and non-uniform shrinkage using a finite element program called ABAQUS (ABAQUS 6.7-1, 2007). In this study both linear and non-linear finite element analyses are carried out to simulate the cracking behavior of the structure and predict tensile stresses in concrete and reinforcement in the vicinity of cracks.

The main objective of this thesis is to find the effective shrinkage and temperature reinforcement in thick reinforced structures subjected to non-uniform shrinkage. The results are compared to the behavior of the structures under non-uniform shrinkage where this situation is of main concern in structures such as dams and liquid containments.

CHAPTER 2

2 Characteristics of the wall

2.1 Introduction

In this study, the computer software ABAQUS version 6.7(ABAQUS 6.7-1, 2007) is used for modeling and analysis. ABAQUS is a commercial software package for finite element analysis developed by SIMULIA, a brand of Dassault Systemes S.A.

The ABAQUS product suite consists of three core products: ABAQUS/Standard, ABAQUS/Explicit and ABAQUS/CAE. ABAQUS/CAE provides an integrated modeling (pre-processing) and visualization (post-processing) environment for the analysis products.

This study investigates response of thick reinforced concrete walls due to uniform and non-uniform shrinkage and, ABAQUS/CAE is used for linear and non-linear modeling and analysis.

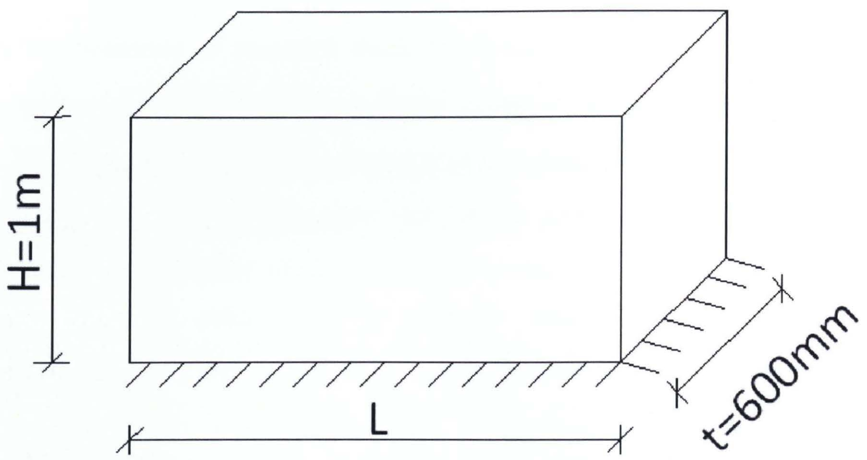
In ABAQUS 6.7, shrinkage is not one of the predefine load cases. Therefore, one of the challenges in the modeling process was to simulate "shrinkage" for the program.

Shrinkage simulation was done with the help of temperature, in a way that in initial step a maximum temperature is applied to the walls and was dropped to zero in step 1.

According to (Gilbert, 1992), in most concrete structures the final shrinkage strain is 600X10-6 mm/mm. A temperature change of 60°C is applied to the walls to simulate this amount of shrinkage strain. It is assumed that the coefficient of thermal expansion of concrete is 10X10-6 per °C.

2.2 Geometry of the walls

The length / height ratios of reinforced concrete walls were as follows: 1, 2, 5, 10 and 20. For all these cases, the thickness and height of the walls were identical, 600mm and 1 m, respectively. Furthermore, in all these cases the structure was fully fixed at the base and was free to move on top of the wall. Figure 2.1 shows oblique elevation of the wall.



L/H=1.0, 2.0, 5.0, 10, 20

Figure 2-1Oblique elevation of typical wall

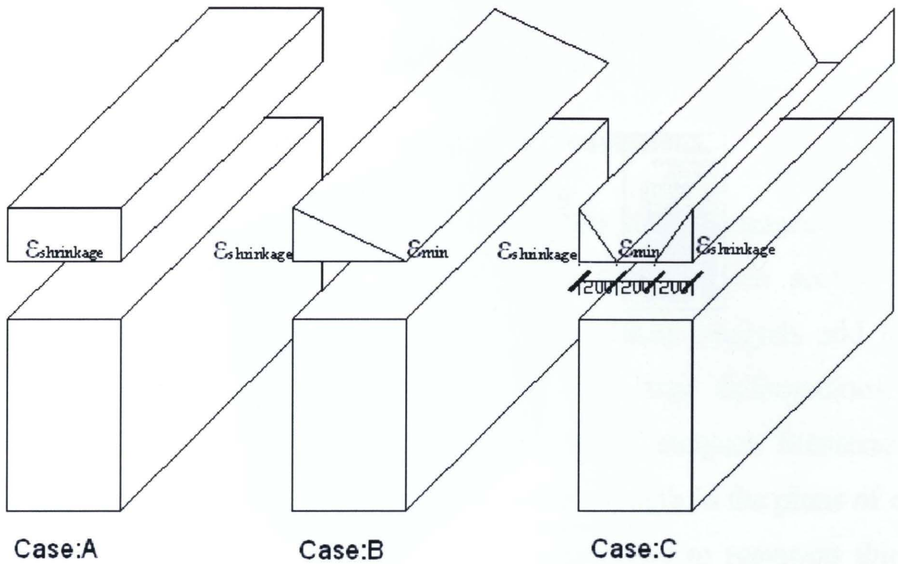
In this study, three shrinkage cases were applied for each length / height ratios:

1- Case A, where structure is subjected to uniform shrinkage ($\varepsilon_{shrinkage}$)
   This case is applicable for thin reinforced Concrete structures like reinforced concrete dome, reinforced concrete barrel vault and so on.

2- Case B, where structure is subjected to non-uniform shrinkage in a way that it starts from $\varepsilon_{min}= 0$ from right side of the wall and increases to $\varepsilon_{shrinkage}$ as it reaches the other face of the wall.
   This type of non uniformity happens where structure is in contact with water or in air at 100% relative humidity from one side and much less humidity from the other side. An example for this case is water tank reinforced concrete structures.

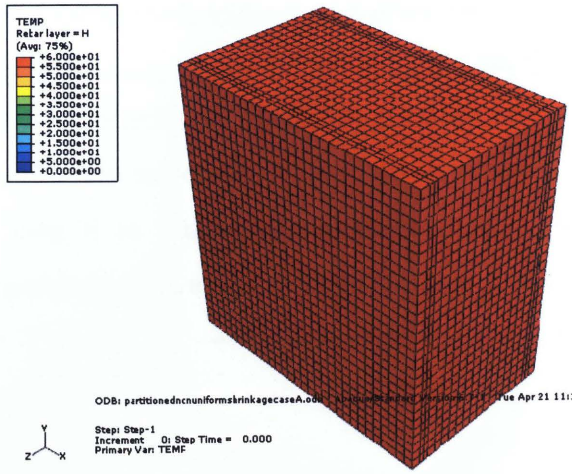
3- Case C, where structure is subjected to non-uniform shrinkage but in this case the wall is divided into three partitions through its thickness. Within the inner partition the shrinkage is constantly zero, but for two other partitions the shrinkage varies linearly from $\varepsilon_{shrinkage}$ and decreases to $\varepsilon_{min}= 0$ as it reaches the adjacent portion of the inner partition.

Another type of non uniform shrinkage distribution is for very thick structures such as dam and nuclear power plant where outer side of the structure is subjected to maximum shrinkage and starts decreasing as it goes to the middle of the structure. Figures 2-2, and 2-3 (a), (b), (c) present shrinkage variations in case A, B, and C.

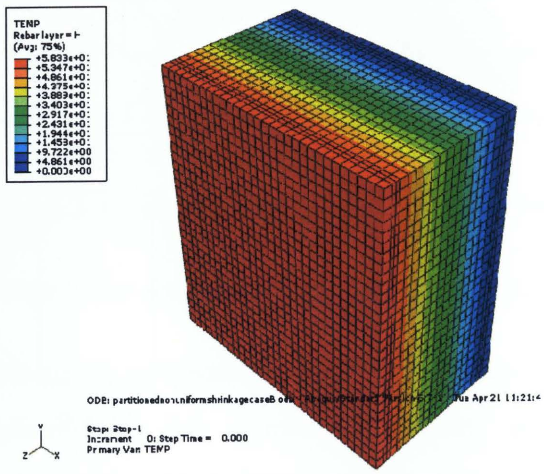


Uniform Triangular Double Triangular

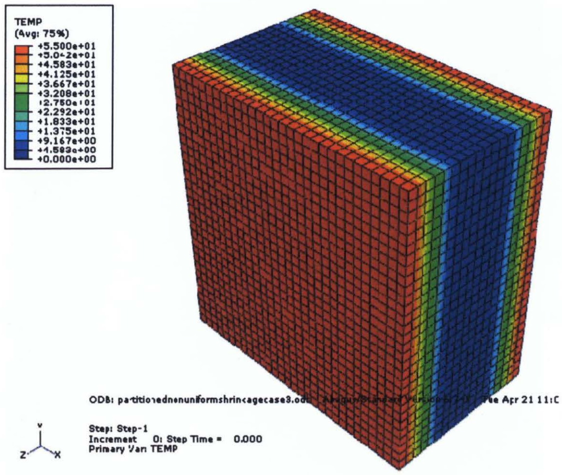
Figure 2-2 Shrinkage variation



(a) Case A



(b) Case B



(c) Case C

Figure 2-3 Temperature variations

The concrete wall was modeled using solid elements with Homogeneous section and reinforcement was modeled using shell elements with Surface section. The solid (continuum) elements in ABAQUS can be used for linear analysis and for complex nonlinear analysis involving contact, plasticity, and large deformations. They are available for stress. Heat transfer, coupled thermal-stress analyses. Membrane elements are used to represent thin surfaces in space that offer strength in the plane of element but have no bending stiffness. In addition, they are often used to represent thin stiffening components in solid structures such as reinforcing layer in a continuum. Two reinforcement layers were embedded 50 mm away from each face of the wall. Figure 2-4 shows a partitioned wall and two layers of reinforcement.

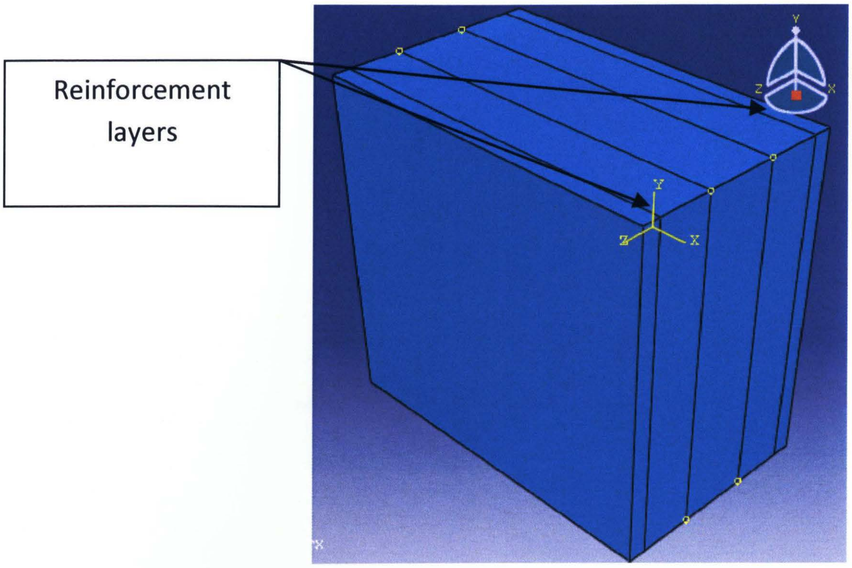


Figure 2-4 Typical Reinforced Concrete wall with two layers of reinforcement

In general, concrete standards and codes of practice recommend shrinkage and temperature reinforcement ratio of 0.3% for walls and slabs. The highest value of the shrinkage and temperature reinforcement ratio recommended by the Standard Requirements for Environmental Engineering Concrete Structures, (ACI 350-06, 2006), is 0.5% for steel grade 60 where the length between movement joints is greater than 12 m. In this study, the reinforcement ratio of the wall is 0.33% in both the horizontal and vertical directions.

2.3 Material properties

In this study, material properties are assumed with respect of linear and non-linear behavior of concrete and steel.

2.3.1 Linear analysis of the wall

In this part, material properties of steel and concrete for linear elastic behavior were assumed as follows:

E_S (Modulus of elasticity of steel) = 210,000 MPa

ν_S (Poison's ratio of steel) = 0.3

α_S (Thermal expansion coefficient of steel) = 0

E_C (Modulus of elasticity of concrete) = 25,000 MPa

ν_C (Poison's ratio of concrete) = 0.15

α_C (Thermal expansion coefficient of concrete) = $10X10^{-6}$

The thermal expansion coefficient of steel was assumed to be zero due to the fact that in reinforced concrete structures, concrete is expected to shrink and not the reinforcement.

2.3.2 Non –linear analysis of the wall

In this part, material properties of steel and concrete for non-linear material behavior were assumed as follows:

E_S (Modulus of elasticity of steel) = 210,000 MPa

ν_S (Poison's ratio of steel) = 0.3

α_S (Thermal expansion coefficient of steel) = 0 1/C°

ρ_S (Density of steel) = $7.8X10^{-6}$ kg/mm^3

f_y (Yield stress of steel) = 400 MPa

E_P (Plastic strain of steel) = 0

E_C (Modulus of elasticity of concrete) = 25,000 MPa

ν_C (Poison's ratio of concrete) = 0.15

α_C (Thermal expansion coefficient of concrete) = $10X10^{-6}$ 1/C°

f_t (Cracking failure stress of concrete) = 2.7 MPa

ρ_C (Density of concrete) = 2.4 $X10^{-6}$ kg/mm^3

The thermal expansion coefficient of steel was assumed to be zero due to the fact that in reinforced concrete structures, concrete is expected to shrink and not the reinforcement.

2.4 The methodology used in ABAQUS

The brittle cracking model in ABAQUS provides a general capability for modeling concrete in all types of structures including beams, trusses, shells, and solids. It can be used for plain concrete, even though it is intended primarily for the analysis of reinforced concrete structures, the brittle cracking model is designed for applications in which the behavior of structure is dominated by tensile cracking and assumes that the compressive behavior of concrete is always linear elastic. In addition, it allows removal of elements based on brittle failure criterion.

The brittle cracking model assumes fixed, orthogonal cracks, with the maximum number of cracks at a material point limited by the number of direct stress components present at that material point of the finite element model. In three dimensional, plane strain, and axisymmetric problems a maximum of three cracks, in plane-stress and in shell problems a maximum of two cracks, and in beam or truss problems a maximum of one crack is considered.

A simple Rankine criterion is used to detect crack initiation. This criterion states that a crack forms when the maximum principle tensile stress exceeds the tensile strength of the concrete.

As soon as the Rankine criterion for crack formation has been met, the model assumes that a first crack has formed. The crack surface is taken to be normal to the direction of the maximum tensile principle stress. Subsequent cracks may form with crack surface normal in the direction of the maximum principle tensile stress.

When one, two, or all three local direct cracking strain components at a material point reach the value defined as the failure strain, the material point fails and all the stress components are set to zero. If all of the material points in an element fail, the element is removed from the mesh.

Cracks are recoverable in the sense that, once a crack has occurred at a point, it remains throughout the rest of the calculation. However, crack closing and reopening may take place along the direction of the crack surface normal. The model neglects any permanent

Strain associated with cracking. It assumes that the cracks can close completely when the stress across them becomes compressive.

Reinforcement is typically modeled using elastic-plastic material behavior models and is superimposed on elements used to model the plain concrete. With this modeling approach, the concrete cracking behavior is considered independently of the reinforcement. Effects associated with the reinforcement-concrete interface, such as bond slip and dowel action, are modeled approximately by introducing some tension stiffening into the concrete cracking model simulate load transfer across cracks through the reinforcement. The tension stiffening is specified by means of a post failure stress-strain relationship which defines the post failure stress as a function of strain across the crack.

The tension stiffening effect depends on factors such as the density of reinforcement, the quality of the bond between the reinforcement and the concrete, the relative size of the concrete aggregate compared to the rebar diameter, and the mesh. A reasonable starting point for relatively heavily reinforced concrete modeled with a fairly detailed mesh is to assume that the strain softening after failure reduces the stress linearly to zero at a total strain about ten times the strain failure. Since the strain at failure in standard concretes is typically 10^{-4} mm/mm this suggests that tension stiffening that reduces the stress to zero at a total strain of about 10^{-3} mm/mm is reasonable.

In static applications, too little tension stiffening will cause the local cracking failure in the concrete to introduce temporarily unstable behavior in the overall response of the model. As cracks open the shear modulus is reduced. ABAQUS offers a shear retention model in which the post cracked shear stiffness is defined as a function of the opening strain across the crack. The brittle cracking model for concrete in ABAQUS applies the maximum principal stress to detect crack initiation. This model is considered functional in the restrained shrinkage problems as the concrete compressive stresses are expected to remain low and within the elastic range of material behavior. In this study, the brittle cracking model for concrete is used in nonlinear analysis of the walls.

CHAPTER 3

3 Linear analysis of uncracked thick wall

3.1 Introduction

Mass concrete is defined in ACI 116R as "any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking" (ACI Committee 207.1R-05, 2006).

A concrete element, if free to move, would have no stress development associated with thermal deformation on cooling. However, in practice the concrete mass will be restrained either externally by the rock foundation or internally by differential deformations within different areas of concrete due to the presence of temperature gradients (Mehta & Monteiro, 2006).

This chapter investigates the response of thick reinforced concrete walls subjected to non–uniform shrinkage strain assuming linear elastic material behavior. Moreover, it compares the results with the walls subjected to uniform shrinkage.

The concrete wall was modeled using solid elements with continuum, three-dimensional, eight nodded, reduced integration C3D8R (33 X 33 X 33mm) assigned for meshing. The reinforcement was modeled using SFM3DR rebar layer in surface element which is a 4-nodded quadrilateral element in 3D space (100 X 100mm) was assigned for meshing.

In this analysis, due to shrinkage strain subjected to walls, the total strain at each point is only caused by restraint and shrinkage from surrounding parts of the member at each point. Therefore, the total strain at each point is given by Equation 1.2 in Chapter 1.

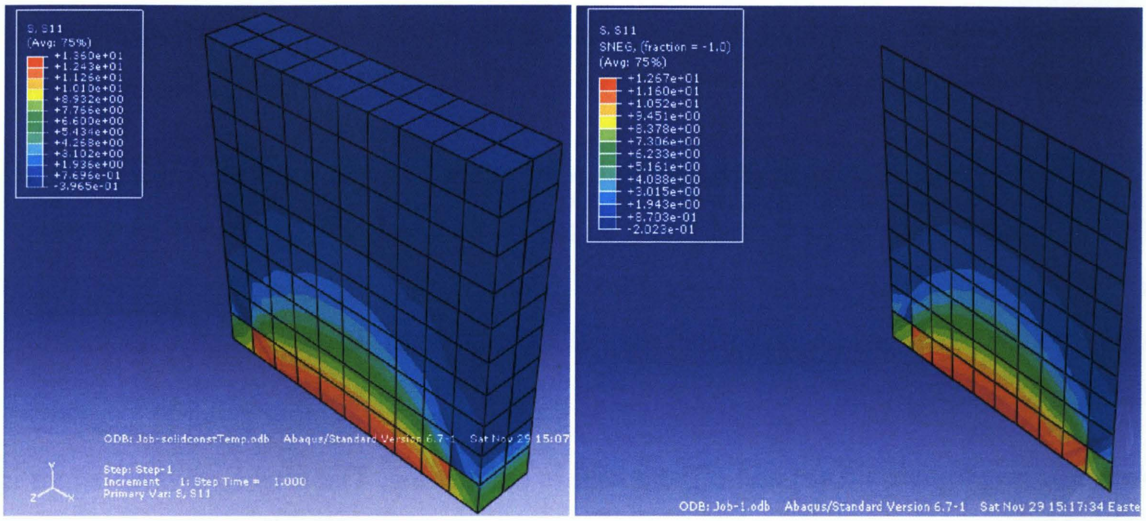
According to (Gilbert, 1992) the shrinkage strain is $600X10^{-6}$ mm/mm for every point in the walls and deriving the total strain at each point on the center point of the walls, the restraint strain can be determined from Eq. 1.2.

3.2 Verification

In this study the solid element is used to model the wall. To make sure that this is an appropriate element, the walls were modeled using both solid element and shell element. The shell element was also used by Ziaolhagh, 2008.

Figure 3-1 shows horizontal stress in concrete for linear analyses in the wall with length/height ratio of 1 and 200 mm thickness.

The maximum horizontal stress in concrete is 13.6 MPa for the wall with solid element and it is close to the maximum stress in the wall with shell element (12.67 MPA). Moreover both walls show similar pattern of stress distribution.



(a) Horizontal Stress in Concrete solid element **(b) Horizontal Stress in Concrete shell element**

Figure 3-1 Horizontal Stress in concrete

3.3 Analysis and results in horizontal direction

The result of analysis on the centerline of the wall with length / height ratios of 1, 2, 5, 10, and 20 are presented in the following sections.

3.3.1 Length/Height ratio of 1

Figure 3-2 shows total strain, restraint strain, stress in reinforcement, and stress in concrete in the horizontal direction on the centerline of the wall. As seen in Figure 2-2, 2-3 (a), (b), (c), it is expected to have identical results at the right and the left sides of the wall due to symmetrical boundary condition for cases A and C, where due to unsymmetrical boundary conditions in case B, non-similar results at the right and left sides of the wall can be expected. The positive and negative values represent tension and compression, respectively.

As seen in Figures 3-2 (a) and (b) concrete is under tension where its maximum value is at the base of the wall and decreases as it approaches the top of the wall. Figure 3-2(a) and (b) shows that stress drops from almost 16 MPa to -0.1 MPa for case A, but in case C the stress is around 15 MPa at the base and it only decreases to 8 MPa on top of the wall. Looking at case B from Figure 3-2 (b) verifies that the right side of the wall is subjected to minimum shrinkage and has its maximum value as it reaches the other side of the wall, as can be seen in Figure 3-2 (a).

Figure 3-2(c) and (d) illustrate horizontal reinforcing bars are under compression and their magnitudes increases from bottom to top of the wall. On one hand, compression stress increases faster in case A compared to case C; on the other hand, Case B has similar behavior as case A on the left side of the wall but it is almost under no stress on the right side of the wall.

According to Figure 3-2 (e) and (f), the wall is contracting. The total horizontal strain is zero at the base where the structure is fully fixed. Case A has a drastic increase compared to case C. Moreover, Case B has similar behavior as case A on the left side of the wall but it has almost zero horizontal strain on the right side of the wall.

As seen in Figure 3-2 (g) and (h), the wall is under tension in all cases from the restraint of the surrounding part, except case B on right side of the wall. The restraint strain value at the base in all cases is equal to the value of shrinkage strain ($600X10^{-6}$) and is decreasing slightly from the bottom to top of the wall, except case B on right side of the wall where restraint strain value is constantly zero from base to top of the structure.

3.3.2 Length /Height ratio of 2

Figure 3-2 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the horizontal direction on the centerline of the wall.

As seen in Figure 3-3(a) and (b) concrete is under tension where its maximum value is at the base of the wall and decreases as it goes on to the top of the structure. It shows that stress drops from almost 16 MPa to 0 MPa for Case A, but in Case C stress is around 15 MPa at the base but only decreases to 7.5 MPa on to the top of the wall. Looking at Case B from Figure 3-3(b) verifies that the right side of the wall is subjected to minimum shrinkage and has its maximum value as it reaches the other side of the wall, as it can be seen in Figure 3-3 (a). It can be seen there is a slight shift to the right for all the cases in these figures.

Figure 3-3 (c) and (d) illustrate that horizontal reinforcing bars are under compression and its magnitude increases from bottom to top of the wall. On one hand, compressive stress increases faster in Case A compared to Case C. On the other hand, Case B almost coincides with Case A from the bottom up to 0.4h and from that point on Case A has a sharper incline on the left side of the wall but is almost under no stress on the right side of the wall.

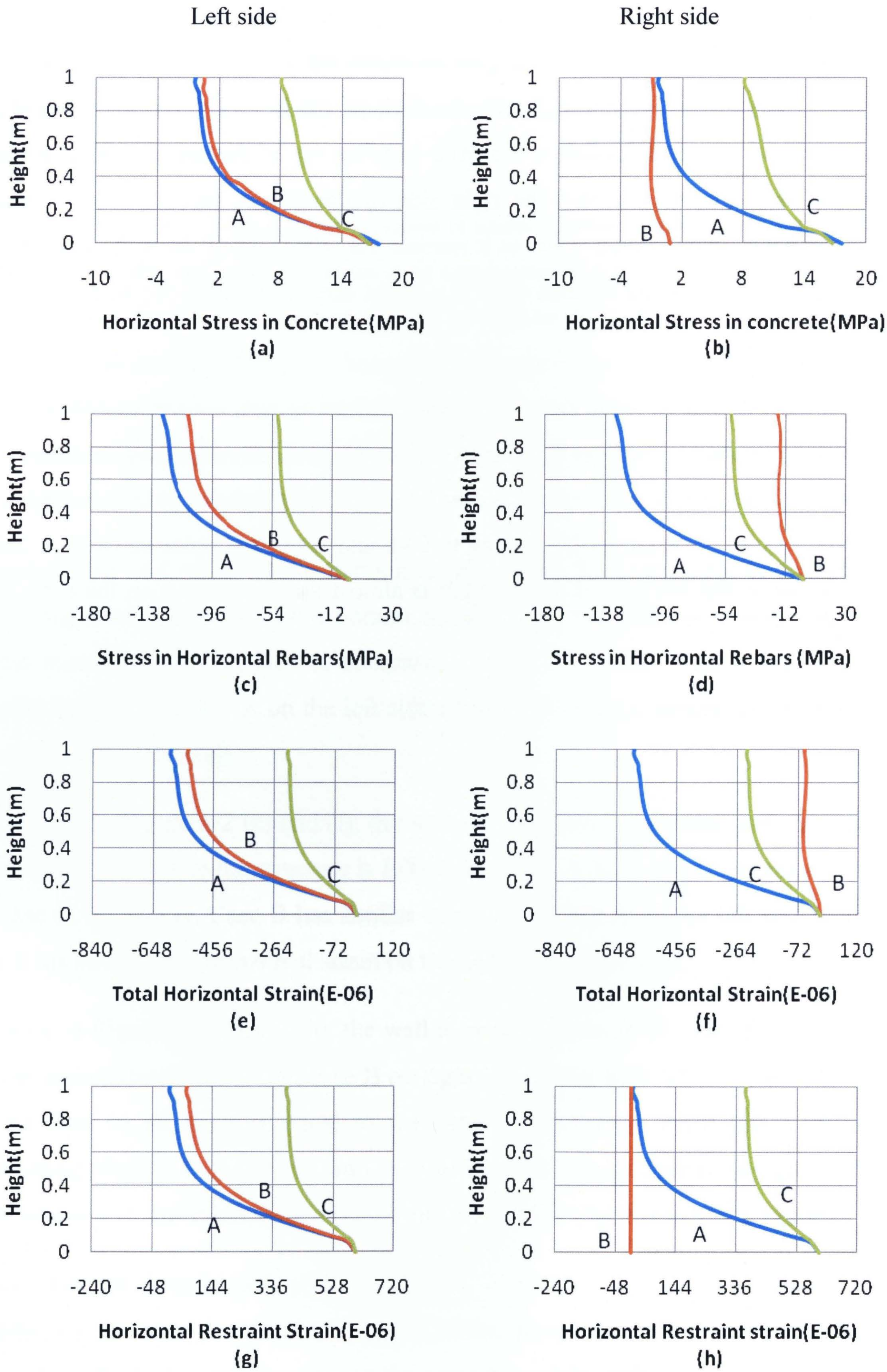


Figure 3-2 Horizontal Stress and Strain Distribution (L/H=1)

According to Figure 3-3 (e) and (f), the wall is contracting. The total horizontal strain is zero at the base where the structure is fully fixed. Case A has drastic increases compared to Case C. Moreover, Case B has a similar behavior to Case A on the left side of the wall, but it has almost zero horizontal strain on the right side of the wall. Cases B and C have very similar behavior on the right side of the wall.

As seen in Figure 3-3(g) and (h), the structure is under tension in all cases from the restraint of the surrounding part, except Case B on the right side of the wall. The restraint strain value at the base in all cases is equal to the value of shrinkage strain ($600X10^{-6}$) and it is decreasing slightly from the bottom to top of the wall, except Case B on the right side of the wall where restraint strain value is constantly zero from base to top of the structure.

3.3.3 Length / Height ratio of 5

Figure 3-4 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the horizontal direction on the centerline of the wall.

As seen in Figure 3-4 (a) and (b) concrete is under tension where its maximum value is at the base of the wall and decreases as it goes on to the top of the structure. Figure 3-4 (a) and (b) shows that stress drops from almost 19 MPa to13 MPa for Case A, but in Case C stress is around 15MPa at the base and decreases to 13.5 MPa on the top of the wall. Looking at Case B from Figure 3-4 (b) verifies that the right side of the wall is subjected to minimum shrinkage and has its maximum value as it reaches the other side of the wall, which shows similar behavior to Case A and C as can be seen in Figure 3-4 (a).

Figure 3-4 (c) and (d) illustrate that the horizontal reinforcing bars in Case A are slightly under compression and its magnitude increases with a very smooth incline from the bottom to the top of the wall. Horizontal reinforcing bars in Case C are under minimal tension. Comparing Case B on the left and right side of the wall shows similar behavior.

According to Figure 3-4 (e) and (f), the wall is contracting in Case A and B but expanding in Case C.

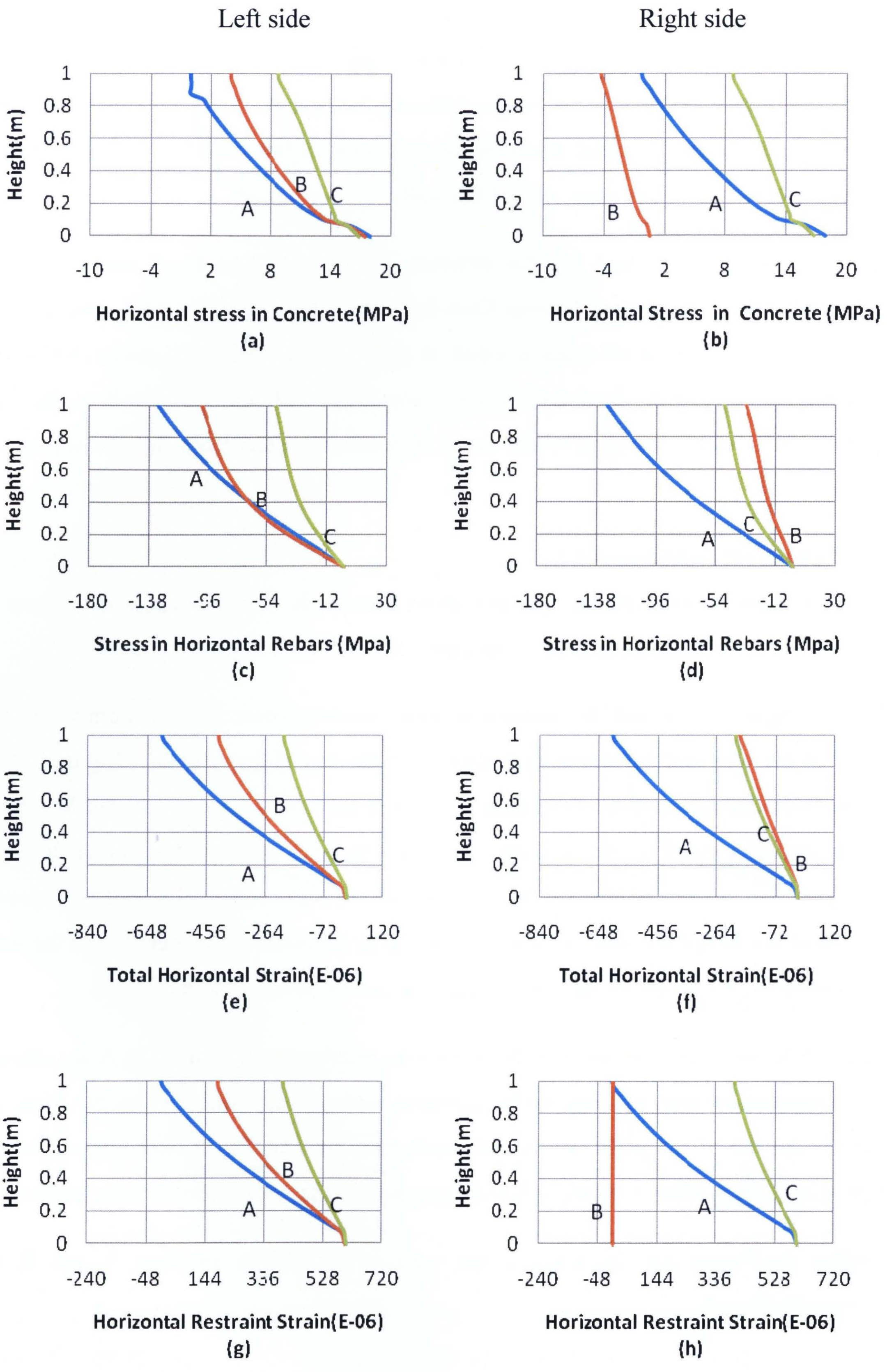


Figure 3-3 Horizontal Stress and Strain distribution (L/H=2)

As seen in Figure 3-4 (g) and (h), the structure is under tension in all cases from the restraint of the surrounding part, except Case B on the right side of the wall. The restraint strain value at the base in all cases is equal to the value of shrinkage strain ($600X10^{-6}$).

3.3.4 Length / Height ratio of 10

Figure 3-5 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the horizontal direction on the centerline of the wall.

As seen in Figure 3-5 (a) and (b) concrete is under tension where its maximum value is at the base of the wall and decreases as it reaches 0.1h. It remains at a constant stress up to the top of the wall for all the cases, except Case B on the right side of the wall where it is subjected to minimum shrinkage.

Figure 3-5 (c) and (d) illustrate that the horizontal reinforcing bars are neither under compression nor tension from the base to the top of the wall.

According to Figure 3-5 (e) and (f), the wall is not contracting nor expanding. The total horizontal strain is zero at the base where the structure is fully fixed and has the same magnitude as it does at the top of the wall.

As seen in Figure 3-5 (g) and (h), the structure is under tension in all the cases from the restraint of the surrounding part, except Case B on the right side of the wall. The restraint strain value at the base in all cases is equal to the value of shrinkage strain ($600X10^{-6}$) and stays constant from the bottom to the top of the wall, except Case B on right side of the wall where the restraint strain value is constantly zero from the base to the top of the structure.

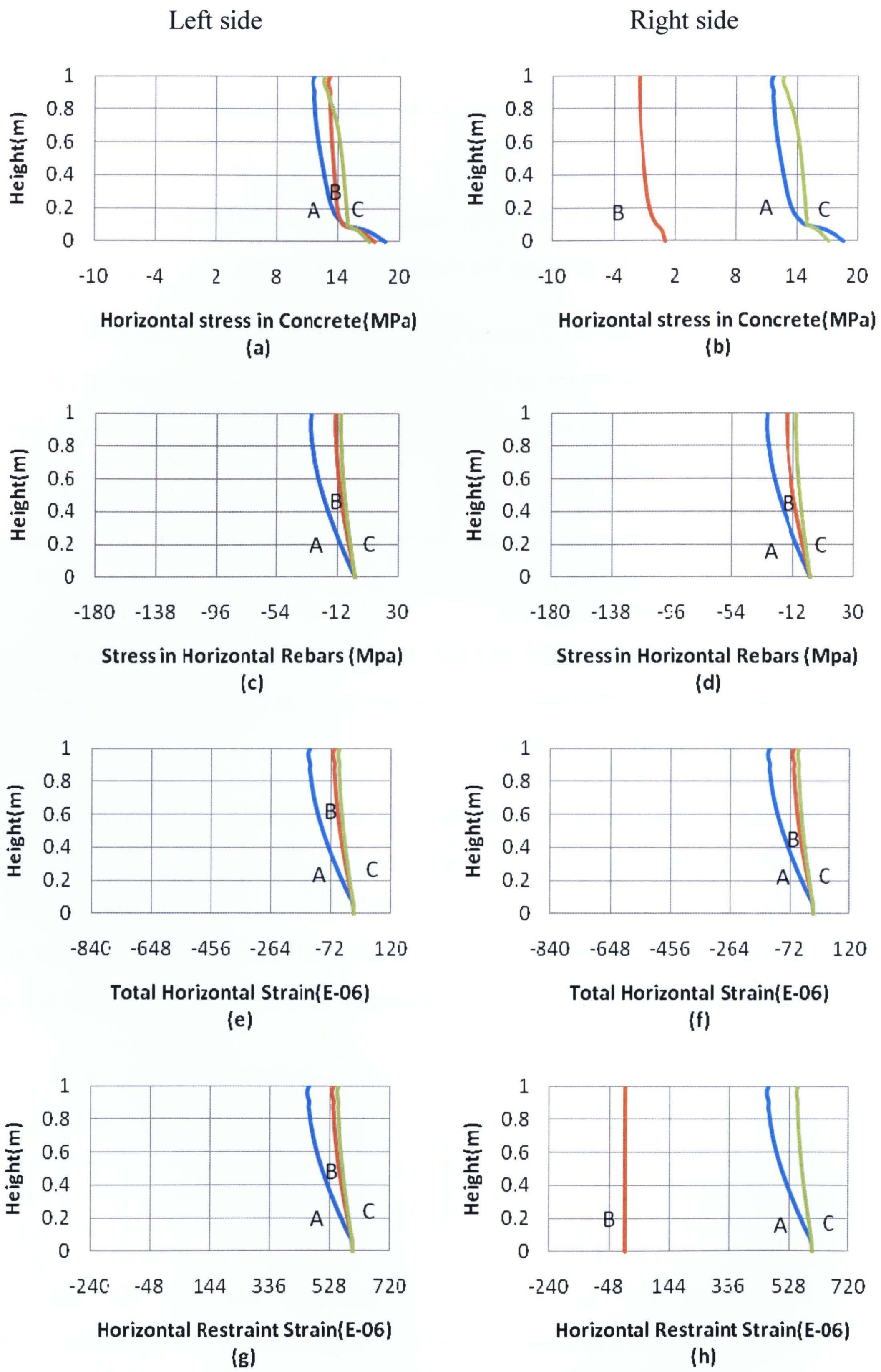


Figure 3-4 Horizontal Stress and Strain distribution (L/H=5)

3.3.5 Length / Height ratio of 20

Figure 3-6 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the horizontal direction on the centerline of the wall.

As seen in Figure 3-6 (a) and (b) concrete is under tension where its maximum value is at the base of the wall and decreases as it reaches 0.1h. It remains at a constant stress up to the top of the wall for all the cases, except Case B on the right side of the wall where it is subjected to minimum shrinkage.

Figure 3-6 (c) and (d) illustrate that the horizontal reinforcing bars are neither under compression nor tension from the base to the top of the wall.

According to Figure 3-6 (e) and (f), the wall is not contracting nor expanding. The total horizontal strain is zero at the base where the structure is fully fixed and has the same magnitude as it does at the top of the wall.

As seen in Figure 3-6 (g) and (h), the structure is under tension in all the cases from the restraint of the surrounding part, except Case B on the right side of the wall. The restraint strain value at the base in all cases is equal to the value of shrinkage strain ($600X10^{-6}$) and stays constant from the bottom to the top of the wall, except Case B on right side of the wall where the restraint strain value is constantly zero from the base to the top of the structure.

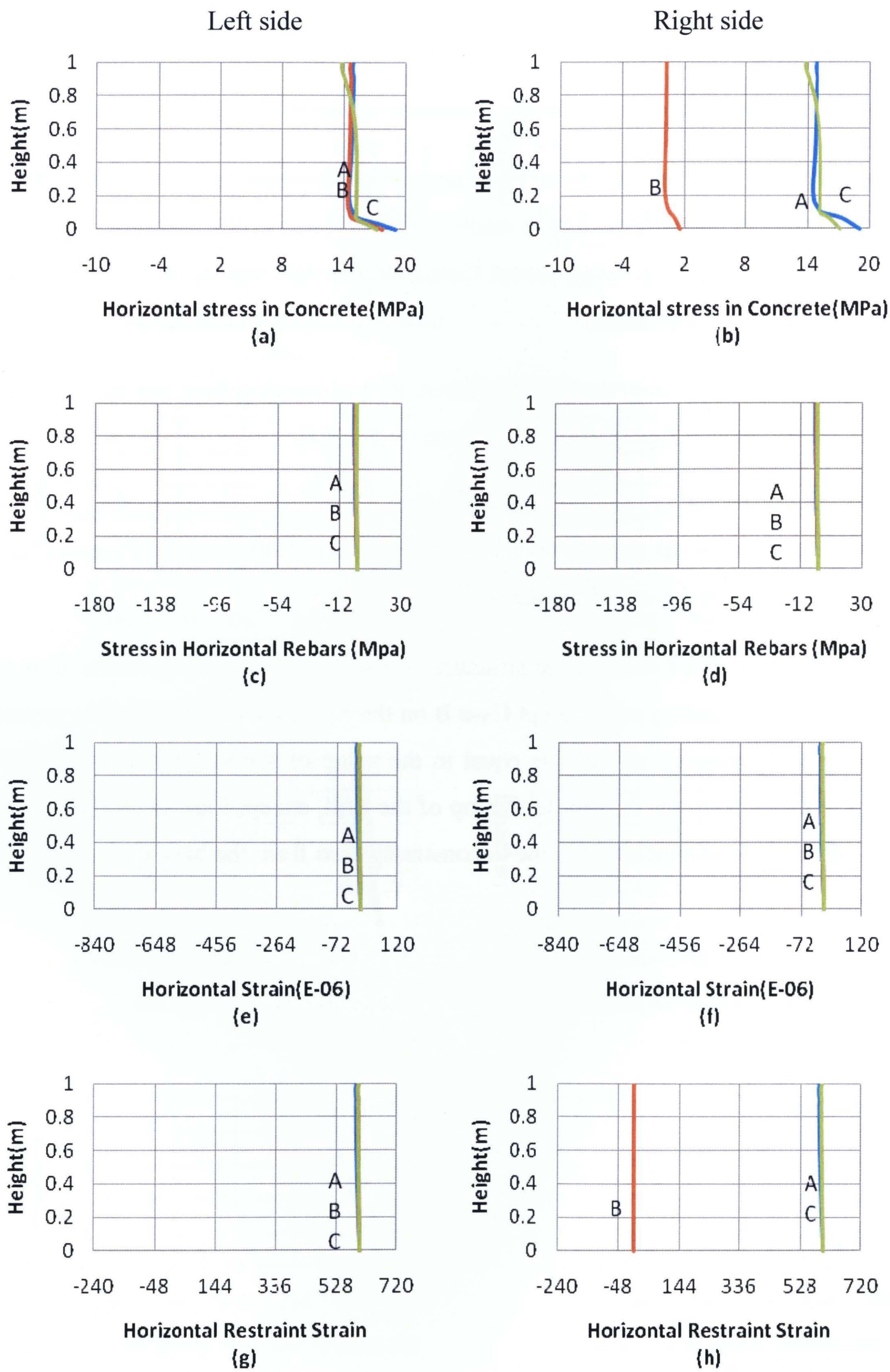


Figure 3-5 Horizontal Stress and Strain distribution (L/H=10)

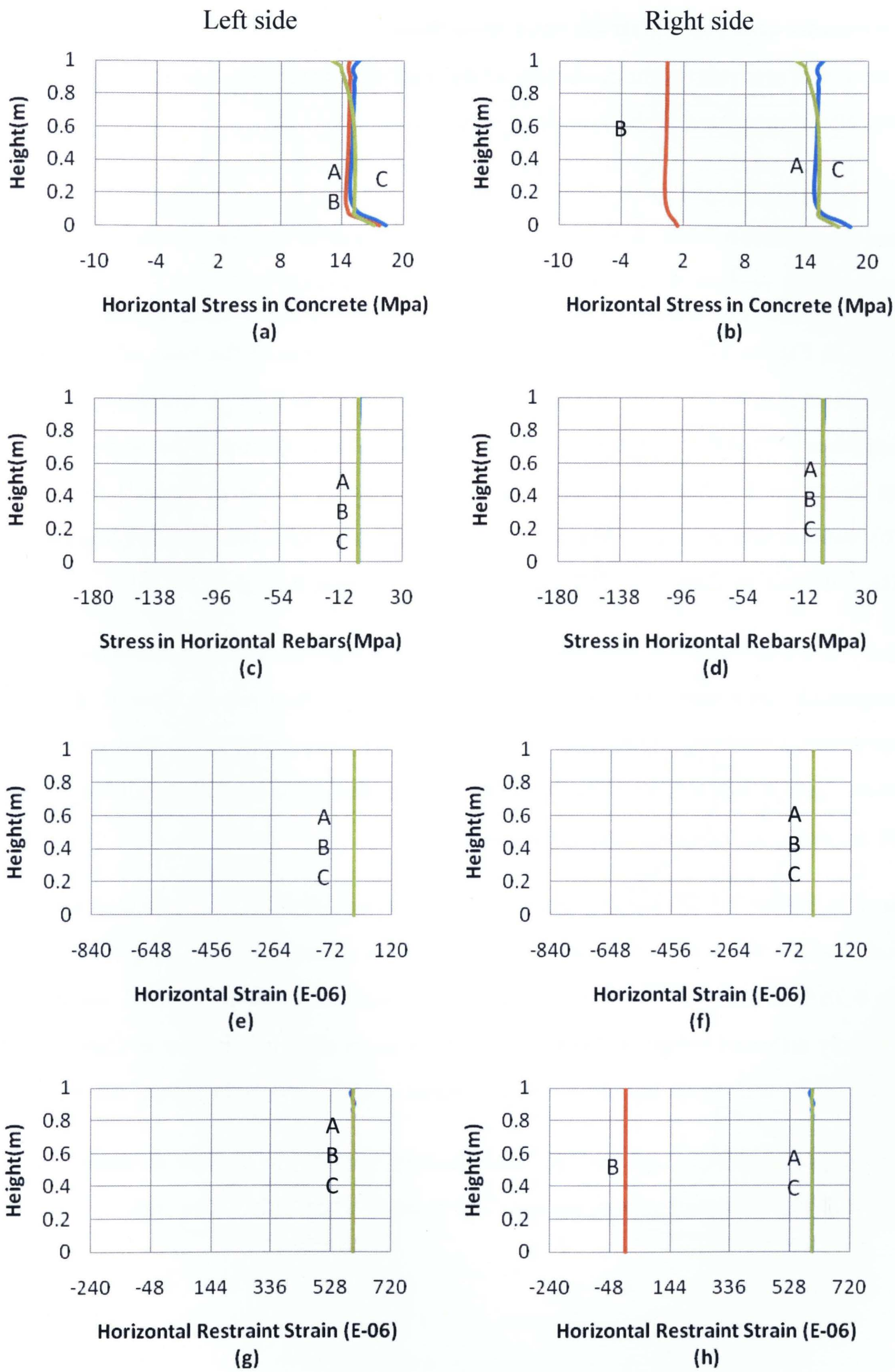


Figure 3-6 Horizontal Stress and Strain distribution (L/H=20)

3.4 Analysis and results in vertical direction

The results of analysis on the centerline of the wall with length / height ratios of 1, 2, 5, 10 and 20 are presented in the following sections.

3.4.1 Length / Height ratio of 1

Figure 3-7 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the vertical direction on the centerline of the wall.

As seen in Figure 3-7 (a) and (b), concrete is under tension at the base of the wall and decreases as it goes on to the top of the structure. Stress in Case A decreases drastically as it reaches 0.2h and stays almost constant from 0.4h until the top of the wall. In Case C, stress decreases too but not as sharp as Case A. Having a look at Case B from Figure 3-7(b) verifies that the right side of the wall is subjected to minimum shrinkage and has similar behavior as Case A on left side of the wall, as seen in Figure 3-7 (a).

Figure 3-7 (c) and (d) illustrate that vertical reinforcing bars are under compression and its magnitude decreases from bottom to top of the wall for Case A. Case C shows that compression decreases slightly up to 0.6h and starts increasing from that point on. In addition, Case B has similar behavior as Case A on the left side of the wall but is almost under no stress on the other side of the wall.

As seen in Figure 3-7 (e) and (f), the wall is contracting. The total vertical strain is zero at the base where the structure is fully fixed. Case A is drastically increasing from the base up to 0.2h and starts decreasing from that point on compared to Case C, which has a completely different behavior. Moreover, Case B has a similar behavior as Case A on the left side of the wall but it has almost zero vertical strain on the right side of the wall.

According to Figure 3-7 (g) and (h), the structure is under tension in all cases from the restraint of the surrounding part, except Case B on the right side of the wall.

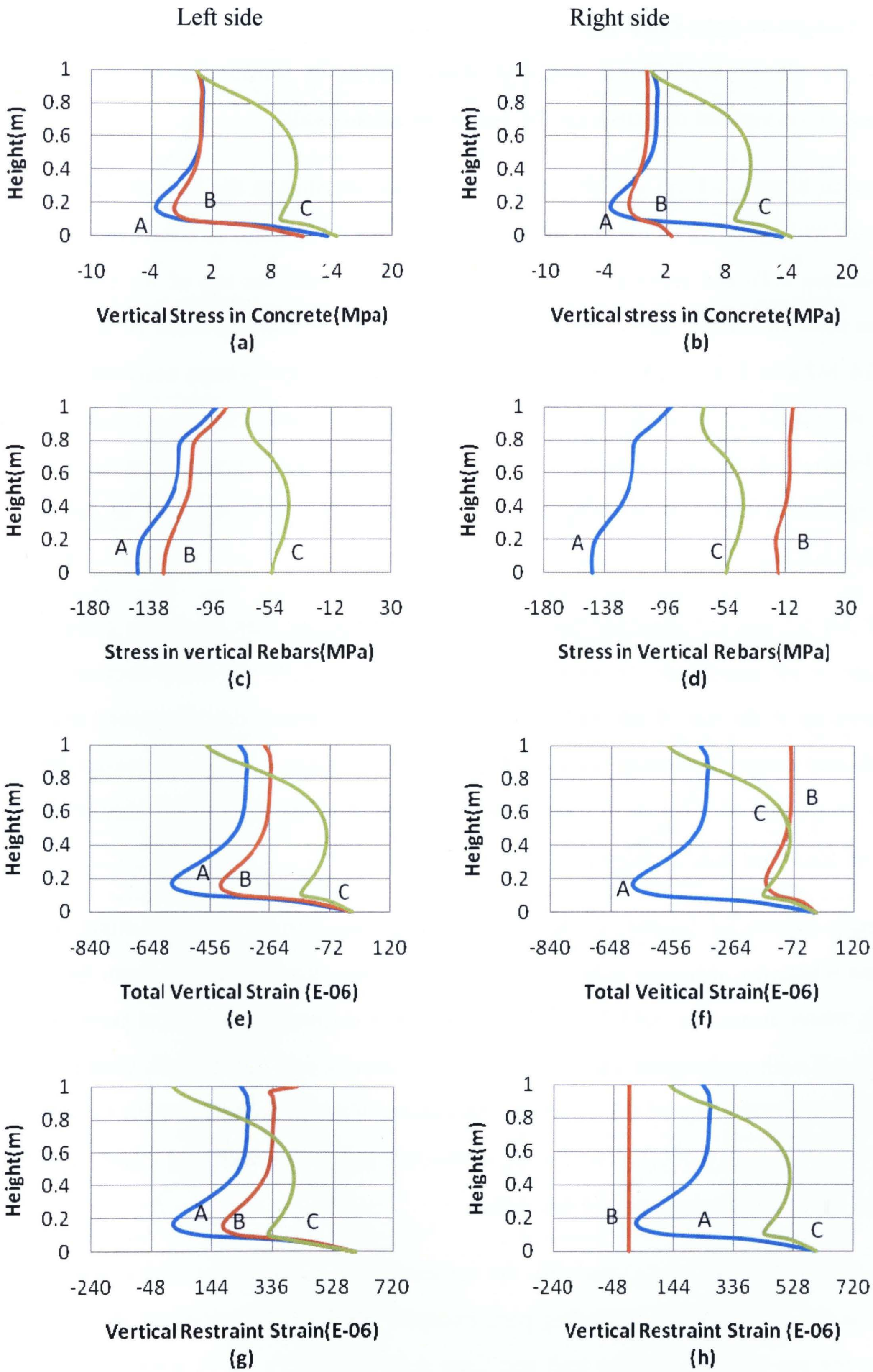


Figure 3-7 Vertical Stress and Strain distribution (L/H=1)

3.4.2 Length/Height ratio of 2

Figure 3-8 shows total strain, restraint strain, stress in reinforcement, and stress in concrete in the vertical direction on the centerline of the wall.

As seen in Figure 3-8 (a) and (b) concrete is under tension at the base of the wall and decreases as it goes on to the top of the structure. Stress in Case A decreases drastically as it reaches 0.2h and stays almost constant from 0.4h until the top of the wall where it reaches zero. In Case C stress decreases as well but not as sharp as Case A; it has a jump from 14 MPa to 8 MPa from the bottom to 0.1h and it stays almost constant until 0.6h where its biggest jump to the top of the structure has happened. Having a Look at Case B from Figure 3-8 (b) verifies that the right side of the wall is subjected to minimum shrinkage and has similar behavior as Case A on the left side of the wall, as can be seen in Figure 3-8 (a).

Figure 3-8 (c) and (d) illustrate that the vertical reinforcing bars are under compression. For Case A its magnitude increases from the bottom to 0.2h and starts decreasing from that point up to the top of the wall. Case C shows that compression decreases slightly up to 0.6h and starts increasing from that point on. Moreover, stress decreases from the bottom to the top of the wall in Case B on the left side of the wall, but is almost under no stress on the other side of the wall.

As seen in Figure 3-8 (e) and (f), the wall is contracting. The total vertical strain is zero at the base where the structure is fully fixed. Case A has a drastic increase from the base up to 0.2h where it reaches -648 $X10^{-6}$ $^{mm}/_{mm}$ and starts decreasing from that point on. Case C starts off with an increase up to 0.1h and stays almost constant to 0.6h where it has its highest jump to the top of the structure. Moreover, Case B coincides with Case A from the base to 0.1h and from 0.6h to the top on the left side of the wall, but it has almost zero vertical strain on the right side of the wall.

According to Figure 3-8 (g) and (h), the structure is almost under tension for all cases from the restraint of the surrounding part, except Case B which has a zero value from the base to the top right side of the wall and Case A between 0.1h - 0.3h goes to the negative side of the diagram.

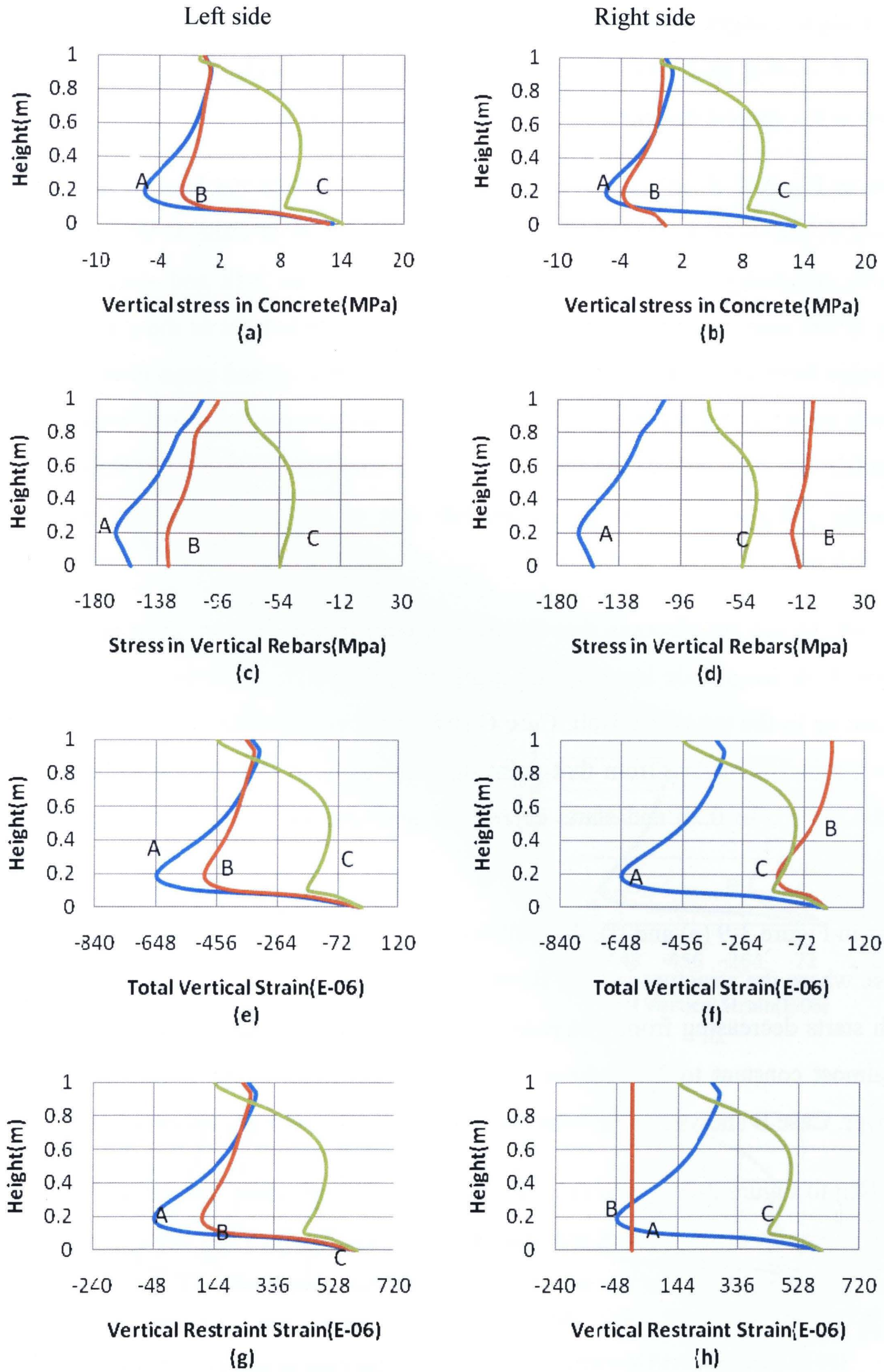


Figure 3-8 Vertical Stress and Strain distribution (L/H=2)

3.4.3 Height/Length ratio of 5

Figure 3-9 shows total strain, restraint strain, stress in reinforcement, and stress in concrete in the vertical direction on the centerline of the wall.

As seen in Figure 3-9 (a) and (b) concrete is under tension at the base of the wall and decreases as it goes on to the top of the structure, except part of Case A. Stress in Case A decreases drastically to the compression zone as it reaches 0.2h and starts increasing slightly to the tension zone. In Case C, stress decreases too but not as sharp as Case A, it has a jump from 15 MPa to 9 MPa from the bottom to 0.1h and stays almost constant until 0.6h where its biggest jump to the top of the structure has happened. Figure 3-9 (b) verifies that the right side of the wall in Case B is subjected to minimum shrinkage and has similar behavior as Case A on the left side of the wall as it can be seen in Figure 3-9 (a).

Figure 3-9 (c) and (d) illustrate that the vertical reinforcing bars are under compression. For Case A its magnitude increases from the bottom to 0.2h and starts decreasing from that point up to the top of the wall. Case C shows that compression is almost constant to 0.6h and starts increasing from that point on. Moreover, in Case B the stress increases from the bottom to 0.2h and starts decreasing until the top of the wall where there is minimal tension.

As seen in Figure 3-9 (e) and (f), the wall is contracting. The total vertical strain is zero at the base where the structure is fully fixed. Case A drastically increases from the base up to 0.2h starts decreasing from that point on. Case C starts off increasing up to 0.1h and stays almost constant to 0.6h where it has its highest jump to the top of the structure. Moreover, Case B shows similar behavior to Case A considering a smoother steepness.

According to Figure 3-9 (g) and (h), the structure is almost under tension in all the cases from the restraint of the surrounding part, except Case B which has zero value from the base to the top right side of the wall and Case A where between 0.1h - 0.5h goes to the negative side of the diagram.

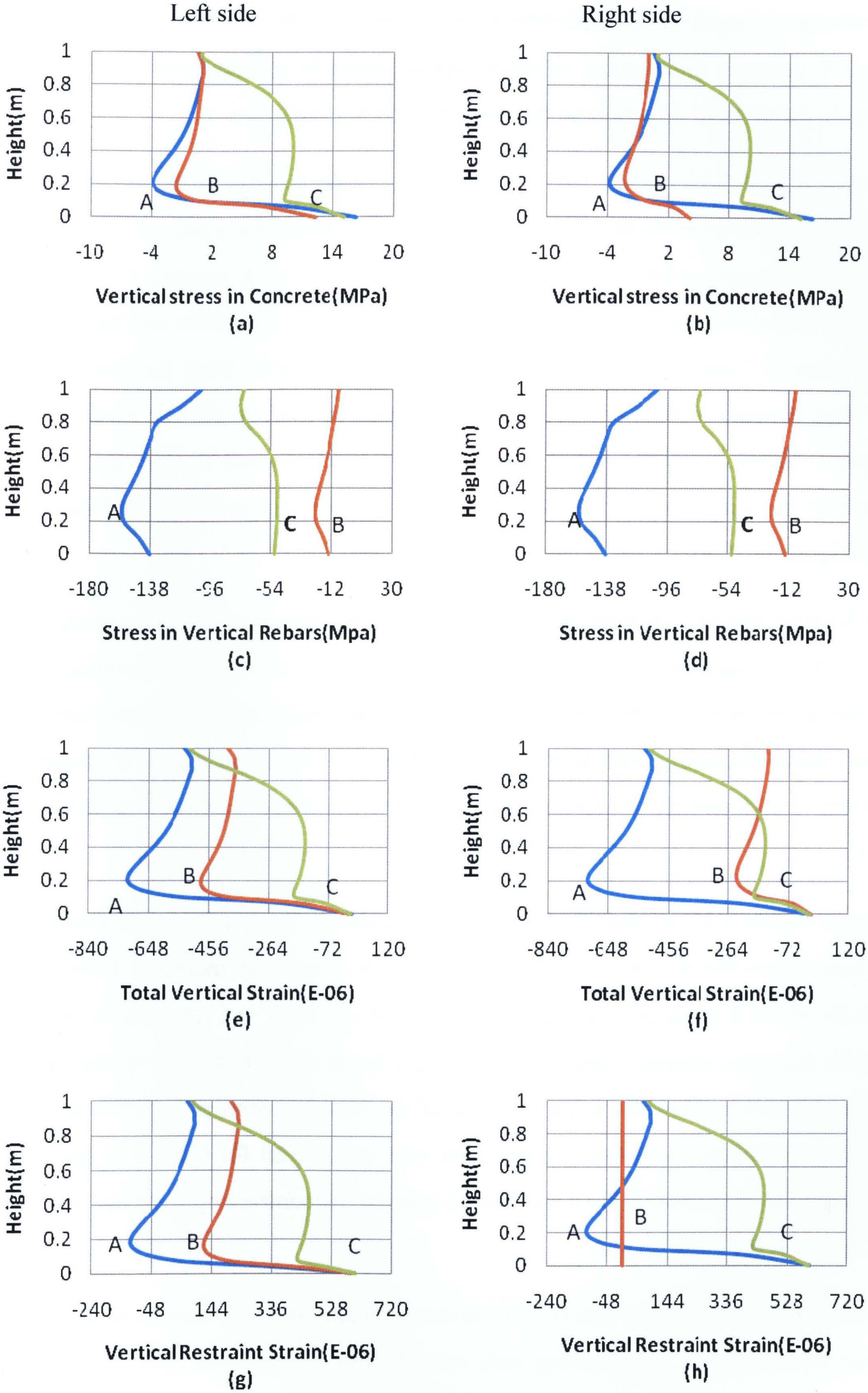


Figure 3-9 Vertical Stress and Strain distribution (L/H=5)

3.4.4 Height/Length ratio of 10

Figure 3-9 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the vertical direction on the centerline of the wall.

As seen in Figure 3-10 (a) and (b), the concrete is under tension at the base of the wall and decreases as it goes on to the top of the structure, except for a part of Case A. Stress in Case A decreases drastically to the compression zone as it reaches 0.2h and starts increasing slightly to the tension zone. In Case C the stress decreases too, but not in the same manner as Case A; it has a jump from 15 MPa to 9 MPa from the bottom to 0.1h and it stays almost constant until 0.6h where its biggest jump to the top of the structure takes place. Figure 3-10 (b) verifies that the right side of the wall in Case B is subjected to minimum shrinkage and has similar behavior as Case A on the left side of the wall, as seen in Figure 3-10 (a).

Figure 3-10 (c) and (d) illustrate that the vertical reinforcing bars are under compression. For Case A its magnitude increases from the bottom to 0.2h and starts decreasing from that point up to the top of the wall. Case C shows that compression is almost constant to 0.6h and starts increasing from that point on. Moreover, in Case B stress increases from the bottom to 0.2h and starts decreasing until 0.6h where it stays constant up to the top of the wall.

As seen in Figure 3-10 (e) and (f), the wall is contracting. The total vertical strain is zero at the base where the structure is fully fixed. Case A drastically increases from the base up to 0.2h where it starts decreasing from that point on. In Case C it starts by increasing up to 0.1h and stays almost constant to 0.6h where it has its highest jump to the top of the structure. Moreover, Case B on the left side of the wall has similar behavior as Case A considering smoother steepness. On the right side of the wall for Case B, it goes to the expanding zone from base to 0.1h and comes back to the contracting zone and stays there up to the top of the wall.

According to Figure 3-10 (g) and (h), the structure is almost under tension in all the cases from the restraint of the surrounding part, except Case B which has zero value from the base to the top right side of the wall, and Case A where between 0.1h - 0.8h it goes to the negative side of the diagram.

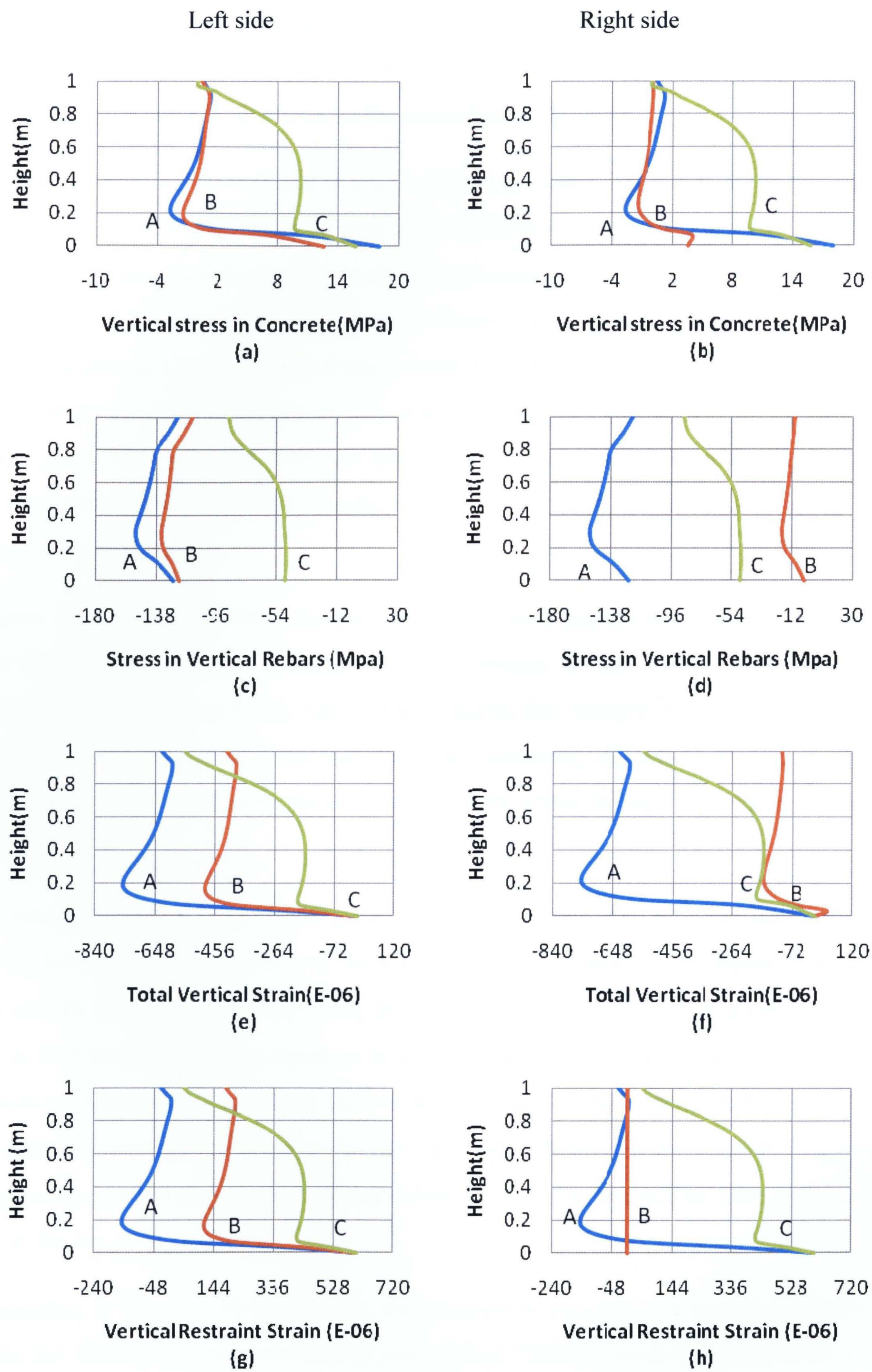


Figure 3-10 Vertical Stress and Strain distribution (L/H=10)

3.4.5 Length / Height ratio of 20

Figure 3-11 presents total strain, restraint strain, stress in reinforcement, and stress in concrete in the vertical direction on the centerline of the wall.

As seen in Figure 3-11 (a) and (b), the concrete is under tension at the base of the wall and decreases as it goes on to the top of the structure, except for a part of Case A and B. Stress in Case A decreases drastically to the compression zone as it reaches 0.2h and starts increasing slightly to the tension zone. In Case C the stress decreases too, but not in the same manner as Case A; it has a jump from 14 MPa to 9 MPa from the bottom to 0.1h and it stays almost constant until 0.6h where its biggest jump to the top of the structure has happened. Figure 3-11 (b) verifies that the right side of the wall in Case B is subjected to minimum shrinkage and has similar behavior as Case A on the left side of the wall, as seen in Figure 3-11 (a).

Figure 3-11 (c) and (d) illustrate that the vertical reinforcing bars are under compression. For Case A its magnitude increases from the bottom to 0.2h and starts decreasing from that point up to the top of the wall. Case C shows that compression is almost constant to 0.5h and starts increasing from that point on. Moreover, in Case B stress has similar behavior as Case A on the left side of the wall and has almost zero stress on the right side of the wall.

As seen in Figure 3-11 (e) and (f), the wall is contracting. The total vertical strain is zero at the base where the structure is fully fixed. Case A drastically increases from the base up to 0.2h where it starts decreasing from that point on. In Case C it starts off increasing up to 0.1h and stays almost constant to 0.6h where it has its highest jump to the top of the structure. Moreover, Case B on the left side of the wall has similar behavior as Case A considering smoother steepness. On the right side of the wall for Case B goes to the expanding zone from base to 0.1h and comes back to the contracting zone and stays there up to the top of the wall.

According to Figure 3-11 (g) and (h), the structure is almost under tension in all the cases from the restraint of the surrounding part, except Case B which has zero value from the base to the top of the wall, as seen in Figure 3-11 (h), and Case A and B between 0.1h - 0.9h it goes to the negative side of the diagram, as seen in Figure 3-11 (g).

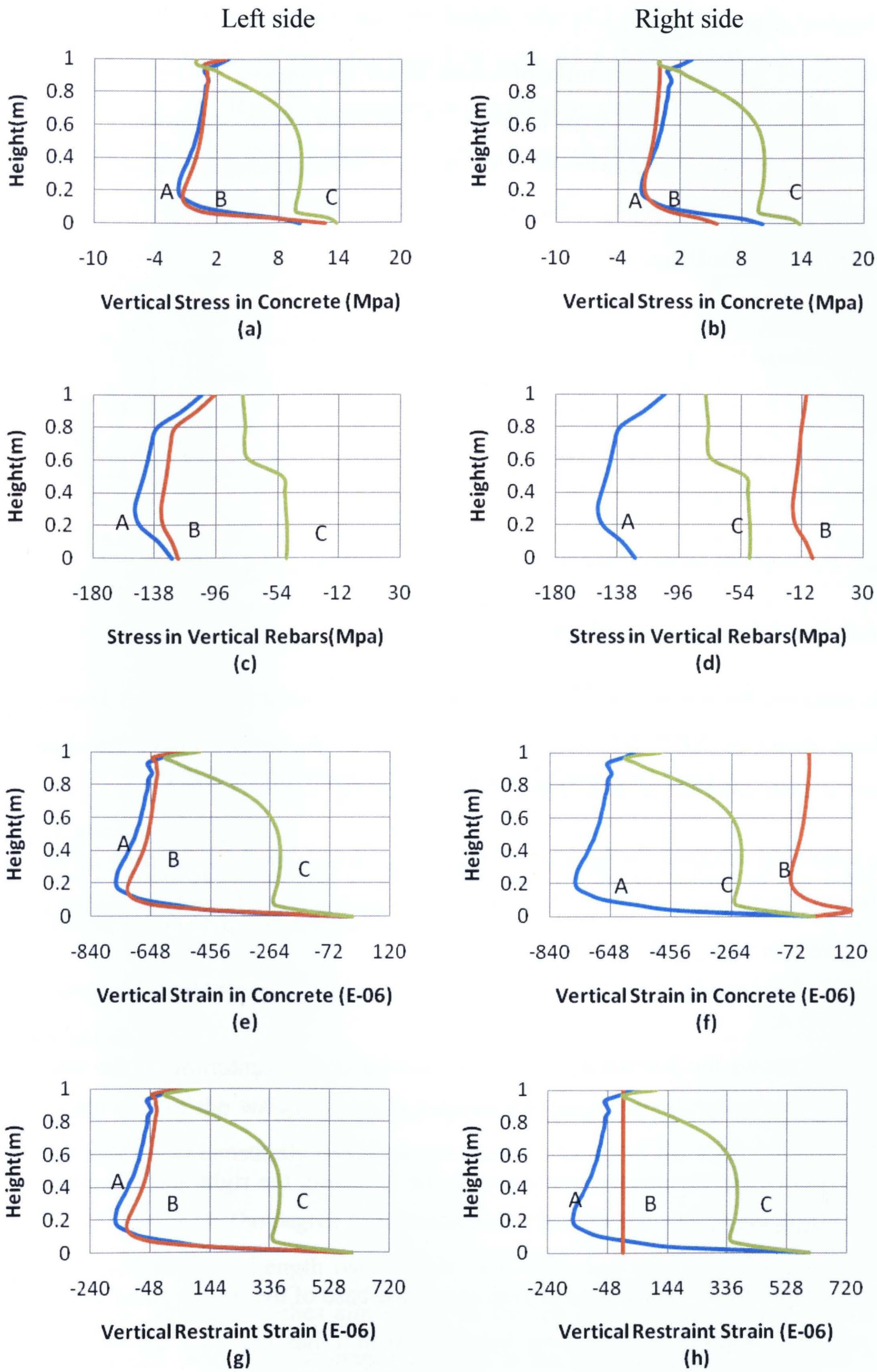


Figure 3-11 Vertical Stress and Strain distribution (L/H=20)

3.5 Degree of Restraint

The degree of restraint is the ratio of actual stress in concrete resulting from volume change to the stress that would result if concrete were completely restrained. Alternatively, that degree of restraint is the ratio of strain of concrete caused by restraint to the strain that would occur if concrete were not restrained. The degree of restraint can be expressed as (Ziaolhagh, 2008)

$$K_R = -\frac{\varepsilon_{restraint}}{\varepsilon_{shrinkage}} \qquad \text{(Eq. 3.1)}$$

where,

K_R is the degree of restraint

$\varepsilon_{restraint}$ is the restraint strain of the concrete

$\varepsilon_{shrinkage}$ is the shrinkage strain of the concrete

In this analysis, the restraint strain at each point is determined from Eq. 3.1 knowing the shrinkage strain is $600X10^{-6mm}/_{mm}$ at every point in the walls. Then, the degree of restraint at each point in the wall is determined from Eq. 3.1.

In the following sections, the horizontal degree of restraint on the centerline of the walls with length/height ratios of 1, 2, 5, 10 and 20 and having fixed boundary condition at its base is given for case A, B, and C.

3.5.1 Case A

Figure 3-12 shows the horizontal degree of restraint on the centerline of the walls with length/height ratios of 1, 2, 5, 10 and 20 and fixed at the base.

Due to symmetrical temperature variation in the structure, the right and left sides of the wall are identical.

As seen in Figure 3-12, the degree of restraint at the base of the wall is equal to 1 due to a fully restrained support. Length over height ratio of 1 has the most dramatic decrease over the height where it reaches almost zero on top of the structure. In the wall with height over length ratio of 2, basically the same magnitude can be seen on the base and top of the wall compared to the height over length ratio of 1. Moreover, L/H ratio of 2 has higher horizontal degree of restraint than L/H ratio of 1. In the wall with length over height ratio of 5 the degree of restraint is decreasing slightly from 1 at the base to approximately 0.8 at the top. Horizontal degree of restraint for height over length ratio of 10 and 20 is constant from the base to the top of the wall.

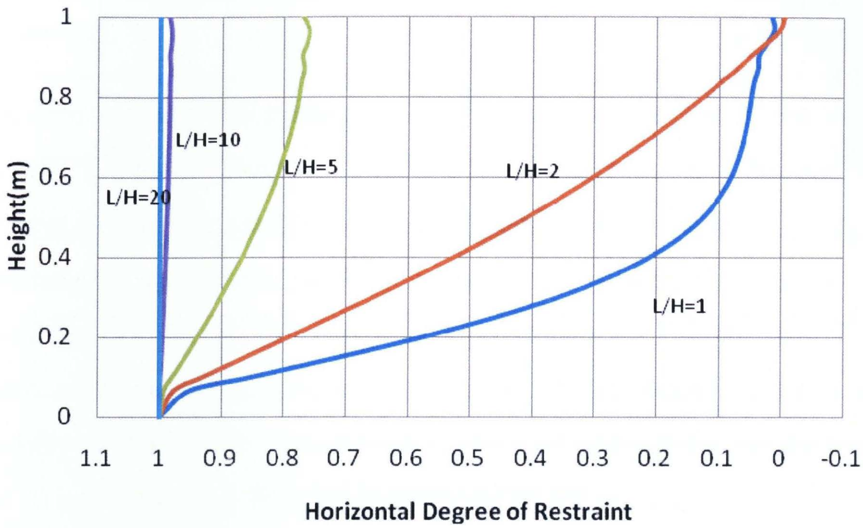


Figure 3-12 Horizontal Degree of Restraint Case A

3.5.2 Case B

Figure 3-13 shows the horizontal degree of restraint on the centerline of the walls with length/height ratios of 1, 2, 5, 10 and 20.

Due to unsymmetrical temperature variation in the structure, the right and left sides of the wall are not similar.

On the right side of the wall where it is subjected to minimum shrinkage, the horizontal degree of restraint is constantly zero from the base to the top of the wall.

As seen in Figure 3-14, the degree of restraint at the base of the wall is equal to 1 due to a fully restrained support. Length over height ratio of 1 has the most dramatic decrease over the height where it reaches almost 0.1 on the top of the structure. In the wall with height over length ratio of 2, the graph is shifted to the left side and the horizontal degree of restraint on the top is 0.3. In the wall with length over height ratio of 5, the degree of restraint is decreasing slightly from 1 at the base to approximately 0.9 at the top. Horizontal degree of restraint for height over length ratio of 10 and 20 is constantly 1 from the base to the top of the wall.

Right side

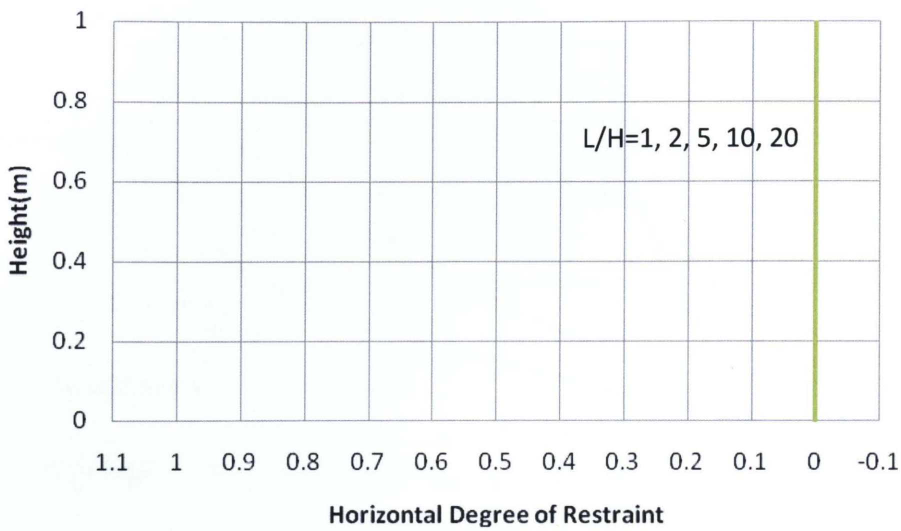


Figure 3-13 Horizontal Degree of Restraint Case B

Left Side

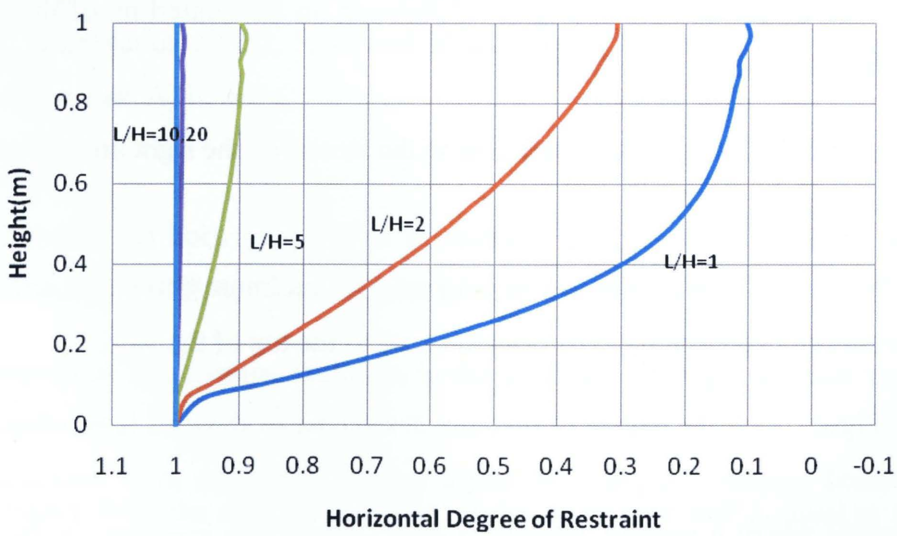


Figure 3-14 Horizontal Degree of Restraint Case B

3.5.3 Case C

Figure 3-15 shows the horizontal degree of restraint on the centerline of the walls with length/height ratios of 1, 2, 5, 10 and 20.

Due to symmetrical temperature variation in the structure, the right and left sides of the wall are identical.

As can be seen in Figure 3-15, the degree of restraint at the base of the wall is equal to 1 due to a fully restrained support. Length over height ratio of 1 has the most dramatic decrease over the height where it reaches almost 0.6 on the top of the structure. In the wall with height over length ratio of 2, the graph is shifted to the left side and the horizontal degree of restraint on the top is approximately 0.7. In the wall with length over height ratio of 5, the degree of restraint is decreasing slightly from 1 at the base to approximately 0.95 at the top. Horizontal degree of restraint for height over length ratio of 10 and 20 is constantly 1 from the base to the top of the wall.

Figure 3-15 Horizontal Degree of Restraint Case C

3.6 Conclusion

This chapter studies the linear behavior of thick reinforced concrete walls with different height over length ratios with a fully restrained base. The walls were subjected to uniform and varying types of non-uniform shrinkage, as seen in Figure 2-2, 2-3 (a), (b), and (c).

The horizontal degree of restraint on the centerline of uncracked walls varies in different ways for Case A, B, and C by the length/height ratio of walls. Along any restraint edge, the horizontal degree of restraint has maximum value of 1.0 except for Case B at the right side of the wall where its value is 0.

Case A shows that the horizontal degree of restraint at the top of the wall at its centerline is as follows: i) zero in the walls with the length/height ratio of 1 and 2, ii) 0.77 in the wall with length/height ratio of 5, and iii) 1.0 in the walls with length/height ratio of 10 and 20.

Case B shows that on the left side of the wall the horizontal degree of restraint at the top of the wall is as follows: i) 0.1 in the wall with the length/height ratio of 1, ii) 0.3 in the wall with length/height ratio of 2, iii) 0.9 in the wall with length/height ratio of 5, and iv) 1 in the walls with length/height ratio of 10 and 20. However on the right side of the wall, it is 0 from the base to the top of the walls.

Case C shows that the horizontal degree of restraint at the top of the wall is as follows: i) 0.6 in the wall with the length/height ratio of 1, ii) 0.65 in the wall with length/height ratio of 2, iii) 0.92 in the wall with length/height ratio of 5, and iv) 1 in the walls with length/height ratio of 10 and 20.

This study shows that by increasing L/H ratios, horizontal degree of restraint tends to increase as well where it reaches to a maximum value of 1 for the height over length ratio of 20. Moreover, Case C (double triangular) increases more dramatically than Cases B (triangular) and A (uniform) due to its double triangular shape of shrinkage distribution. This type of shrinkage distribution causes an additional restraint strain in the wall.

CHAPTER 4

4 Non–linear analysis of thick wall

4.1 Introduction

The cause of shrinkage cracking in a concrete member is a combination of the member's tendency to shrink and restraint that prevent it to do so (Al Rawi & Kheder, 1990).

This chapter investigates the response of thick reinforced concrete walls subjected to non–uniform shrinkage strain assuming non-linear elastic material behavior. Moreover, it compares the results with the walls subjected to uniform shrinkage.
In chapter three, behavior of concrete assumed to be linear where the base of the wall undergoes horizontal stress between 15-17 MPa and decreases its value over the height of the wall.

According to material properties of concrete, when the tensile strain in the wall exceeds the tensile strain capacity of the concrete, cracks will propagate in the wall. Broadly speaking, as soon as tensile stress in the wall exceeds the cracking failure stress of concrete (f_t = 2.7 MPa), the first crack occurs. At the crack, the steel carries the entire stress, and the stress in the concrete is zero. Equation 4.1 shows the cracking strain of the concrete (ε_{crack}).

$$\varepsilon_{crack} = \frac{f_t}{E_c} = \frac{2.7X\,10^{-6}}{25000} = 108X10^{-6} \quad \text{mm/mm} \qquad \text{(Eq. 4.1)}$$

The concrete wall was modeled using solid elements with a Homogeneous section where an 8-node linear brick (33 X 33 X 33mm) with 8 reduced integration points was assigned for meshing. The reinforcement was modeled using shell elements with a Surface section where a 4–node quadrilateral surface element (50 X 50mm) was assigned for meshing.

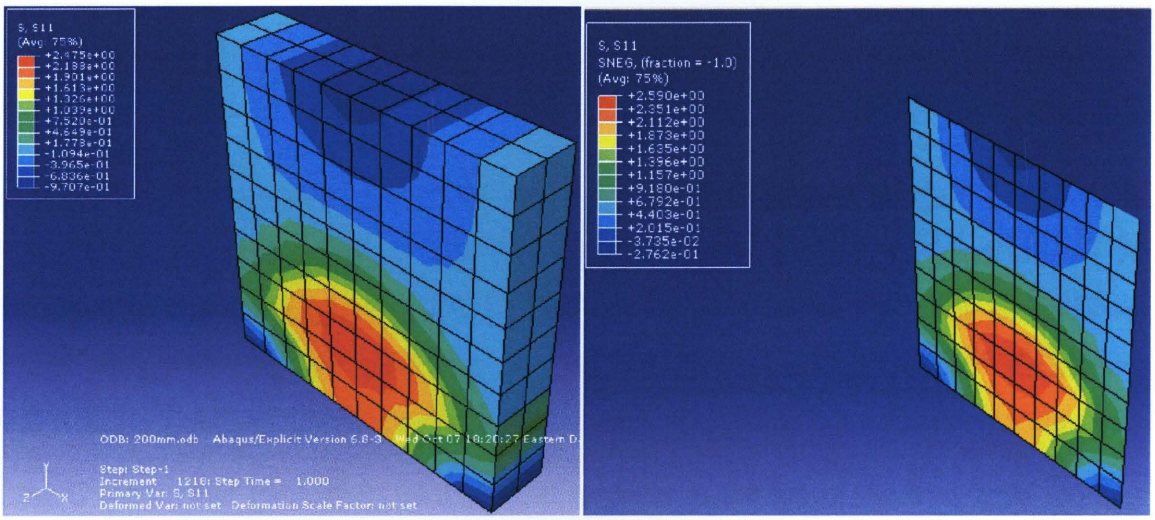
In this analysis, due to shrinkage strain subjected to walls, the total strain at each point is only caused by restraint and shrinkage from surrounding parts of the member at each point. The total strain at each point is given by Equation 1.2 in Chapter 1.

4.2 Verification

In this study the solid element is used to model the wall. To make sure that this is an appropriate element, the walls were modeled using both solid element and shell element. The shell element was also used by Ziaolhagh, 2008.

Figure 4-1 shows horizontal stress in concrete for nonlinear analyses in the wall with length/height ratio of 1 and 200 mm thick.

The maximum horizontal stress in concrete is 2.47 MPa for the wall with solid element and it is close to the maximum stress in the wall with shell element (2.59 MPa). Moreover, both walls show similar pattern of stress distribution.



(a) Horizontal stress in Concrete solid element **(b) Horizontal Stress in Concrete shell element**

Figure 4-1 Horizontal Stress in Concrete

4.3 Analysis and results in horizontal direction

The result of analysis on the centerline of the wall with length over height ratios of 1, 2, 5, and 10 are presented in the following sections. It is expected to have identical result at the right and the left sides of the wall due to symmetrical boundary conditions for Cases A and C, where due to unsymmetrical boundary conditions in Case B, non-similar results at the right and left sides of the wall can be expected.

4.3.1 Horizontal Restraint Strain for Case A

Figure 4-2 shows the horizontal restraint strain in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

As seen in Figure 4-2, in the wall with length/height ratio of 1, cracks develop from the top to nearly 0.4 m away from the base and slightly less than 0.8 m from the base in the wall with length/height ratio of 2. It is clear that full height of the wall cracks for length/height ratios of 5 and10.

Moreover, the restraint strain increases from base to 0.2h and start to decrease up to 0.5h where it stays almost constant up to the top of the wall where length/height ratio is 1. Almost the same behavior occurs for length/height ratio of 2 but it is shifted upward whereas, in the walls with length/height ratio of 5 and 10 the restraint strain increases from the base to the top of the structure. Consequently cracks are wider at the top of the wall compared to those near the base of the walls with the length/height ratio of 5 and 10.

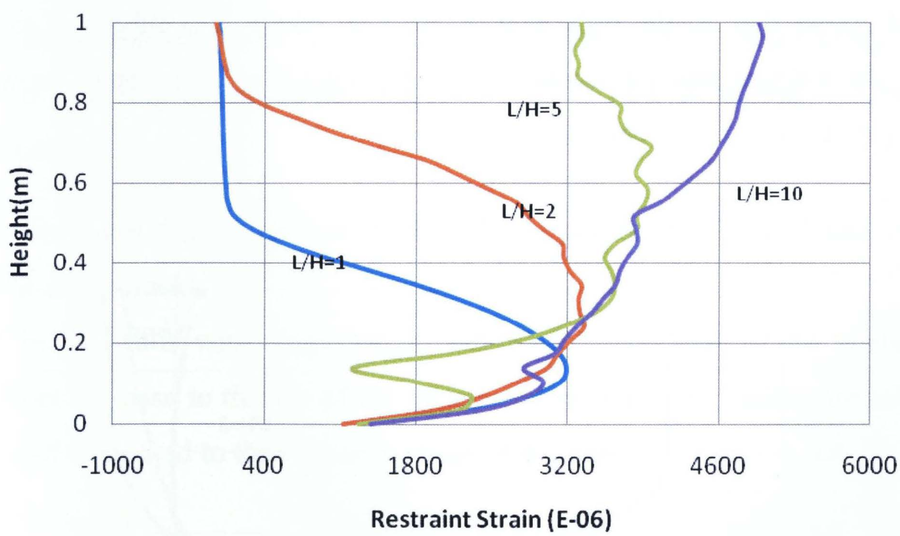


Figure 4-2 Horizontal Restraint Strain for Case A

4.3.2 Horizontal Restraint Strain for Case B

Figure 4-3 and 4-4 shows the horizontal restraint strain in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

Due to unsymmetrical shrinkage variation in the structure, the right and left sides of the wall are not similar.

As seen in Figure 4-3 for the wall with length/height ratio of 1, cracks develop nearly 0.4 m away from the base. It is clear that full height of the wall cracks for length/height ratios of 2, 5 and10.

Moreover, the restraint strain increases from the base to 0.15h and starts to decrease up to 0.55h and stays almost constant up to the top of the wall where length/height ratio is 1. In the walls with length/height ratio of 2, 5 and 10, the restraint strain increases from the base to the top of the structure. Consequently, cracks are wider at the top of the wall compared to those near the base of the walls with the length/height ratios of 2, 5 and 10.

Figure 4-4 shows that on the right side of the wall where it is subjected to minimum shrinkage, the restraint strain is constantly zero from the base to the top of the wall for the length/height ratios of 1, 2, 5 and 10.

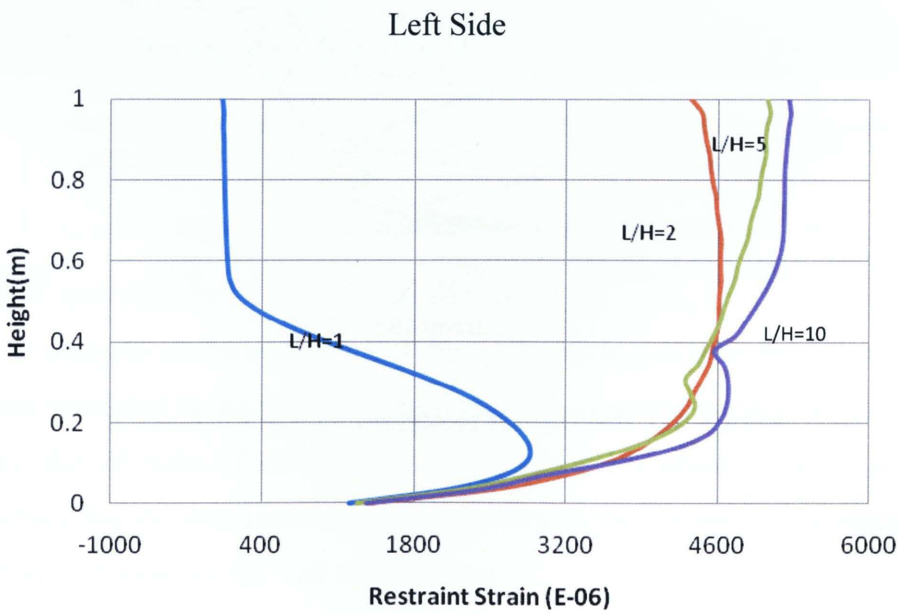


Figure 4-3 Horizontal Restraint Strain for Case B

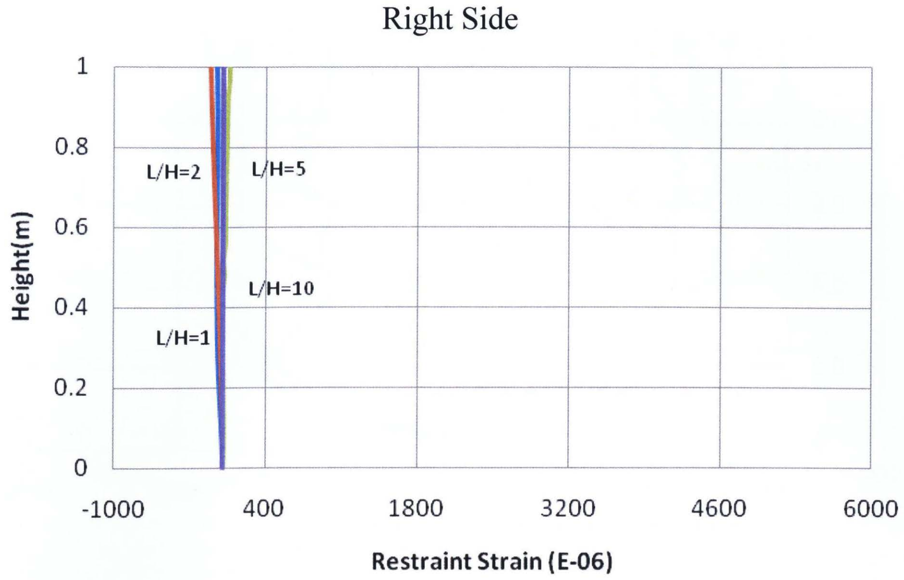


Figure 4-4 Horizontal Restraint Strain for Case B

4.3.3 Horizontal Restraint Strain for Case C

Figure 4-5 shows the horizontal restraint strain in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

Figure 4-5 illustrates that in the wall with length/height ratios of 1, 2, 5 and 10, the full height of the walls cracks.

Moreover, in the walls with length/height ratios of 1, 2, 5 and 10 the restraint strain increases from the base to the top of the structure. Consequently, cracks are wider at the top of the wall compared to those near the base of the wall.

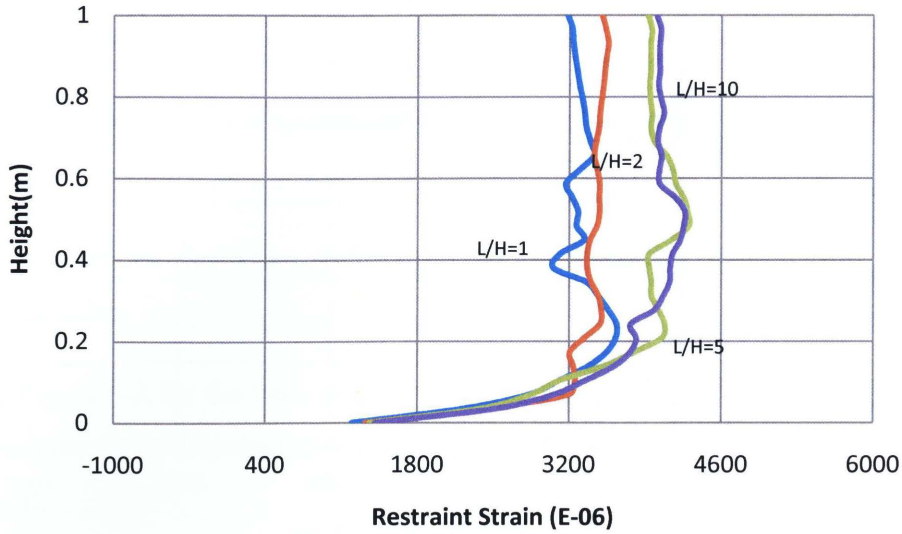


Figure 4-5 Horizontal Restraint Strain Case C

4.3.4 Stress in horizontal Reinforcement for Case A

Figure 4-5 shows the horizontal stress for rebars in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

Figure 4-6 presents in the wall with length/height ratio of 1, reinforcement bars are under tension up to almost 0.4h and rebars go under compression from that point up to the top of the wall. In the wall with length/height ratio of 2, the tensile stress in rebars develop up to nearly 0.77 m of the height from the base, and in the rest of the height, the rebars are under compression. Tensile stress develops over the height of the wall for Height/Length ratios of 5 and10.

As can be seen in the Figure 4-6, the maximum tensile stress happens where Length/Height ratio of the wall is 10, which is almost 280 MPa.

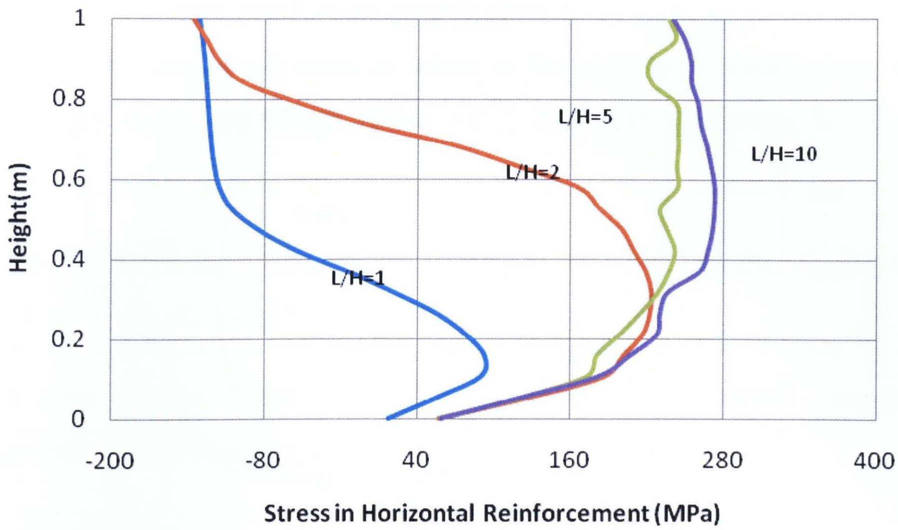


Figure 4-6 Stress in horizontal Reinforcement in Case A

4.3.5 Stress in horizontal reinforcement for Case B

Figure 4-6 and 4-7 shows stress in horizontal reinforcement in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

Due to unsymmetrical shrinkage variation in the structure, the right and left sides of the wall are not similar.

Figure 4-7 shows that in the wall with length/height ratio of 1, reinforcement bars are under tension up to almost 0.35h and rebars go under compression from that point up to the top of the wall. Tensile stress develops over the height of the wall for length/height ratios of 2, 5 and10.

As can be seen in Figure 4-7, the maximum tensile stress happens where length/height ratio of the wall is 10, which is almost 360 MPa.

As seen on Figure 4-8, on the right side of the wall where it is subjected to minimum shrinkage, the stress in the reinforcement barely goes under tension and its magnitude is quite small in the walls with length/height ratio of 1 and 2. Tensile stress develops over the height of the walls with length/height ratio of 5 and10, but the maximum tensile stress occurs where length/height ratio of the wall is 10, which is almost 120 MPa.

Left Side

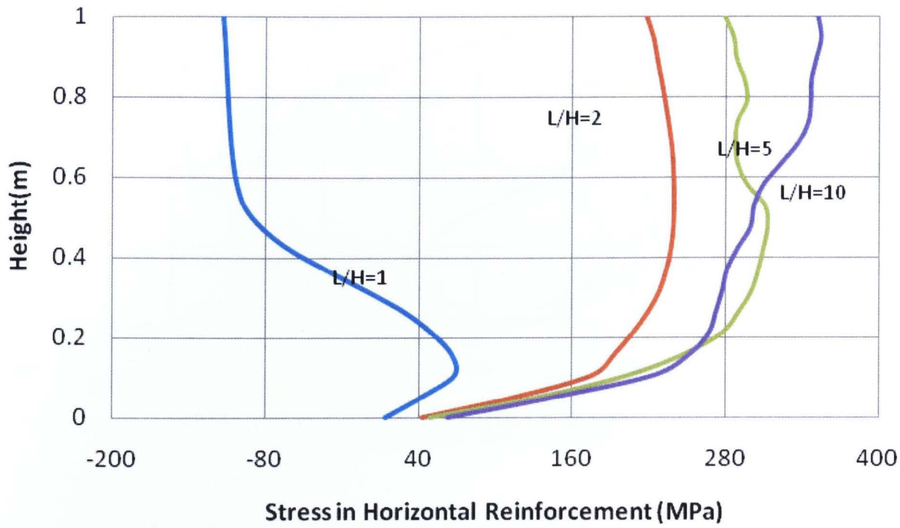


Figure 4-7 Stress in Horizontal Reinforcement for Case B

Right Side

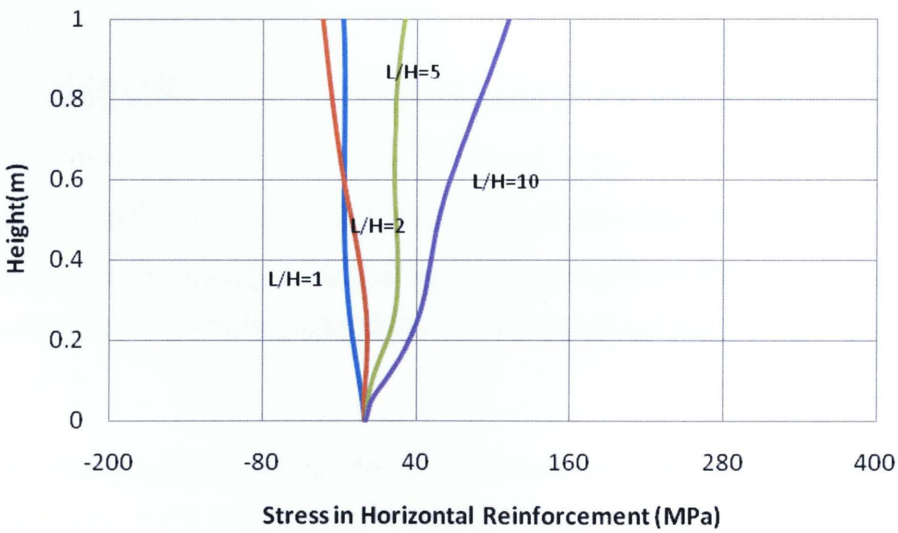


Figure 4-8 Stress in Horizontal Reinforcement for Case B

4.3.6 Stress in horizontal reinforcement for Case C

Figure 4-9 shows the horizontal stress in rebars in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

According to Figure 4-9, tensile stress develops over the height of the walls for length/height ratio of 1, 2, 5 and10.

As can be seen in the Figure 4-9, the maximum tensile stress happens where length/height ratio of the wall is 10, which is almost 185 MPa.

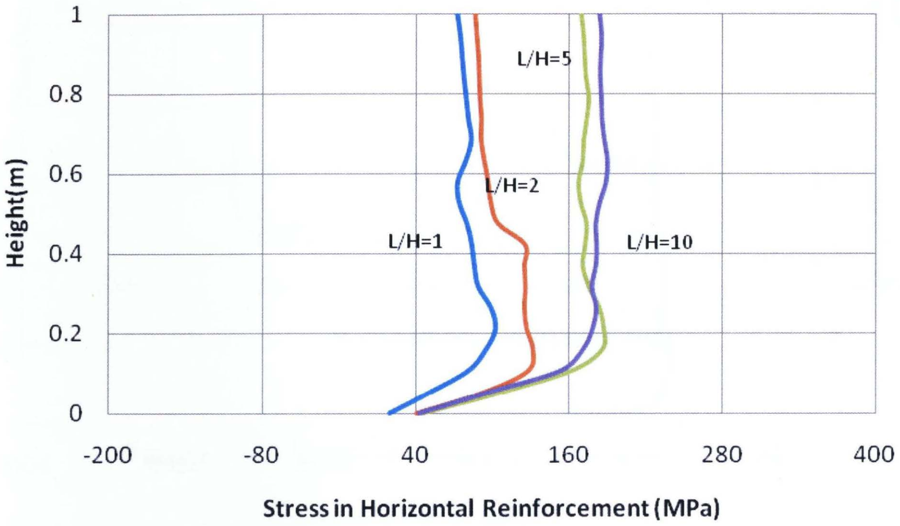


Figure 4-9 Stress in Horizontal Reinforcement for Case C

4.4 Analysis and results in vertical direction

The result of analysis on the centerline of the wall with length over height ratios of 1, 2, 5 and 10 are presented in the following sections. It is expected to have identical result at the right and the left sides off the wall due to symmetrical boundary conditions for Cases A and C, and due to unsymmetrical boundary conditions in Case B, non-similar results at the right and left sides of the wall can be expected.

4.4.1 Vertical Restraint Strain for Case A

Figure 4-9 shows the vertical restraint strain in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

As seen in Figure 4-10, in the walls with the length/height ratio of 1, 2, 5 and 10, cracks only develop slightly above the base and the rest of the wall remains uncracked.

In addition, restraint strain stays almost constant from slightly above the base up to the top of the wall.

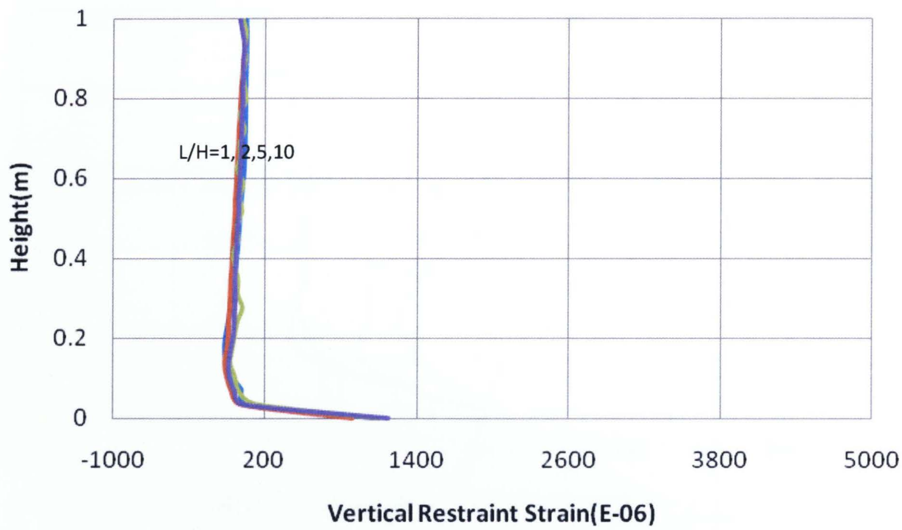


Figure 4-10 Vertical Restraint Strain for Case A

4.4.2 Vertical Restraint Strain for Case B

Figure 4-11 and 4-12 shows the vertical restraint strain in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

As seen in Figure 4-11 and 4-12, in the wall with the length/height ratios of 1, 2, 5 and 10, cracks only develop slightly above the base and the rest of the wall stays uncracked. The only difference in these two figures is that on the left side of the wall, restraint strain at the base is almost 1200(E-06), but this value on the right side of the wall is 400(E-06) for length/height ratio of 10. Furthermore, in the wall with length/height ratios of 1, 2 and 5 is almost 200(E-06).

In addition, restraint strain stays almost constant from slightly above the base up to the top of the wall.

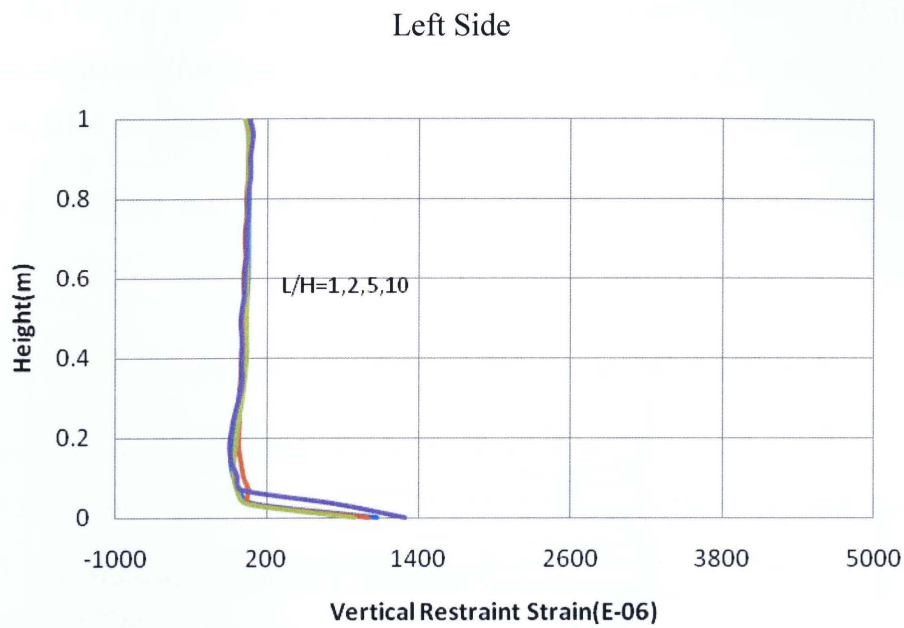


Figure 4-11 Vertical Restraint Strain for Case B

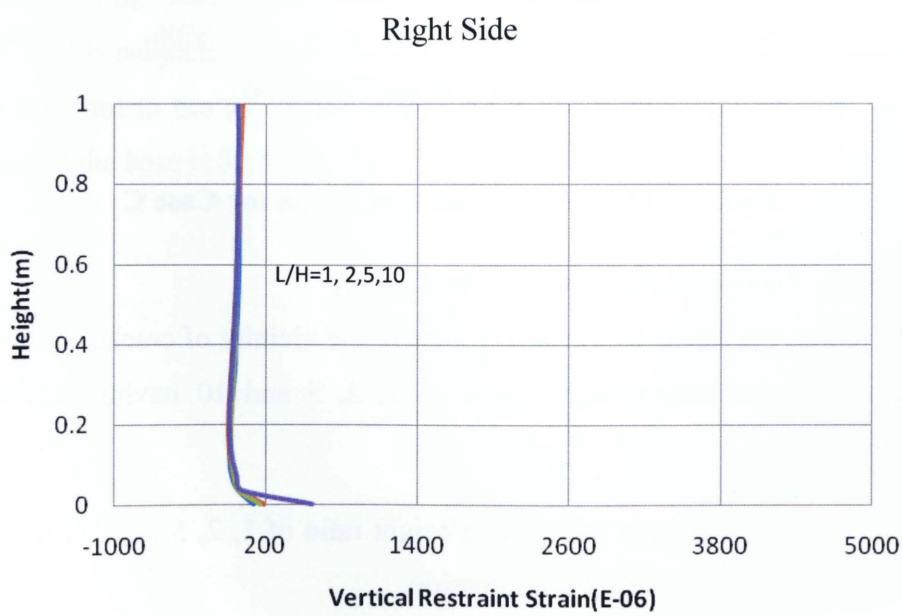


Figure 4-12 Vertical Restraint Strain for Case B

4.4.3 Vertical Restrain Strain for Case C

Figure 4-13 shows the vertical restraint strain in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

As seen in Figure 4-13, cracks develop on and off over the height of the wall with length/height ratios of 1, 2, 5 and 10. For instance, in the wall with length/height ratio of 10, the maximum restraint strain happens at 0.42h and has its minimum value at 0.39h.

Consequently, cracks are wider at 0.42h compared to those near the base or top of the wall.

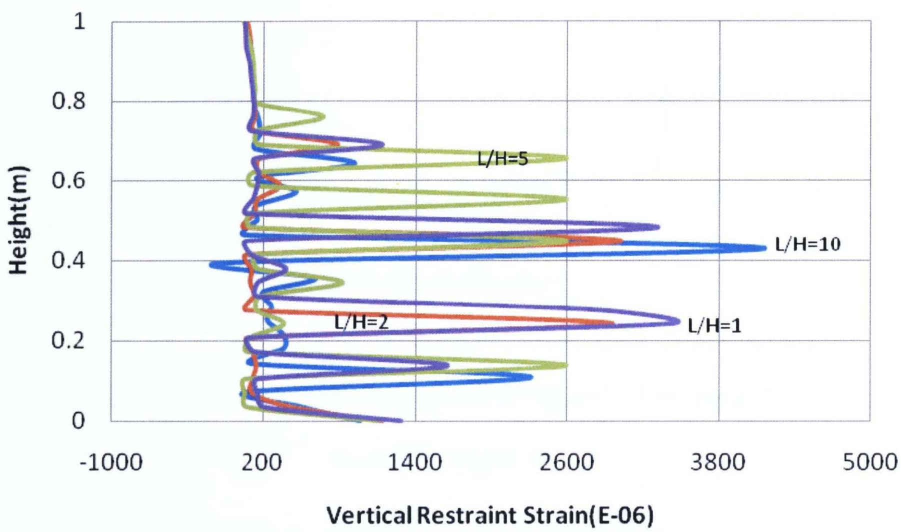


Figure 4-13 Vertical Restraint Strain for Case C

4.4.4 Stress in Vertical Reinforcement for Case A

Figure 4-14 shows the Stress in Vertical Rebars in the vicinity of cracks along the height of the walls with the length/height ratios of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

Figure 4-14 shows in the walls with length/height ratio of 1, 2, 5 and 10, reinforcement over the height of the wall is under compression.

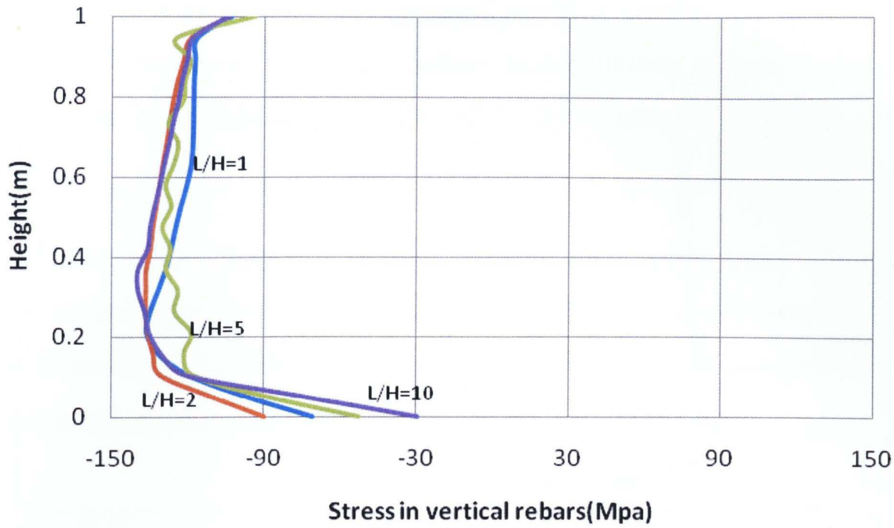


Figure 4-14 Stress in Vertical Reinforcement for Case A

4.4.5 Stress in Vertical Reinforcement for Case B

Figure 4-15 and 4-16 shows the Stress in Vertical Rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

Figure 4-15 shows in the walls with length/height ratio of 1, 2, 5 and 10, reinforcement over the height of the wall is under compression. As can be seen in Figure 4-15, the right side of the wall is subjected to minimum shrinkage; therefore, stresses are almost around zero from the base to the top of the wall, except in length/height ratio of 10 where its tensile stress at the base is 32 MPa.

Left Side

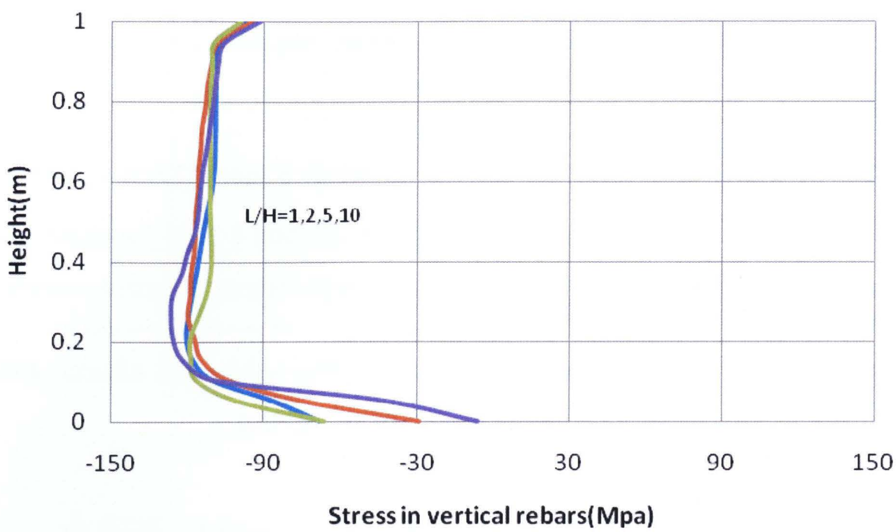


Figure 4-15 Stress in Vertical Reinforcement for Case B

Right Side

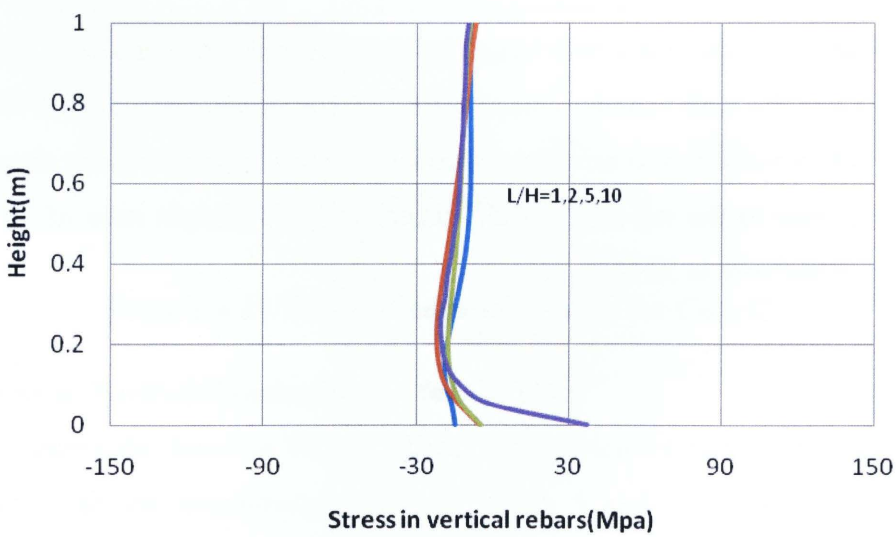


Figure 4-16 Stress in Vertical Reinforcement for Case B

4.4.6 Stress in Vertical Reinforcement for Case C

Figure 4-17 shows the Stress in Vertical Rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.33% uniform reinforcement.

As seen in Figure 4-17, Stress in vertical reinforcement goes under compression and tension in an irregular shape over the height of the walls with length/height ratio of 1, 2, 5 and 10. For instance, in the wall with length/height ratio of 1, the maximum tensile stress takes place at 0.42h and has a maximum compressive stress at 0.95h.

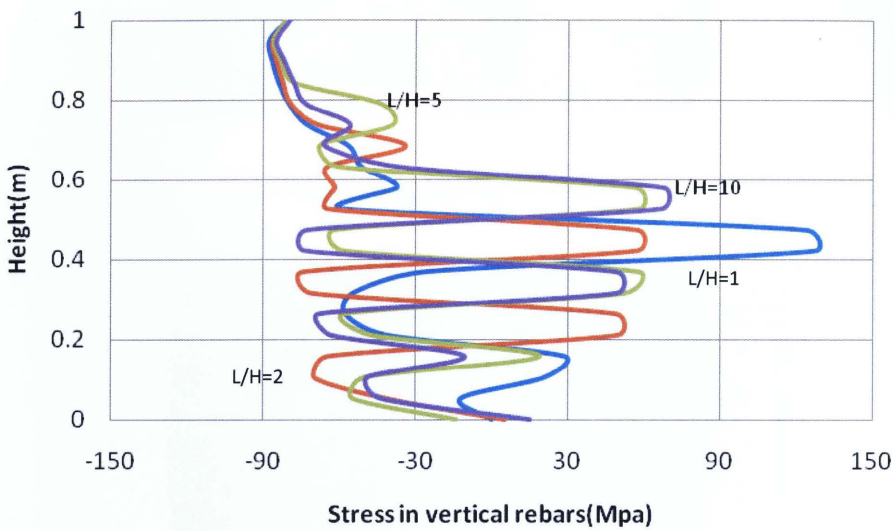


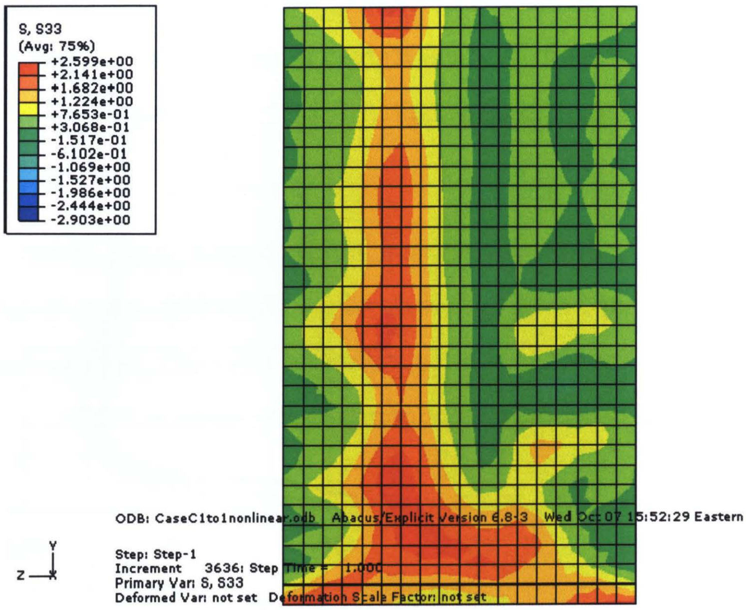
Figure 4-17 Stress in Vertical Reinforcement for Case C

4.4.7 Horizontal Stress in concrete through its thickness

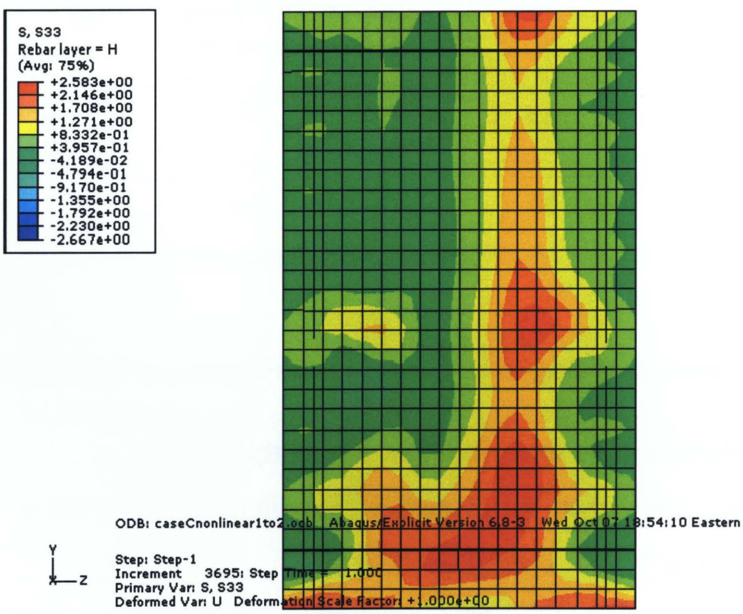
Figure 4-18 shows, stress distribution pattern through thickness of the walls with the length/height ratios of 1, 2, 5, and 10 for Case C.

The cracking failure stress of concrete is equal to 2.7 MPa and, concrete cracks as soon as tensile stress in the concrete exceeds the tensile strength of concrete.

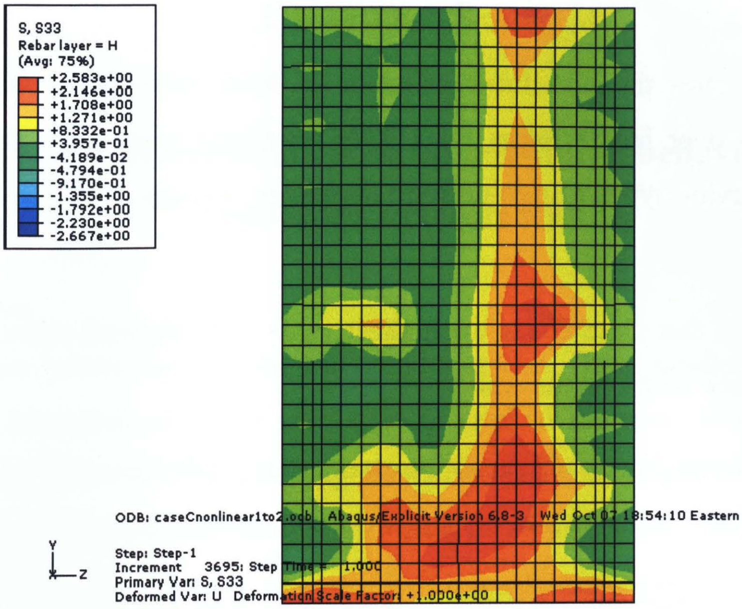
The maximum tensile stress in the wall with length/height ratio of 1, 2, 5 and10 is less than 2.7MPa. Therefore, concrete does not crack in any of these walls.



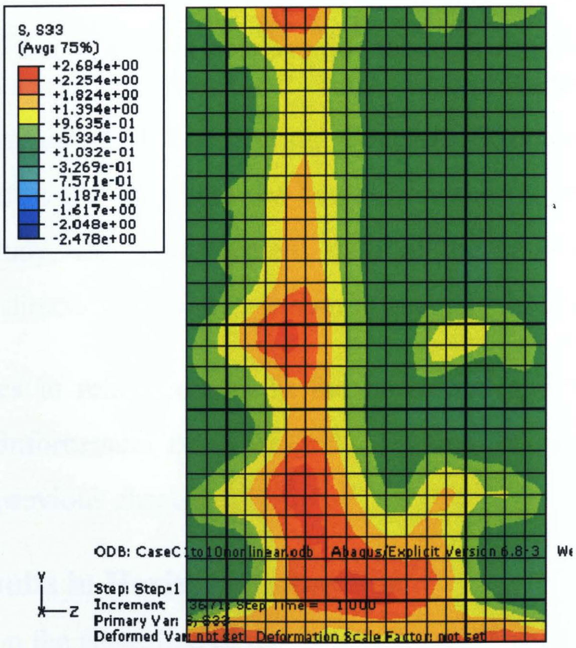
(a) length/height = 1



(b) Length/height=2



(c) length/height=5



(d) length/height=10

Figure 4-18 Stress distribution pattern

4.5 Conclusion

This chapter studies the non-linear behavior of thick reinforced concrete walls with different height over length ratios for a fully restrained base. They were subjected to uniform and varying types of non-uniform shrinkage, as seen in Figure 2-2, 2-3 (a), (b), and (c).

This study shows that Case B has the highest value of Horizontal restraint strain, which causes wider crack width on the wall.

Moreover, maximum horizontal tensile stresses in the reinforcement are observed in Case B while Case C has the lowest horizontal stress compared to the other cases.

Vertical restraint strain graphs verify that the wall does not crack in Cases A and B, whereas in Case C the wall cracks might be a concern.

In addition, maximum vertical tensile stresses in the reinforcements were observed in Case C. The reinforcement was under compression in Case A and B.

CHAPTER 5

5 Influence of reinforcement ratios on non-linear behavior of thick reinforced concrete wall

5.1 Introduction

Reinforcement can induce the formation of smaller cracks. These smaller cracks can aid in delaying the formation of major cracks under applied moment. In case of heavily reinforced concrete, the risk of cracking is much less than experiments with plain concrete suggest (ACI Committee 122, 2002). Furthermore, the presence of reinforcement enables the concrete to make its pre-peak strain capacity operational as cracking is delayed.

In general, concrete standards and codes of practice recommend shrinkage and temperature reinforcement ratio of 0.3% for walls and slabs. The highest value of the shrinkage and temperature reinforcement ratio recommended by the Standard Requirements for Environmental Engineering Concrete Structures, (committe350-06, 2006), is 0.5% for steel grade 60 where the length between movement joints is greater than 12 m. In this study, the reinforcement ratio of the wall is 0.33% in both the horizontal and vertical directions, which is shown in chapters three and four.

In this chapter, stresses in reinforcement in the horizontal and vertical directions are investigated for the reinforcement ratios of 0.5%, 1% and 2%, in additional to 0.33%, which is shown in the previous chapter.

5.2 Analysis and results in Horizontal direction

The result of analysis on the centerline of the wall with length over height ratios of 1, 2, 5 and 10 are presented in the following sections. It is expected to have identical result at the right and the left sides of the wall due to symmetrical boundary conditions for Case A and C, whereas due to unsymmetrical boundary conditions in Case B, non-similar results at the right and left sides of the wall can be expected.

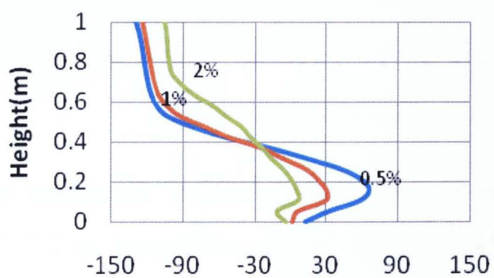
5.2.1 Stress in Horizontal Reinforcement for Case A

Figure 5-1 shows the Stress in horizontal rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10, having 0.5%, 1% and 2% uniform reinforcement ratios.

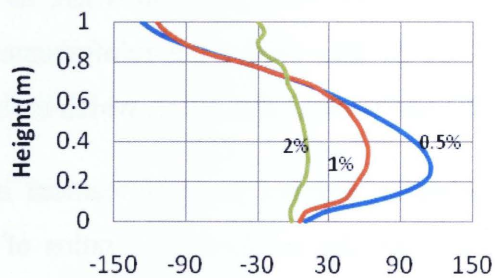
As seen in Figure 5-1 (a), the tensile stress in reinforcement develops up to nearly 0.35h from the base where reinforcement ratio is 0.5% and tensile stress are reduced by increase of reinforcement ratio from 0.5% to 1% and 2%.

According to Figure 5-1 (a), (b), (c), (d), horizontal tensile stress in rebars are reduced by increase of reinforcement ratio. Moreover by increase of length/height ratio of the wall tensile stress are increased as well. For instance, maximum tensile stress in the wall with length/height ratio of 1 and reinforcement ratio of 0.5% is almost 60 MPa; the number for length/height ratio of 10 is nearly 210 MPa.

In addition, in the wall with length/height ratio of 1 maximum tensile stress takes place at 0.2h, whereas in the wall with length/height ratio of 10, maximum tensile stress is at the top of the wall.



Stress in Horizontal Rebars (Mpa)
L/H=1(a)



Stress in Horizontal Rebars (MPa)
L/H=2(b)

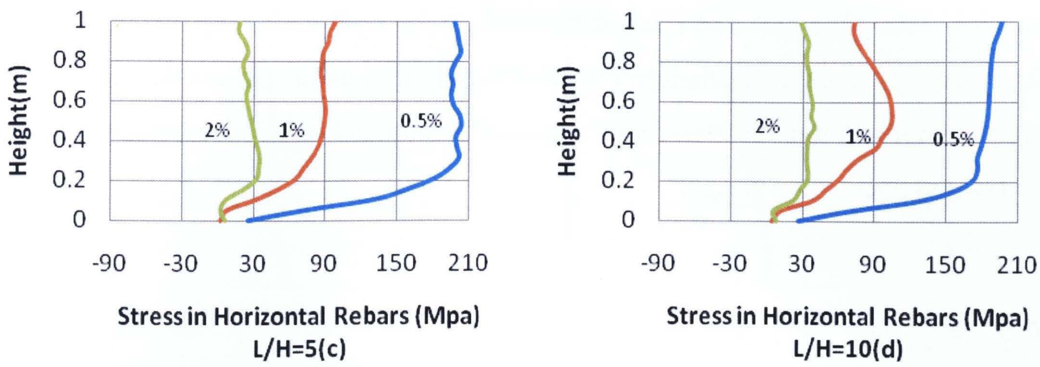


Figure 5-1 Stress in Horizontal Reinforcement for Case A

5.2.2 Stress in Horizontal Reinforcement for Case B

Figures 5-2 and 5-3 show the stress in horizontal rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.5%, 1% and 2% uniform reinforcement ratios.

Due to nonsymmetrical shrinkage variation in the structure, the right and the left sides of the wall are not similar.

As seen in Figure 5-2 (a), the tensile stress in reinforcement develops up to nearly 0.2h from the base where reinforcement ratio is 0.5% and tensile stress are reduced by increase of reinforcement ratio from 0.5% to 1% and 2%.

According to Figure 5-2 (a), (b), (c), (d), horizontal tensile stress in rebars are reduced by increasing the reinforcement ratio. Moreover, by increasing the length/height ratio of the wall, tensile stresses are increased as well. For instance, maximum tensile stress in the wall with length/height ratio of 1 and reinforcement ratio of 0.5% is almost 25 MPa; the number for length/height ratio of 10 is nearly 260 MPa.

In addition, in the wall with length/height ratio of 1, maximum tensile stress takes place at 0.1h, whereas, in the wall with length/height ratio of 10, maximum tensile stress is at the top of the wall.

As seen in Figure 5-3 (a), (b), (c), (d), on the right side of the wall where it is subjected to minimum shrinkage, the stress in reinforcement does not go under tension and increase of reinforcement ratio does not make any difference in the wall with length/height ratios of 1 and 2. In the wall with length/height ratios of 5 and 10, tensile stresses develop over the height of the wall and tensile stresses are reduced by increase of reinforcement ratio from 0.5% to 1% and 2%.

Left Side

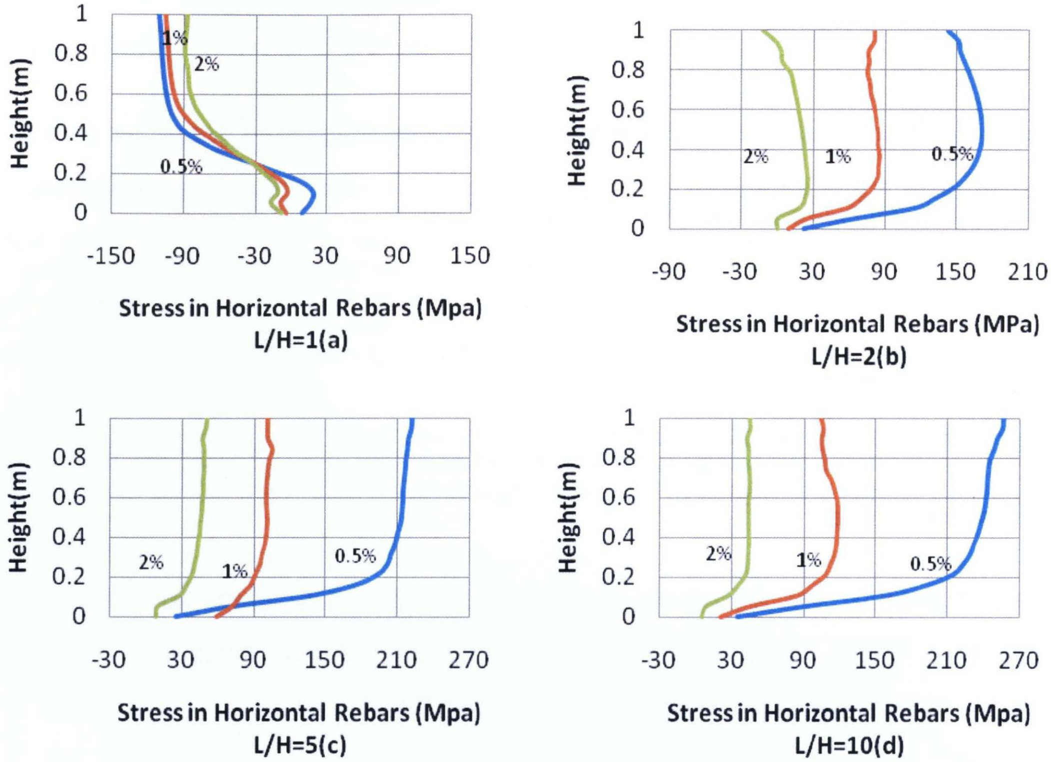


Figure 5-2 Stress in Horizontal Reinforcement for Case B

Right Side

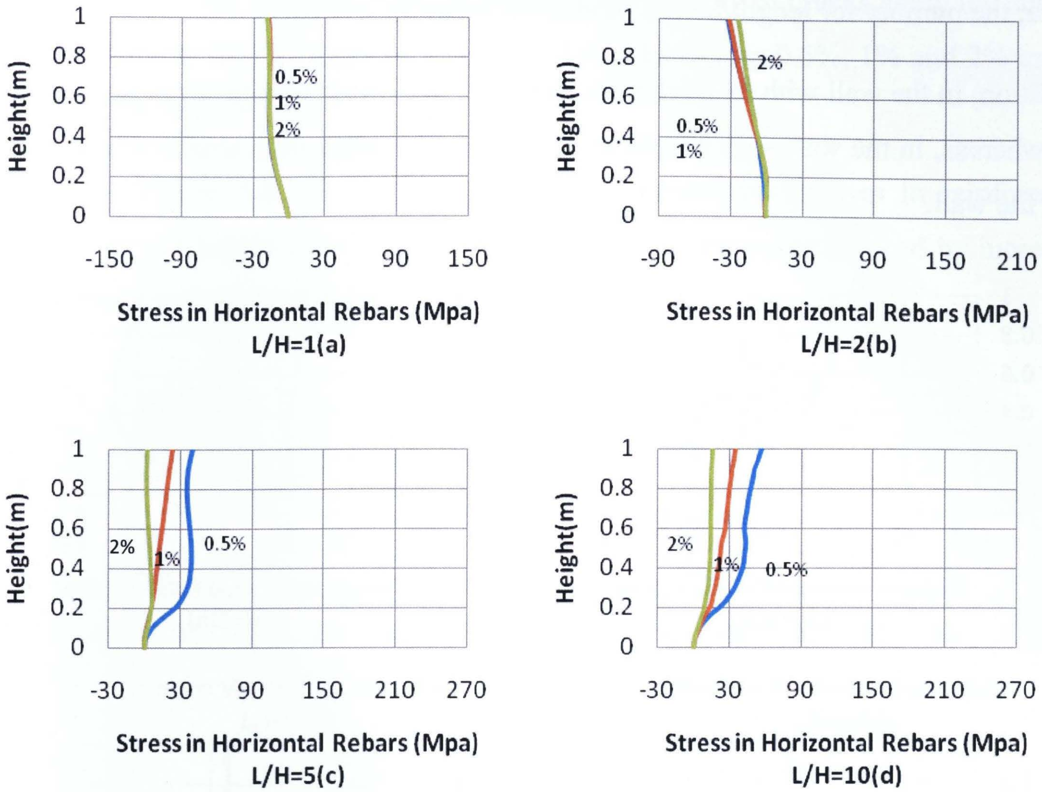


Figure 5-3 Stress in Horizontal Reinforcement for Case B

5.2.3 Stress in Horizontal Reinforcement for Case C

Figure 5-4 shows the Stress in horizontal rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5, and 10 having 0.5%, 1% and 2% uniform reinforcement's ratios.

As seen in Figure 5-4 (a), the tensile stress in reinforcement develops up to nearly 0.2h from the base and tends to go under compression up to 0.6h then goes back to tension up to the top of the wall where reinforcement ratio is 0.5% and tensile stress are reduced by increase of reinforcement ratio from 0.5% to 1% and 2%.

According to Figure 5-4 (a), (b), (c), (d), horizontal tensile stress in rebars are reduced by increasing the reinforcement ratio. Moreover by increasing the length/height ratio of the wall, tensile stresses are increased as well, except in the wall with length/height ratio of 2 which has the maximum tensile stress out of all the other. For instance, maximum tensile stress in the wall with length/height ratio of 1 and reinforcement ratio of 0.5% is almost 40MPa; the number for length/height ratio of 10 is nearly 140 MPa.

In addition, in the wall with length/height ratio of 1 maximum tensile stress takes place at 0.2h, whereas, in the wall with length/height ratio of 10, maximum tensile stress is at the top of the wall.

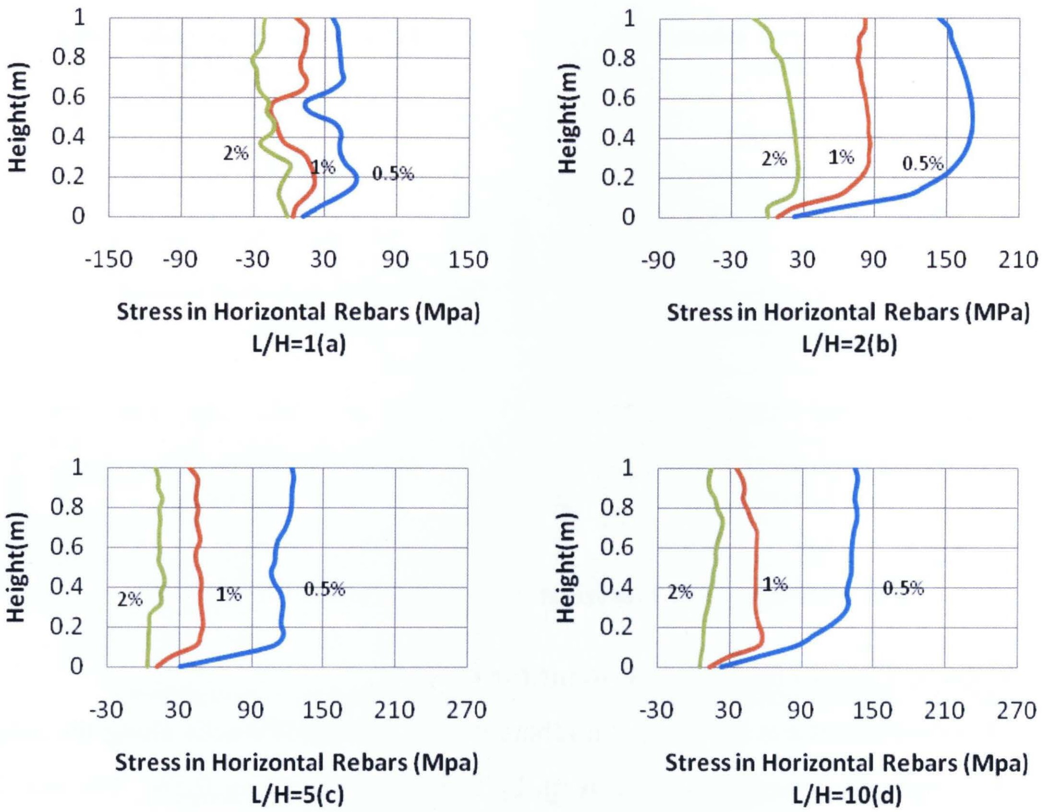


Figure 5-4 Stress in horizontal Reinforcement for Case C

5.3 Analysis and results in Vertical directions

The result of analysis on the centerline of the wall with length over height ratios of 1, 2, 5 and 10 are presented in the following sections. It is expected to have identical result at the right and the left sides of the wall due to symmetrical boundary conditions for Cases A and C, whereas due to unsymmetrical boundary conditions in Case B, non-similar results at the right and left sides of the wall can be expected.

5.3.1 Stress in Vertical Reinforcement for Case A

Figure 5-5 shows the Stress in Vertical rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.5%, 1% and 2% uniform reinforcement's ratios.

As seen in Figure 5-5 (a), (b), (c), (d), only compression stresses in reinforcement develop over the height of the wall and compression stresses are reduced by increase of reinforcement ratio from 0.5% to 1% and 2%.

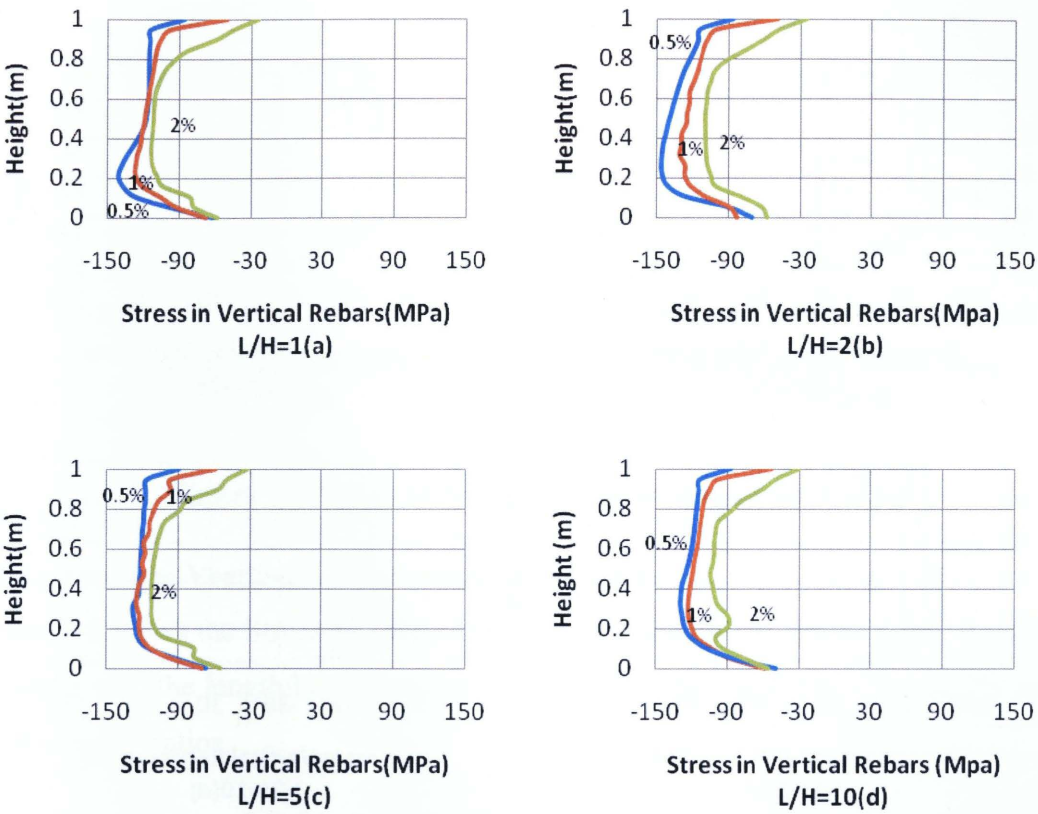


Figure 5-5 Stress in Vertical Reinforcement for Case A

5.3.2 Stress in Vertical Reinforcement for Case B

Figure 5-6 and 5-7 shows the Stress in Vertical rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.5%, 1% and 2% uniform reinforcement ratios.

As seen in Figure 5-6 (a), (b), (c), (d), only compression stresses in reinforcement develop over the height of the wall and compression stresses are reduced by increase of reinforcement ratio from 0.5% to 1% and 2%.

According to Figure 5-7 (a), (b), (c), (d), the right side of the wall is subjected to minimum shrinkage. Therefore, stresses are almost around zero and it is clear that an increase of reinforcement ratio does not make any difference in the walls.

Face Left

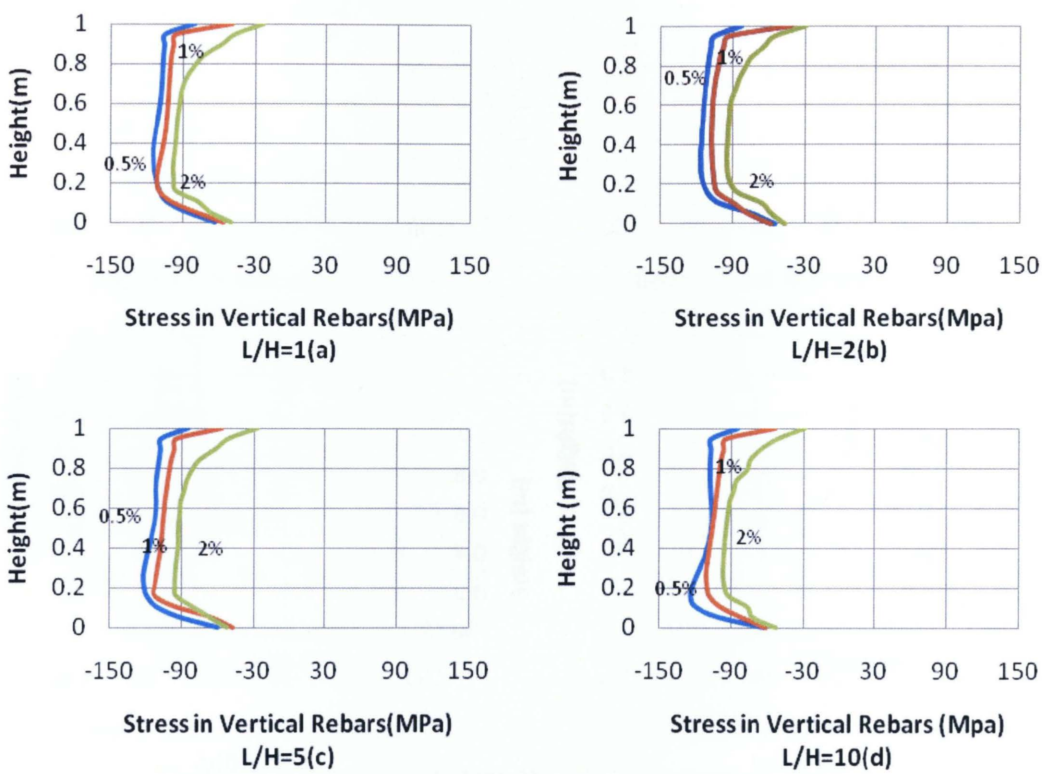


Figure 5-6 Stress in Vertical Reinforcement for Case B

Face Right

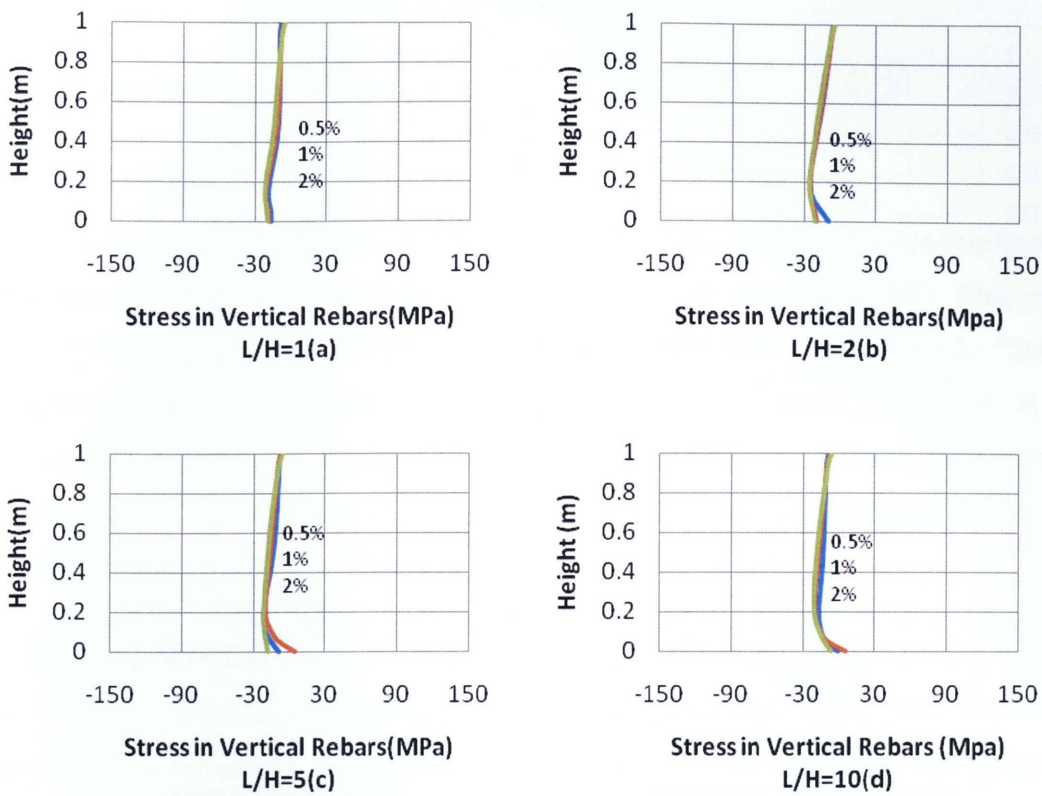


Figure 5-7 Stress in Vertical Reinforcement for Case B

5.3.3 Stress in Vertical Reinforcement for Case C

Figure 5-8 shows the Stress in Vertical rebars in the vicinity of cracks along the height of the walls with the length/height ratio of 1, 2, 5 and 10 having 0.5%, 1% and 2% uniform reinforcement ratios.

According to Figure 5-8 (a), (b), (c), (d), vertical tensile stress in rebars are reduced by increasing the reinforcement ratio. Moreover, stress in vertical reinforcement goes under compression and tension in an irregular shape over the height of the wall. In addition, by increasing the length/height ratio of the wall, tensile stress is increased too. For instance, maximum tensile stress in the wall with length/height ratio of 1 and reinforcement ratio of 0.5% takes place at 0.4h, whereas, in the wall with length/height ratio of 10, tensile stress has its maximum value almost at three places over the height like 0.2h, 0.6h and 0.75h.

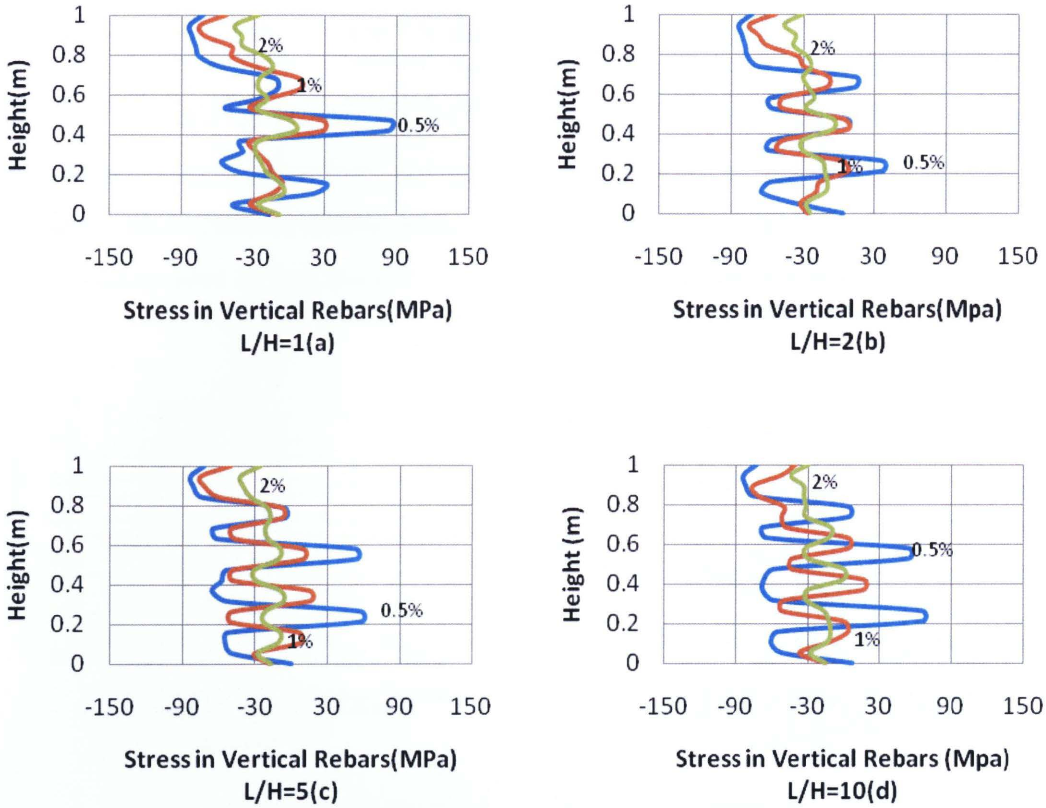


Figure 5-8 Stress in Vertical Rebars for Case C

5.4 Conclusion

This chapter studies non-linear behavior of thick reinforced concrete walls with different length over height ratios and reinforcement ratios.

This study shows that maximum horizontal tensile stress in the reinforcement is observed in case B with 0.5% reinforcement ratio, which is almost 260 (0.65fy) MPa and, it may cause serviceability problems. Serviceability defines the performance criterion for serviceability and corresponds to conditions beyond which specified service requirements resulting from the planned use are no longer met.

Moreover, maximum vertical tensile stress in the reinforcement was observed in Case C having 0.5% ratio, the tensile stress in reinforcement reaches to nearly 90 MPa, which may not cause any problems.

CHAPTER 6

6 Design Criteria

6.1 Introduction

This chapter focuses on design requirements of shrinkage and temperature reinforcement recommended in well-known concrete standards and codes of practice. This chapter refers to the “Design of Concrete Structures”, CSA A23.3-04 (Canada), ”Standard Requirements for Environmental Engineering Concrete Structures”, ACI 350-06 (US), Euro code 2, “Design of concrete structures, General Rules and Rules for Buildings”, EN1992-1-1 (EU), and ”Code of practice for Design of Concrete Structures for Retaining Aqueous Liquids”, BS 8007:1987 (UK).

6.2 CSA A23.3-04

The Canadian Standard on design of Concrete Structures, CSA A23.3-04 (2004), recommends a minimum reinforcement ratio of $\rho=0.002$ for shrinkage and temperature effect in walls and slabs.

Shrinkage and temperature reinforcement shall be provided in each direction and shall not be spaced farther than the smaller of five times the slab thickness or 500 mm.

The code recommends that for exposure conditions where crack control is essential, reinforcement exceeding that required by code shall be provided. However, the required reinforcement calculation is not mentioned.

6.3 ACI 350-06

Standard Requirements for Environmental Engineering Concrete Structures, ACI 350-06 (2006), recommends a minimum reinforcement ratio for shrinkage and temperature effect for members subjected to environmental exposure conditions or required to be liquid-tight. The minimum shrinkage and temperature reinforcement ratio shall be provided according to Table 6.1.

Length between movement joints,m	Minimum shrinkage and temperature reinforcement ratio	
	Grade 40	Grade 60
Less than 6	0.003	0.003
6 to less than 9	0.004	0.003
9 to less than 12	0.005	0.004
12 and greater	0.006	0.005

Table 6-1 Minimum shrinkage and temperature reinforcement ratio

In members without movement joints, the maximum shrinkage and temperature reinforcement indicated in the table shall be provided. This table applies to spacing between expansion joints or full contraction joints. When partial contraction joints are used in a member, the minimum reinforcement ratio shall be determined by multiplying the actual length between partial contraction joints by 1.5.

Concrete sections that are at least 610 mm may have the minimum shrinkage and temperature reinforcement based on a 300 mm concrete layer at each face. At least 1/3 of the required area of shrinkage and temperature reinforcement shall be distributed at any one face. The reinforcement in the bottom of base slabs in contact with soil may be reduced to 50 percent of that required in Table 6.1. Shrinkage and temperature reinforcement shall not be spaced farther apart than 300 mm with the minimum bar size of No. 4.

The minimum shrinkage and temperature reinforcement ratio recommended by the ACI Code is empirical and has been satisfactory where shrinkage and temperature movements are permitted to occur. The code recommends that for members where shrinkage and temperature movements are significantly restrained, it may be necessary to increase the reinforcement ratio. However, it does not mention how to calculate the required reinforcement.

ACI Committee 350 is currently revising the requirements for the shrinkage and temperature reinforcement in members subjected to environmental exposure conditions or required to be liquid-tight. In a proposed draft, the effect of degree of restraint has been included in the design of shrinkage and temperature reinforcement. In this revision, three levels of restraint are considered in a concrete member:

1. Reduced Restraint

2. Normal Restraint

3. Maximum Restraint

Reduced restraint includes membrane slab-on-grade construction with positive means of separation from a smooth and stable sub-grade or mud mat. Reduced restraint also applies to the horizontal reinforcement in walls initially separated from (and without dowels directly into) the footing or base slab.

In a reduced restraint zone, the minimum shrinkage and temperature reinforcement ratio is determined from

$$\rho = 0.005 - \frac{0.002(13-8d_b)}{S-3} \qquad \text{(Eq.6.1)}$$

Where p is the ratio of reinforcement area to gross concrete area, db is the diameter of the bar or steel wire in inches, and s is the spacing of reinforcing bars or wires in inches.

Normal restraint includes conventional slab-on-grade construction (on backfill or gravel). Normal restraint also applies to the horizontal reinforcement in conventional wall, and suspended slab, construction away from the maximum restraint zones for these elements defined below. Normal restraint may always be assumed for movement joint spacing of less than 20 ft.

In a normal restraint zone, the minimum shrinkage and temperature reinforcement ratio is determined from

$$\rho = 0.006 - \frac{0.002(13-8d_b)}{S-3} \qquad \text{(Eq.6.2)}$$

Where p is the ratio of reinforcement area to gross concrete area, db is the diameter of the bar or steel wire in inches, and s is the spacing of reinforcing bars or wires in inches.

Maximum restraint includes the first six feet above a horizontal construction joint, and the first six feet adjacent to a vertical construction joint (on the subsequently placed side of the joint). When suspended slabs are doweled into walls, the shrinkage and temperature reinforcement parallel to the wall shall be based on the maximum restraint ratio for the first half-bay, or 10 ft of the slab, whichever is larger. Other portions of the slabs may be considered as a normal restraint zone.

In a maximum restraint zone, the minimum shrinkage and temperature reinforcement ratio is determined from

$$\rho=0.010 - \frac{0.002(13-8d_b)}{S-3} \qquad \text{(Eq.6.3)}$$

Where p is the ratio of reinforcement area to gross concrete area, db is the diameter of the bar or steel wire in inches, and s is the spacing of reinforcing bars or wires in inches.

Shrinkage and temperature reinforcement shall not be spaced farther apart than 12 in and the minimum size of reinforcing bars shall be No.4. At least 1/3 of the total required reinforcement area shall be distributed at any one face.

The proposed revision specifies absolute values to identify different levels of restraint within a concrete member. Instead, it is suggested that the length/height ratio of an element be specified. As indicated in the ACI Committee Report 207.2R, the variation of restraint factor is dependent on the length/height ratio not the length of the member alone. This study also shows that the length/height ratio has considerable effects on the crack patterns and tensile stresses in the reinforcement of a concrete member.

6.4 EN 1992-1-1

Eurocode 2 (1992), Design of Concrete Structures, General Rules and Rules for Buildings, recommends a minimum reinforcement ratio for shrinkage and temperature effect in walls and slabs as in Equation 6.5.

$$\rho= K_c K \frac{f_{ct,eff}}{\sigma_s} \qquad \text{(Eq.6.4)}$$

where ρ is the ratio of reinforcement area to gross concrete area.

k_c is a coefficient taking account of the form of the loading.

K is a coefficient taking account of the possible presence of non-linear stress distributions.

$f_{ct,eff}$ is the mean value of the tensile strength of the concrete effective at the time when the first crack forms.

σ_s is the steel stress.

The code offers a table to determine the value of $f_{ct,eff}$. The stress in steel can generally be taken as the specified yield strength of the steel. However, there are cases where it may be more convenient to use lower values.

The value of k_c is 1.0 and 0.4 for pure tension and pure flexure in rectangular reinforced concrete sections, respectively. The value of k_c can be reduced if there is a compressive force applied to the section and similarly can be increased where there is applied tension.

The factor k includes the effect of internal self-equilibrating stresses. In cases where concrete is restrained, the deformation of the surface concrete is restrained by the interior concrete and higher tensions will be developed near the surface. In the design of shrinkage and temperature reinforcement, k should be taken as 1.0 and 0.65 for members less than 300 mm deep and greater than 800 mm deep, respectively. The intermediate values may be interpolated.

6.5 BS 8007:1987

Code of Practice for Design of Concrete Structures for Retaining Aqueous Liquids, BS 8007:1987, adopts three options for the design of shrinkage and temperature reinforcement. The code applies provisions for movement joints and their spacing to allow or restrain shrinkage and thermal contractions in walls and slabs, and accordingly recommends the amount of reinforcement to control crack widths and crack spacing.

The three main options for the design of shrinkage and temperature reinforcement are as follows:

1. Design for full restraint

In this case, no movement joints are provided within the wall or slab, and crack widths and crack spacing are controlled by providing substantial amount of reinforcement in the form of small diameter bars at close spacing. The code recommends a minimum reinforcement ratio as:

ρ = 0.0064 for steel grade 250

ρ = 0.0035 for steel grade 460 (Eq.6.5)

Where ρ is the ratio of reinforcement area to gross concrete area.

2. Design for partial restraint

In this case, crack widths and crack spacing are controlled by providing movement joints and reinforcement. The movement joint spacing is such that some of the daily and seasonal movements in the mature wall or slab are accommodated at the joints. Therefore, the amount of movement to be accommodated at cracks is reduced. In the case of complete movement joint and partial movement joint, the joint spacing shall be less than 15 m and 7.5 m, respectively. Again, the code recommends a minimum reinforcement ratio as in Equation 6.5.

3. Design for freedom of movement

In this case, closely spaced movement joints are provided within the wall or slab in conjunction with a moderate proportion of reinforcement. The reinforcement should be sufficient to transmit movement at any cracked section to the adjacent movement joints and significant cracking between movement joints should not occur. The code recommends a minimum reinforcement ratio as:

ρ = 0.0043for steel grade 250

ρ = 0.0023 for steel grade 460 (Eq.6.6)

Where ρ is the ratio of reinforcement area to gross concrete area.

6.6 Comparison of codes versus this study

The Canadian Standard and Design of concrete Structures recommends a minimum reinforcement ratio of 0.2%, as can be seen in Eq.6.1. Moreover, American Concrete Institute (ACI) recommends a minimum reinforcement ratio of 0.3%. This chapter compares the most critical cases from this study in horizontal and vertical directions those recommended by ACI. The critical cases are the left side of the wall for Case B in horizontal direction and, Case C in vertical direction.

As can be seen in Figure 6.1, ACI graph has more dramatic increase of tensile stress over the height of the walls. For instance, in the wall with length/height ratio of 10, ACI tensile stress is almost 1.7 times more than the wall with 0.5% of reinforcement.

This study shows that a structure provided with adequate tensile reinforcement based on uniform shrinkage distribution may result in severe cracking, or pose further structural problems. For instance, the wall provided with a 0.33% reinforcement ratio and subjected to non-uniform shrinkage develops 30% (1.3 times) more tensile stresses than the second wall, which has the same reinforcement ratio (0.33%), but is subjected to uniform shrinkage. This shows tensile stresses that develop in rebars are more of a concern within the wall subjected to non-uniform shrinkage. Furthermore, a non-uniform shrinkage distribution causes additional restraint strains and vertical stresses to develop, as exhibited by the wall. Therefore, the results of this study illustrate the minimum reinforcement ratio of 0.3% recommended by the ACI may cause serviceability problems.

Figure 6.2 shows ACI graph goes under more tensile stress over the height of the walls compare to the walls with 0.5%, 1%, and 2% of reinforcement ratios

Left side

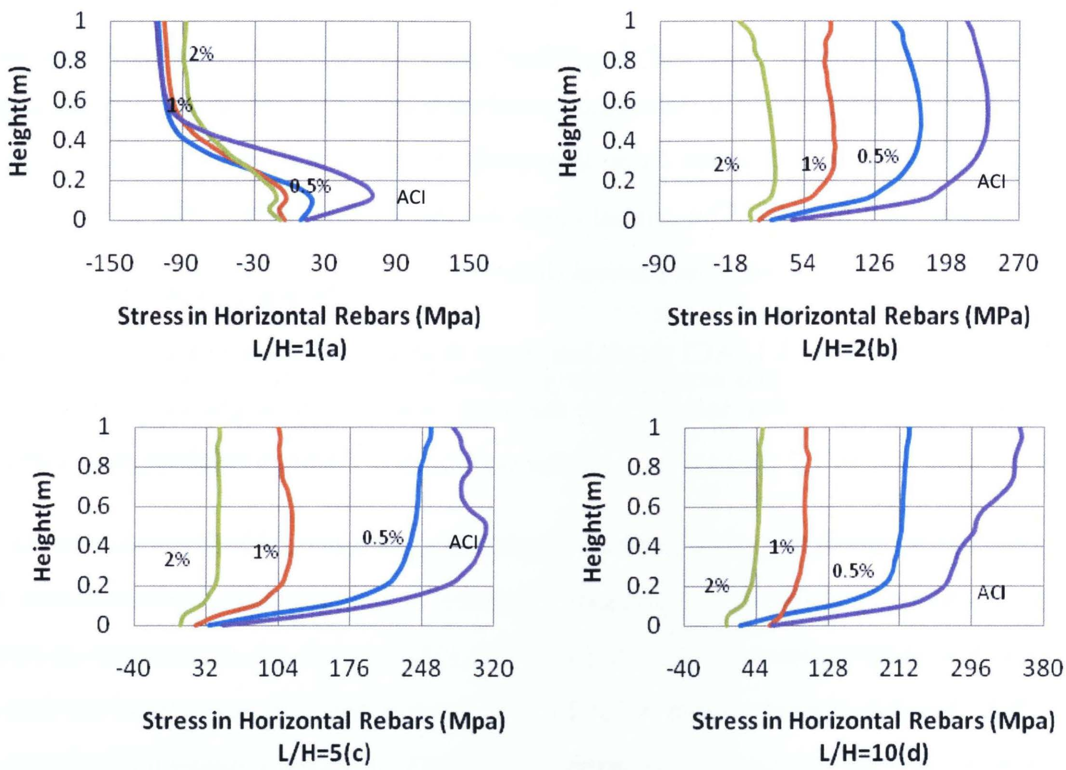


Figure 6-1 Stress in Horizontal Reinforcement for Case B

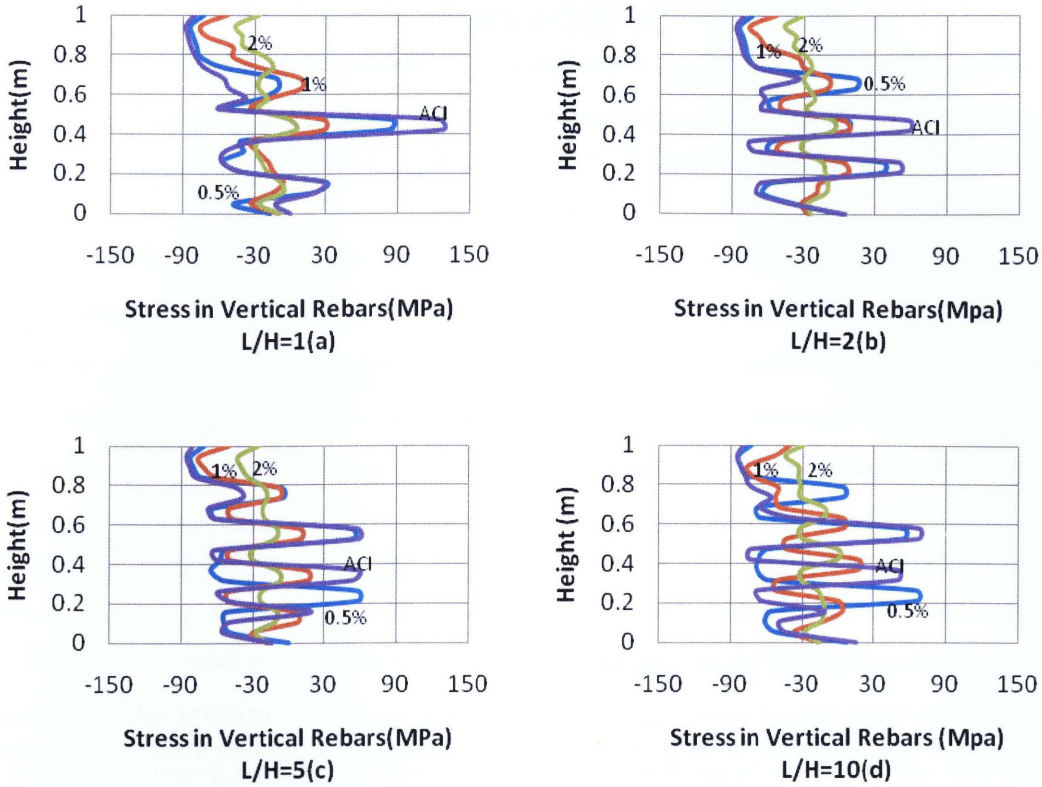


Figure 6-2 Stress in Vertical Reinforcement for Case C

CHAPTER 7

7 Summary, Conclusion and Future Work

7.1 Summary

Unless kept under water or in air at 100 % relative humidity, concrete loses moisture with time and decreases in volume, a process known as shrinkage. The amount shrinkage depends upon the composition of the concrete, thickness and boundary condition of the structure. Therefore, three cases are studied in this thesis as follows.

Case A, where the structure is subjected to uniform shrinkage (Uniform). This case is applicable for thin reinforced concrete structures like reinforced concrete domes, reinforced concrete barrels, vaults and so on.

Case B, where the structure is subjected to non-uniform shrinkage in a way that it starts from $\varepsilon_{min}= 0$ from the right side of the wall and increases to $\varepsilon_{shrinkage}$ as it reaches the other face of the wall (Triangular). This type of non-uniformity occurs where the structure is in contact with water or in air at 100% relative humidity from one side and much less humidity from the other side. An example of this case is a water tank reinforced concrete structure.

Case C, where the structure is subjected to non-uniform shrinkage, the wall is divided into three partitions through its thickness. Within the inner partition the shrinkage is constantly zero, but for the two other partitions the shrinkage varies linearly from $\varepsilon_{shrinkage}$ and decreases to $\varepsilon_{min}= 0$ as it reaches the adjacent portion of the inner partition (Double Triangular). Another type of non-uniform shrinkage distribution is for very thick structures such as dams and nuclear power plants where the outer side of the structure is subjected to maximum shrinkage and starts decreasing as it goes to the middle of the structure.

These parameters are applied for the reinforced concrete walls with different length/height ratios using linear and non-linear finite element method to simulate the cracking behavior of the concrete.

Concrete cracks when tensile stress reaches tensile strength of the concrete. If structure is not provided with adequate tensile reinforcement it could crack severely or pose other structure problems. Therefore, this study also investigates the influence of reinforcement ratio for the thick reinforced concrete wall.

7.2 Concluding Remarks

Based on the results of this analytical study, the following conclusions were made.

1. In the linear uncracked analysis:

i) The degree of restraint in Cases A and B considerably change from the base to the top of the wall with the length over height ratio of 1 and 2; but in Case C, even for a height to length ratio of one, it does not change dramatically over the height.

ii) The reinforcement is under compression for height over length ratios of 1, 2 and 5, but is neither under tension nor compression for the height over length ratio of 10 and 20. It is worth mentioning that in real structures, due to cracking of concrete, the reinforcement is under tension at crack locations and under compression between cracks, which was not seen in uncracked linear analysis.

2. In fixed base non-linear cracked concrete walls by providing 0.3% reinforcement ratio, it was found that:

i) Case B has the highest value of horizontal restraint strain compared to Cases A and C.

ii) Maximum horizontal tensile stress in Case A happens where length/height ratio of the wall is 10, which is almost 280 ($0.7f_y$) MPa. It reaches 360 ($0.9f_y$) MPa in Case B and 185 ($0.46\ f_y$) MPa in Case C.

iii) Vertical restraint strain verifies that walls do not crack in Case A and B but it cracks in Case C.

iv) Vertical tensile stresses are only observed in Case C, whereas Case A and B are under compression over the height of the walls.

3. In non-linear analysis of reinforced concrete walls by providing 0.5% reinforcement ratio and applying $600X10^{-6}$ mm/mm shrinkage strain, it was found that:

i) Case A shows that, cracks develop from base to 0.35h and 0.7h in the walls with length/height ratio of 1 and 2, whereas in the walls with Length/Height ratio of 5 and 10, full height cracks were observed.

ii) Case B shows that on the left side of the wall cracks develop to 0.2 h in the wall with Length/Height ratio of 1, whereas in the walls with length/height ratio of 2, 5 and 10, full height cracks were observed. However, on the right side of the wall no cracks appear in the walls with length/height ratio of 1 and 2. In the walls with length/height ratio of 5 and 10, full height cracks appears.

iii) Case B shows that on the left side of the wall in the walls with length/height ratio of 1, 2, 5 and 10, full height cracks were observed.

iv) Vertical tensile stress happens in Case C having 0.5% and 1% reinforcement ratios, whereas in Case A and B, concrete does not crack over the height of the walls.

7.3 Future work

Based on the results of this analytical study, further studies can be carried out as follows.

1. In this study, drying shrinkage of concrete was taken in to account whereas other factors should be considered, such as heat of hydration and creep.
2. Shrinkage is a time dependent phenomenon but has been assumed to be time independent in this study.
3. Restraint strain of reinforced concrete not only comes from drying shrinkage but is also due to autogenous shrinkage, which is not included in this study.

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Appendix:

A. Input data for non- Linear analysis of thick reinforced concrete wall with L/H=1

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 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288
 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304
*Elset, elset=_PickedSet10, internal, instance=Part-1-1, generate
 5401, 10800,     1
*Nset, nset=_PickedSet12, internal, instance=Part-1-1
  1,  2,  3,  4,  5,  6,  7,  8,  17,  18,  19,  20,  21,  22,  23,  24
 25,  26,  27,  28,  29,  30,  31,  32,  33,  34,  35,  36,  37,  38,  39,  40
 41,  42,  43,  44,  45,  46,  47,  48,  49,  50,  51,  52,  53,  54,  55,  56
 57,  58,  59,  60,  61,  62,  63,  64,  65,  66,  67,  68,  69,  70,  71,  72
 73,  74,  75,  76,  77,  78,  79,  80,  81,  82,  83,  84,  85,  86,  87,  88
 89,  90,  91,  92,  93,  94,  95,  96,  97,  98,  99, 100, 101, 102, 103, 104
105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120
121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136
137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152

*Elset, elset=_PickedSet12, internal, instance=Part-1-1, generate
```

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  1, 5400,    1
*Nset, nset=_PickedSet17, internal, instance=Part-2-1, generate
  1, 441,   1
*Elset, elset=_PickedSet17, internal, instance=Part-2-1, generate
  1, 400,   1
*Nset, nset=_PickedSet18, internal, instance=Part-1-1
   3,    4,    6,    7,   13,   14,   15,   16,   51,   52,   53,   54,   55,   56,   57,   58
  59,   60,   61,   62,   63,   64,   65,   66,   67,   68,   69,   70,   71,   72,   73,   74
  75,   76,   77,   78,   79,  119,  120,  121,  122,  123,  124,  125,  126,  127,  128,  129
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 146,  147,  153,  154,  155,  156,  157,  158,  159,  160,  161,  162,  163,  164,  165,  166
 167,  168,  169,  170,  171,  172,  173,  174,  175,  176,  177,  178,  179,  180,  181,  211
 212,  213,  214,  215,  216,  217,  218,  219,  220,  221,  222,  223,  224,  225,  226,  227
 228,  229,  230,  231,  232,  233,  234,  235,  236,  237,  238,  239,  405,  406,  407,  408
 409,  410,  411,  412,  413,  414,  415,  416,  417,  418,  419,  420,  421,  422,  423,  424
*Elset, elset=_PickedSet18, internal, instance=Part-1-1, generate
 10801, 16200,    1
*Nset, nset=_PickedSet19, internal, instance=Part-2-2, generate
  1, 441,   1
*Elset, elset=_PickedSet19, internal, instance=Part-2-2, generate
  1, 400,   1
*Nset, nset=_PickedSet20, internal, instance=Part-1-1
   1,    2,    5,    8,    9,   10,   11,   12,   17,   18,   19,   20,   21,   22,   23,   24
  25,   26,   27,   28,   29,   30,   31,   32,   33,   34,   35,   36,   37,   38,   39,   40
  41,   42,   43,   44,   45,   85,   86,   87,   88,   89,   90,   91,   92,   93,   94,   95
  96,   97,   98,   99,  100,  101,  102,  103,  104,  105,  106,  107,  108,  109,  110,  111
 112,  113,  182,  183,  184,  185,  186,  187,  188,  189,  190,  191,  192,  193,  194,  195
 196,  197,  198,  199,  200,  201,  202,  203,  204,  205,  206,  207,  208,  209,  210,  240
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 273,  274,  275,  276,  277,  278,  279,  280,  281,  282,  283,  284,  285,  286,  287,  288
 289,  290,  291,  292,  293,  294,  295,  296,  297,  298,  299,  300,  301,  302,  303,  304
 305,  306,  307,  308,  309,  310,  311,  312,  313,  314,  315,  316,  317,  318,  319,  320
*Elset, elset=_PickedSet20, internal, instance=Part-1-1, generate
 5401, 10800,    1
*Nset, nset=_PickedSet24, internal, instance=Part-1-1
   1,    2,    5,    8,    9,   10,   11,   12,   17,   18,   19,   20,   21,   22,   23,   24
```

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 25,  26,  27,  28,  29,  30,  31,  32,  33,  34,  35,  36,  37,  38,  39,  40
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 96,  97,  98,  99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111
112, 113, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195
196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 240
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257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272
273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288
*Elset, elset=_PickedSet24, internal, instance=Part-1-1, generate
 5401, 10800,     1
*Nset, nset=_PickedSet25, internal, instance=Part-1-1
   1,   2,   5,   8,   9,  10,  11,  12,  17,  18,  19,  20,  21,  22,  23,  24
  25,  26,  27,  28,  29,  30,  31,  32,  33,  34,  35,  36,  37,  38,  39,  40
  41,  42,  43,  44,  45,  85,  86,  87,  88,  89,  90,  91,  92,  93,  94,  95
  96,  97,  98,  99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111
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 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 240
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 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288
 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304
*Elset, elset=_PickedSet25, internal, instance=Part-1-1, generate
 5401, 10800,     1
*Nset, nset=_PickedSet26, internal, instance=Part-1-1
   1,   2,   3,   4,   5,   6,   7,   8,  17,  18,  19,  20,  21,  22,  23,  24
  25,  26,  27,  28,  29,  30,  31,  32,  33,  34,  35,  36,  37,  38,  39,  40
  41,  42,  43,  44,  45,  46,  47,  48,  49,  50,  51,  52,  53,  54,  55,  56
  57,  58,  59,  60,  61,  62,  63,  64,  65,  66,  67,  68,  69,  70,  71,  72
  73,  74,  75,  76,  77,  78,  79,  80,  81,  82,  83,  84,  85,  86,  87,  88
  89,  90,  91,  92,  93,  94,  95,  96,  97,  98,  99, 100, 101, 102, 103, 104
 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120
 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136
 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152
 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168

*Elset, elset=_PickedSet26, internal, instance=Part-1-1, generate
   1,  5400,     1
```

```
*Nset, nset=_PickedSet27, internal, instance=Part-1-1
  1,   2,   3,   4,   5,   6,   7,   8,  17,  18,  19,  20,  21,  22,  23,  24
 25,  26,  27,  28,  29,  30,  31,  32,  33,  34,  35,  36,  37,  38,  39,  40
 41,  42,  43,  44,  45,  46,  47,  48,  49,  50,  51,  52,  53,  54,  55,  56
 57,  58,  59,  60,  61,  62,  63,  64,  65,  66,  67,  68,  69,  70,  71,  72
 73,  74,  75,  76,  77,  78,  79,  80,  81,  82,  83,  84,  85,  86,  87,  88
 89,  90,  91,  92,  93,  94,  95,  96,  97,  98,  99, 100, 101, 102, 103, 104
105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120
*Elset, elset=_PickedSet27, internal, instance=Part-1-1, generate
  1, 5400,    1
*Nset, nset=_PickedSet28, internal, instance=Part-1-1
   3,    4,    6,    7,   13,   14,   15,   16,   51,   52,   53,   54,   55,   56,   57,   58
  59,   60,   61,   62,   63,   64,   65,   66,   67,   68,   69,   70,   71,   72,   73,   74
  75,   76,   77,   78,   79,  119,  120,  121,  122,  123,  124,  125,  126,  127,  128,  129
 130,  131,  132,  133,  134,  135,  136,  137,  138,  139,  140,  141,  142,  143,  144,  145
 146,  147,  153,  154,  155,  156,  157,  158,  159,  160,  161,  162,  163,  164,  165,  166
 167,  168,  169,  170,  171,  172,  173,  174,  175,  176,  177,  178,  179,  180,  181,  211
 212,  213,  214,  215,  216,  217,  218,  219,  220,  221,  222,  223,  224,  225,  226,  227
 228,  229,  230,  231,  232,  233,  234,  235,  236,  237,  238,  239,  405,  406,  407,  408
*Elset, elset=_PickedSet28, internal, instance=Part-1-1, generate
 10801, 16200,     1
*Nset, nset=_PickedSet29, internal, instance=Part-1-1
   3,    4,    6,    7,   13,   14,   15,   16,   51,   52,   53,   54,   55,   56,   57,   58
  59,   60,   61,   62,   63,   64,   65,   66,   67,   68,   69,   70,   71,   72,   73,   74
  75,   76,   77,   78,   79,  119,  120,  121,  122,  123,  124,  125,  126,  127,  128,  129
 130,  131,  132,  133,  134,  135,  136,  137,  138,  139,  140,  141,  142,  143,  144,  145
 146,  147,  153,  154,  155,  156,  157,  158,  159,  160,  161,  162,  163,  164,  165,  166
 167,  168,  169,  170,  171,  172,  173,  174,  175,  176,  177,  178,  179,  180,  181,  211
 212,  213,  214,  215,  216,  217,  218,  219,  220,  221,  222,  223,  224,  225,  226,  227
 228,  229,  230,  231,  232,  233,  234,  235,  236,  237,  238,  239,  405,  406,  407,  408
 409,  410,  411,  412,  413,  414,  415,  416,  417,  418,  419,  420,  421,  422,  423,  424
*Elset, elset=_PickedSet29, internal, instance=Part-1-1, generate
 10801, 16200,     1
** Constraint: Constraint-1
*Embedded Element, host elset=_PickedSet18
_PickedSet17
** Constraint: Constraint-2
```

```
*Embedded Element, host elset=_PickedSet20
_PickedSet19
*End Assembly
**
** MATERIALS
**
*Material, name=Concrete
*Brittle Cracking
 2.7,    0.
  0., 0.002
*Brittle Shear
1.,    0.
0., 0.002
*Density
 2.4e-06,
*Elastic
25000., 0.15
*Expansion
 1e-05,
*Material, name=steel
*Density
 7.8e-06,
*Elastic
210000., 0.3
*Expansion
0.,
*Plastic
400.,0.
**
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet8, ENCASTRE
**
** PREDEFINED FIELDS
**
```

```
** Name: Predefined Field-1   Type: Temperature Using Field: CaseB
*Initial Conditions, type=TEMPERATURE
Part-1-1.1, 19.9998
Part-1-1.2, 19.9998
Part-1-1.5, 19.9998
Part-1-1.8, 19.9998
Part-1-1.9, 0.
Part-1-1.10, 0.
Part-1-1.11, 0.
Part-1-1.12, 0.
Part-1-1.17, 19.9998
Part-1-1.18, 19.9998
Part-1-1.19, 19.9998
Part-1-1.20, 19.9998
Part-1-1.21, 19.9998
Part-1-1.22, 19.9998
Part-1-1.23, 19.9998
Part-1-1.24, 19.9998
Part-1-1.25, 19.9998
Part-1-1.26, 19.9998
Part-1-1.27, 19.9998
Part-1-1.28, 19.9998
Part-1-1.29, 19.9998
Part-1-1.30, 19.9998
Part-1-1.31, 19.9998
Part-1-1.32, 19.9998
Part-1-1.33, 19.9998
Part-1-1.34, 19.9998
Part-1-1.8779, 33.333
Part-1-1.8780, 33.333
Part-1-1.8781, 33.333
Part-1-1.8782, 33.333
** Name: Predefined Field-5   Type: Temperature Using Field: CaseB
*Initial Conditions, type=TEMPERATURE
Part-1-1.3, 39.9996
Part-1-1.4, 39.9996
Part-1-1.6, 39.9996
```

```
Part-1-1.7, 39.9996
Part-1-1.13, 60.
Part-1-1.14, 60.
Part-1-1.15, 60.
Part-1-1.16, 60.
Part-1-1.51, 39.9996
Part-1-1.52, 39.9996
Part-1-1.53, 39.9996
**
** STEP: Step-1
**
*Step, name=Step-1
*Dynamic, Explicit
, 1.
*Bulk Viscosity
0.06, 1.2
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-2   Type: Temperature
*Temperature
_PickedSet25, 0.
** Name: Predefined Field-4   Type: Temperature
*Temperature
_PickedSet27, 0.
** Name: Predefined Field-6   Type: Temperature
*Temperature
_PickedSet29, 0.
**
** OUTPUT REQUESTS
**
*Restart, write, number interval=1, time marks=NO
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
```

```
U,
*Element Output, directions=YES
E, S, TEMP
*Element Output, rebar, directions=YES
E, S, TEMP
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```

(2)
BL-4-8