RESTRAINED SHRINKAGE: AN ENEMY CRYPTIC

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ABSTRACT *Shrinkage, by wording, means loss of volume due either to a chemical process, or a thermal activity or due and mainly to the loss of free water from the composite material itself; all having distinct names, such as autogenous, thermal and drying shrinkage. Shrinkage may mainly be divided into two categories: free shrinkage and restrained shrinkage. Free shrinkage does not result in any internal force in the reinforced concrete members. Such a shrinkage usually takes place in statically determinate structures. Simply supported bridge beams, beams and columns of a pin supported type of precast construction or a single foundation member of a precast frame may be listed as the members of a statically determinate system. On the other hand, restrained shrinkage may yield forces well beyond the capacity of either the shrinking member or the restraining members. In case of a staged construction, where the shear walls are cast before the reinforced concrete floor slabs, the shear walls undergo free shrinkage throughout the curing period, while the slabs casted afterwards and attached to these cured members experience restrained shrinkage. In turn, lateral loads causing flexural moments and shears are observed on shears walls, while in plane tensile forces are observed in the slab plates during the curing period of the floor slab itself. The in-plane floor slab forces are consistent with the lateral stiffness of the vertical members. In other words, the stiffer the shear walls, the higher the in plane tensile stresses in the floor slabs. The forces, either moment, shear or in plane tension, may cause unexpected and immature failures.*

Restrained shrinkage should be considered in the structural analysis in order to calculate the reinforcement required to carry the induced loads. Experimental and analytical research yielded that the shrinkage induced member forces results in cracks and the reinforcement crossing such cracks may reach yielding. It should be noted that the yielded reinforcement may no more create an increasing resistance to existing loads, moreover undergoes increasing unpredictable deformations.

Authors have experienced several structural overloads, sometimes failures, due to restrained or partially restrained shrinkage. The reinforcement amount and the distribution calculated through linear structural analysis performed without shrinkage loads is usually not enough in the case of shrinkage loading. The shrinkage cracking strength may well be calculated via the material properties of the concrete, while the shrinkage force is calculated through the shrinkage properties of the concrete and through the adverse environmental affects.

In this paper, failures due to shrinkage in some structures will be given and the means of shrinkage calculation in structural analysis will be discussed.

INTRODUCTION

In this paper case studies on restrained shrinkage and its adverse effects on reinforced concrete structures are discussed. National reinforced concrete design codes all over the world enforce the shrinkage analysis, in particular for the structures with thick concrete members. The current practice in structural analysis to include the shrinkage affects is very similar to the temperature analysis. In the subsequent part of this study, general information on shrinkage will be summarized, design code approaches and the design equations will be highlighted, finally some case studies will be outlined.

Shrinkage Mechanisms

Concrete is a strong and solid material that is composed of cement paste matrix and aggregates, such as gravel, and sand out of limestone, diabase, etc. Aggregates are used to fill the unit volume with strong and stiff materials, whereas the cement paste matrix, which is out of cement and water, takes the duty of uniting the aggregates and revealing a solid and strong composite material, which is concrete. Cement is a material that needs water for hydration. Hydration is a chemical reaction between cement and water that produces heat and sort of volume changes. The necessary amount of water for a through hydration is approximately 25% to 27% by weight of cement. However green concrete with this amount of water could not get its famous property, which is workability. Therefore, water content of green concrete is usually kept between 40% to 70%, by weight of the cement content. Compressive strength is one of other famous and demanded property of concrete. The higher the water to cemet ratio (w/c), the lower the strength of the concrete.

Volume change of concrete, which can be named as the most adverse property of concrete along with the creep, may happen throughout the life of the concrete member, either in the form of shrinking or swelling cycles. Shrinkage, by wording, means loss of volume due either to a chemical process, or a thermal activity or due and mainly to the loss of free water from the porous composite material itself. Green concrete w/c ratio, ingredients of concrete such as cement type, silica fume existence, aggregate type and shape, curing conditions, ambient conditions such as evaporation speed, temperature and wind speed, and the ratio between the total area of drying face to the total volume of the drying member affects the shrinkage issue.

Concrete is faced with several types of shrinkage throughout its service life. Most common and known type is the plastic shrinkage. It is described as the water loss from concrete by evaporation and the rate of evaporation faster then bleeding water in concrete body to the surrounding environment resulting contraction. This phenomenon happens before concrete set and already in plastic phase.

Besides contraction in the plastic phase due to the loss of water, shrinkage may also be categorized into three groups after the set of concrete. Chemical shrinkage, which may be categorized as autogenous and the carbonation are the first group. Holt and Jansen explain that the autogenous shrinkage is associated with the loss of water from the capillary pores due to the hydration of the cement (Mokarem et all 2003). Autogenous shrinkage described as a self-desiccation event which creates empty pores within the hydrating paste structure and if no external water supplied for these "empty pores". It is reported that considerable shrinkage may result due to the autogenous shrinkage (Bentz and Jensen 2004). Carbonation shrinkage is caused by the chemical reaction of various cement hydration products with carbon dioxide present in the air (Mokarem et all 2003). This kind of shrinkage also causes and to be blamed corrosion and rusting of reinforcing bars in concrete. Carbonation is generally considered a durability issue that takes a long time, in the order of many years, to affect a concrete structure (Holt 2001).

Second group of the shrinkage classification is the thermal shrinkage. It happens both in the early and late ages. During the setting process of concrete, the volume of concrete members increase due to the heat of hydration. The reach of maturity and the highest temperature developed due to hydraion takes place approximately simultaneously. When the hydration stops, or slows down, the concrete member starts to shrink due to the loss of heat resulting thermal contraction, which is called the thermal shrinkage (Nejadi 2005). It is important to note that the tensile strength of green concrete hardening at such a high temperature level is much lower because of the shorter hydration process. Thus, temperature increase during the hydration period may not cause cracking of concrete; rather the cracking results from the stresses that exceed the strength of the material during the cooling period. The relationships between strength development, modulus of elasticity and the coefficients of thermal expansion and contraction are very important for the cracking of concrete (Ah-Sha et all 2001). It should be emphasized as a common knowledge that thermal expansion coefficient of concrete also varies in early age of concrete. Especially mass concrete and thick concrete sections are vulnerable to thermal restrained shrinkage.

The last item in the list is the drying shrinkage as commonly called just "shrinkage". Basically drying shrinkage is the loss of water from the concrete member. It refers to the evaporation of the non-hydrated free water from the composite after concrete set. In general, the plastic shrinkage may be described as drying shrinkage of concrete localized near surface at early ages. Drying shrinkage sustain several years with a decreasing rate like other kind of shrinkages. Drying shrinkage is also a partially reversible event.

Restrained Shrinkage

Shrinkage causes length reduction in two dimensional freely supported concrete members. Moreover it does not originate stress in concrete unless it is restrained or has a relatively large volume. It is a well known fact that tensile stresses arise in concrete whenever the member is restrained from shrinking freely. Retrains can be either interior or exterior. Reinforcing bars embedded in concrete provide certain amount of restraint by it self. Large amount of volume thought to be an interior restraint situation. Inner portion of massive concrete may restrain the outer portion of it. Aggregates are also considered as interior restraints.

In general, shrinkage cracks are induced by exterior restraints, if the mass concrete is not the topic of the discussion. In case of a staged construction, where the shear walls are cast before the reinforced concrete floor slabs, the shear walls undergo free shrinkage throughout the curing period, while the slabs casted afterwards and attached to these cured members experience restrained shrinkage. In turn, lateral loads causing flexural moments and shears are observed on shear walls, while in plane tensile forces are observed in the slab plates during the curing period of the floor slab itself. It is obvious that the stiffer the shear wall, the higher the in plane tensile stresses in the floor slabs. The forces, either moment, shear or in plane tension, may cause unexpected and immature failures.

Early age shrinkage cracks, mostly caused by plastic shrinkage, can be quite wide on the outer surface of the concrete members reaching widths of 2 to 3 mm. But their width often decreases rapidly below the open surface. Plastic cracks typically do not exceed 1 mm but may pass through the full depth of the member; however the mechanisms leading to the formation of plastic shrinkage cracking does not explain the full depth cracks. It is probable that the subsequent events including drying shrinkage and loading through the formwork replacement can cause the plastic shrinkage cracks to propagate (Transportation Research Board, 2006).

If flexure and shear forces are not dominant on member, stresses induced from restrained shrinkage control the behavior. In general shrinkage strains are bigger than concrete tensile strain capacity. Direct tension cracks caused by restrained deformations are induced by shrinkage and thermal strains and often penetrate completely through the cross-section of a member. They are one of the most difficult and troublesome peculiarities of structural concrete (Nejadi 2005).

Shrinkage Phenomenon in Design Codes

Stresses and deformations due to shrinkage action in reinforced structures are calculated similar to the contraction deformations through temperature analysis. Therefore one needs to alter the strains caused by the shrinkage to the temperature differences that will cause the same effects on structural deformations and member forces in the structural analysis. The fallowing expression (Eq.1) is used to change the shrinkage strain to the temperature difference.

$$\varepsilon = \alpha \quad \Delta T \tag{1}$$

where ε is the shrinkage strain, α is coefficient of thermal expansion for concrete and ΔT is temperature difference for the structural analysis model. The temperature load (ΔT) calculated using Eq1 is used in structural analysis being a part of factored load combination as implied by the national design codes. Resulting forces from the structural analysis are used to calculate the required amount of reinforcing bars not only for dead, live or earthquake loads but also for the adverse effect of the shrinkage action.

There are several methods derived so far to evaluate the shrinkage strains. Since there are many parameters affecting the shrinkage, and it is difficult to certainly evaluate the effect of every parameter on shrinkage, many simplifications and assumptions are made in shrinkage strain calculations. It can be claimed that quantifying and analyzing the time dependent volume changes, shrinkage, is more difficult than a strength based analysis.

Most popular and useful shrinkage strain calculation procedures are placed in Eurocode 2 (Give Reference) and ACI 209 (Give Reference). In the following paragraphs, the above mentioned code approaches along with the Turkish design and construction code TS500/2000 formulas are discussed in brief. Expressions from Euracode 2 and ACI 209 are time sensitive equations. One can calculate shrinkage strain by using these codes for any given maturity day. In contrast, shrinkage strain evaluation method in TS500/2000 gives only long term values saying more than two or three years.

In Eurocode 2, total shrinkage strain is given as a composition of drying and autogenous shrinkage strains (Eq.2).

$$\varepsilon_{cs} = \varepsilon_{cd} \quad + \quad \varepsilon_{ca} \tag{2}$$

where ε_{cs} is the total shrinkage strain, ε_{cd} is the drying shrinkage strain and ε_{ca} is the autogenous shrinkage strain. Drying shrinkage strain ($\varepsilon_{cd,0}$(t)) is calculated with respect to environmental conditions, concrete strength, drying time and the dimensions of the structural member (Eq.3, Eq.4). Autogenous shrinkage strain, on the other hand, is evaluated with time and concrete strength (Eq.5, Eq.6, Eq.7).

$$\varepsilon_{cd}(t) = \beta_{ds}(t, t_s) \quad k_h \quad \varepsilon_{cd,0} \tag{3}$$

$$\beta_{ds}(t, t_s) = \frac{(t - t_s)}{(t - t_s) \quad + \quad 0{,}04 \quad \sqrt{h_0^3}} \tag{4}$$

where:

$\varepsilon_{cd,0}$ is nominal or basic unrestrained shrinkage strain that can be determined either by using the equation in Annex B or by following Table 3.2 in the code

k_h is a coefficient depending on the size h_0 according to Table 3.3 in the code

t is the age of the concrete at the time considered, in days

t_s is the age of the concrete (days) at the beginning of drying shrinkage (normally this is at the end of curing)

h_0 is the notional size (mm) of the cross-section (=$2A_c/u$, A_c is the cross-sectional area and u is the perimeter of that part of the cross section which is exposed to drying)

$$\varepsilon_{ca}(t) = \beta_{as}(t) \quad \varepsilon_{ca}(\infty) \tag{5}$$

$$\varepsilon_{ca}(\infty) = 2{,}5 \quad (f_{ck} - 10) \quad 10^{-6} \tag{6}$$

$$\beta_{as}(t) = 1 - \exp(-0{,}2t^{0,5}) \tag{7}$$

where t is given days.

ACI has a more simple method; however it is founded on lots of assumptions. Equation 8 is the basic expression for shrinkage strain ($(\varepsilon_{sh,})_t$) calculations in ACI 209.

$$(\varepsilon_{sh})_t = \frac{t^{\alpha}}{f \quad + \quad t^{\alpha}}(\varepsilon_{sh})_u \tag{8}$$

where t is the time from the end of the initial curing(in days), $(\varepsilon_{sh,})_u$ is the ultimate shrinkage strain. f (in days) and α are considered constants for a given member shape and size which define the time-ratio part. α coefficient is considered 1 for shrinkage. Normal ranges of $(\varepsilon_{sh,})_u$ and f constant have been founded to be 415 x10^{-6} to 1070x10^{-6} and .20 to 130 days respectively.

In TS500/2000, it is told that if one can not reach accurate and meaningful data, he can take the approximate values as shrinkage strain from the table in code namely Table 3.4. This method gives just the long term shrinkage strain values. It is based on equivalent member thickness, curing condition and ambient humidity data. Equivalent member thickness, l_e is determined same as h_0 (=$2A_c/u$) in Eurocode 2, as described above.

INVESTIGATIN of RESTRAINED SHRINKAGE EFFECTS IN STRUCTURES

Four cast-in-situ reinforced concrete structures, severely suffering from restrained shrinkage cracks are discussed as case studies in this part of the study. Identification information like cities, designing companies, and owner's names are kept confidential. It should be noted that, no shrinkage analysis was made during the project phase of these structures, resulting wild cracking in structural members. Linear elastic shrinkage analysis is performed for the structures and results are compared with the on-site observations.

Selected Cases

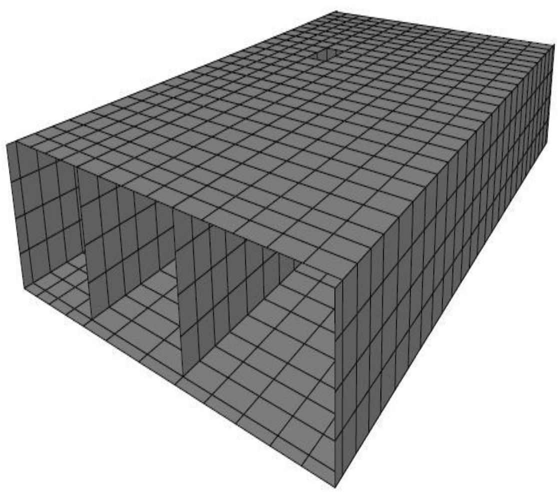
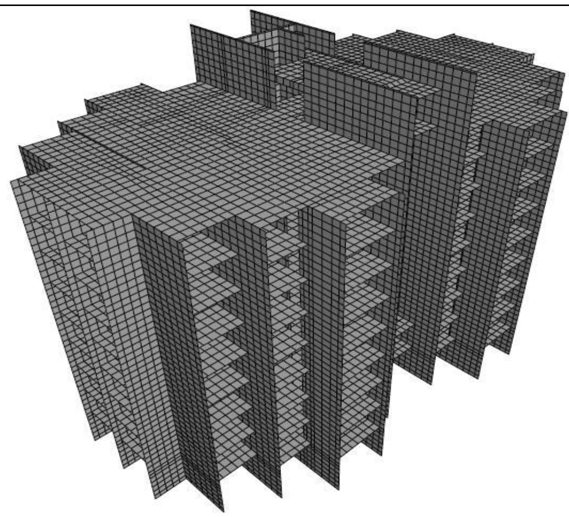
Case1 is a relatively massive and multi-storey transportation structure which is designed for general public services. It is a part of big structural complex that is separated with construction joints from each other. Design material properties are f_{ck}=30 MPa for concrete and f_{yk}=420 MPa for the reinforcing steel. Structure is composed of reinforced concrete shear walls, slab. There are three bays with lengths of 10.30m, 7.50m and 5.70m. The transverse dimension of the structure is 45.50m in plan. The story height is 7.55m. Other dimensional information is given in Figure 1. Field investigation was made after approximately three months from the first poring of concrete.

<u>Case 2</u> is an eight storey apartment building. Reinforced concrete tunnel form construction technology was used to build the structure. Stairs were precast concrete. Plan dimensions are 38.60m and 23.70m with 2.80m storey height. Design material properties are f_{ck}=20 MPa for concrete and f_{yk}=420 MPa for reinforcing steel. Site investigation was made about one and a half year after the overall construction is completed. The very long, single piece reinforced concrete shear walls placed in the East-West direction may be the main peculiarity of the structure under investigation

<u>Case 3</u> is the basement of a 10 storey apartment building with elevator and stair well openings in the middle. Perimeter of the openings and two parallel sides of the building had been surrounded with shear walls. Plan dimensions are approximately 22.00m and 23.00m with 3.25m storey height. There are 1.05m x 1.05m columns placed at each corners of the building. The seismic loads are jointly carried by frames and shear walls. Design material properties are f_{ck}=25 MPa for concrete and f_{yk}=420 MPa for reinforcing steel. Investigation was done after couple of month of construction.

<u>Case 4</u> is the first floor of a public service structure that seismic loads are jointly resisted by frames and shear walls together. Plan dimensions are 48.00m and 30.00m, with a 3.00m storey height. There are two stair wells placed facing one another in the middle of the long direction. Stair wells had been formed with reinforced concrete shear walls. Design material properties are f_{ck}=30 MPa for concrete and f_{yk}=420 MPa for reinforcing steel. Structure was examined 6 months after the first poring of concrete.

Basic views and properties of the structures are shown in Fgure 1

Case1		Case2	
			
$t_{outer\ walls}$ = 130cm t_{slab} = 50cm	$t_{inner\ walls}$ = 150cm $t_{foundation}$ = 200cm	t_{slab} = 14cm	$t_{shearwall}$ = 16cm

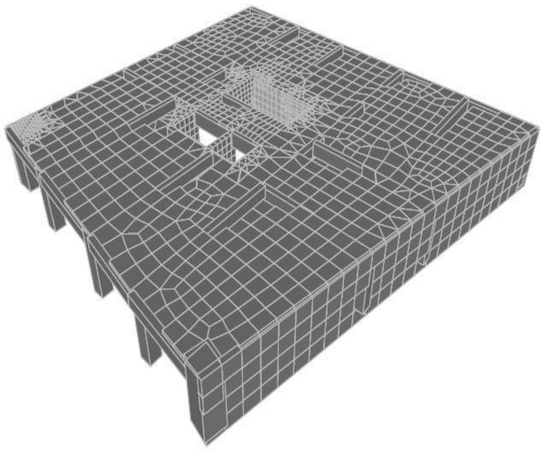
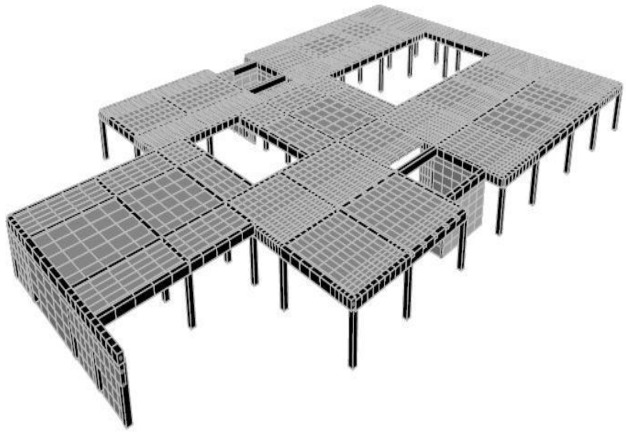
Case3	Case4
	
t $_{slab}$ = 15cm t $_{shearwall}$ = 25cm c $_{column}$ = 105cm	t $_{slab}$ = 15cm t $_{shearwall}$ = 25cm

Figure-1. Views and properties of structures investigated

Shrinkage Analysis

Shrinkage strain data of the structures in all cases were derived according to Turkish reinforced concrete design and construction code, TS500/2000. The shrinkage strains belonging to the structure in case 4 also calculated by using other codes that is Eurocode 2 and ACI 209 to observe the differences among the code expressions.

In the equivalent length calculations, interpolation was made if necessary and required as told in TS500/2000. Relative humidity was taken as %65 in case1, %50 in case2 and %80 in both case3 and case4. The equivalent length values are given in Table 1 accordingly appropriate curing conditions. ε_{cs} and ΔT data are also shown in Table 1.

Table-1. Equivalent length, shrinkage strains and equivalent temperature differences

	Case1	Case2	Case3	Case4
l_e (mm)	500	150	150	200
ε_{cs} (x10^{-3})	-0,374	-0,400	-0,400	-0,400
ΔT (°C)	-38	-40	-40	-40

Thermal expansion coefficient is taken as 1x10^{-5}/°C in all structural models. Stress strain relationship under tension is thought to be linear for long term shrinkage. Simply fallowing the Hooke Law, whether cracking of concrete in the structures takes place or not can be judged. Table 2 shows the results. Concrete tensile strength (f_{ctk}) and elastic modulus (E) for each structure is determined by the formula in TS500/2000. It should be kept in mind that these shrinkage strains are occurred after at least two years according to TS500/2000.

Table-2. Stress evaluation

	Case1	Case2	Case3	Case4
f_{ctk} (MPa)	1,917	1,565	1,750	1,917
E (Mpa)	31800	28535	30250	31800
$\sigma_{cs,\ Elastic}$ (MPa)	11,893	11,414	12,100	12,720
Cracking	Yes	Yes	Yes	Yes

Although creep in tension is also occurred in concrete and decrease these values by a certain amount, stresses due to shrinkage never take place below tensile strengths of concrete in all cases.

Moreover reinforcing bars have faced with extreme tension under no considerable loading like earthquake. It is obvious that capacities designed before the construction could never be reached during any important loading. In addition, it should be noted that the reinforcing steel has been fairly stressed even under service loads. In certain situations progressed shrinkage cracks in slabs may lead to noticeable vibrations, due to loss of flexural stiffness values.

Case4	Eurocode 2	ACI 209	TS500/2000
$\varepsilon_{cs,28}$ ($x10^{-3}$)	-0,069	-0,073	---
$\varepsilon_{cs,730}$ ($x10^{-3}$)	-0,248	-0,352	-0,400

Table-3. Shrinkage strains for case4 according to different codes

Table 3 shows that shrinkage strains evaluated according to different codes and variant time periods for the structure in Case 4. TS500/2000 formula as mentioned before is not time sensitive. Hence shrinkage strain at early age could not be calculated using the TS500/2000 code. ACI and Eurocode expressions yield similar values. In long term evaluation of shrinkage strain in concrete, different results are obtained. Eurocode2 formula has given the least strain value still leads to stress above the limit of concrete tensile strength.

Comparison of Results with the On-Site Observations

Computer models with the commercially available FEM program SAP2000 were made for the structures of 4 cases. Comparison of analysis results and in-situ observations is made case by case. Informations provided on site investigations are varied for each study case.

In Case 1, excessive amount of cracks concentrated on the floor slabs in the middle of each bay through the long direction of slabs were observed. Moreover diagonal cracks located generally at the free edge to shear wall connection regions of slabs were observed. In certain locations of slabs, transverse cracks (in the short direction) were also formed through the bays. A detailed on-site investigation on crack propagation and crack width could be done. Carbonation shrinking products were observed in some cracks. It was measured that maximum crack width was 0,45mm. Analysis has shown that the stresses induced by shrinkage in the slabs are beyond the concrete tensile strength limit. Stresses in slab reinforcing bars are calculated as 260MPa at certain locations. This is rather a high value for the service loads and at a relatively early age of concrete. Furthermore shrinkage stresses in slabs were lead extra moments on outer shear walls in their weak axis. These shear walls were forced about %26-%39 of their moment capacities in their weak axis. In the point of an earthquake loading, the combined moments and forces may go beyond the section capacities resulting plastic hinges, where deformations are not easily predictable

In Case 2, cracks concentrated on the shear walls that placed in the middle of the building through long dimension and on the slabs jointed these shear walls. These shear walls are symmetric according to stair well axis and just a single pieces in both part of the building. These cracks located in outer sides have started from the bottom and pass through upward with an angle towards the stair well. It was seen that these cracks also tend to develop properly through slabs at floor levels. Cracks were also observed in the beams and slabs parallel to the shear walls, located in the middle and joining each part of the building. These cracks were mainly perpendicular to the shear walls and were followed through cross section with same width. Resultant stresses of shrinkage analysis are in a good tendency with the situation. It was noted that concrete tensile strength exceeded in the analysis appropriately at regions concentrated of cracks in-situ. In plane tensile strength of the shear wall was calculated 1.02MPa accordance to supplied reinforcement for comparison. It was seen that this value exceeded in certain regions wherever cracking occurred in the shear wall. It is thought that reinforcement was reached to its yield limit at particular locations Values were founded as 0,54MPa and 2,29MPa respectively parallel and perpendicular to the shear wall in slabs. It explains that the cracks tend towards the direction perpendicular to the shear walls.

In case 3, it is observed that cracks have formed in diagonal direction near corners and they have turned to parallel line near shear walls placed opposite of outer perimeter. Cracks were fallowed with same width on both faces of slab. Tensile strength of the slab according to both steel and concrete was calculated as 2,87MPa in both direction. It is understand that several regions this limit was exceeded. Floor vibration was also reached to considerable amount.

In case 4, there were crack on beams and slabs appropriately especially between shear walls placed at perimeter of stair wells constructed oppositely. Cracks on beam were not induced by shear or flexure forces. They were at same line around the beam and has same width through cross section. They concentrated at the section that additional support reinforcement cut off. The tensile strength of cracked beam section was 2,67MPa. It was seen that there was stresses beyond this limit even reached to yield in the analysis.

CONCLUSION

Although shrinkage is thought to be a simple and unimportant issue mostly, it could be fairly harmful. Stresses in reinforced concrete members should be very low level under service loads however it was observed that they might be reach at yield points due to shrinkage in this study. The analyses were shown that maximum stresses induced shrinkage and the cracks observed in the field follow each other. It was also seen that Eurocode 2 could be determine shrinkage strains more realistic. In short age situation ACI and Eurocode 2 gives closer results where as TS500/200 give no sound. Creep strains in tension should be taken into account otherwise resultant stresses yields too high values.

The restrained shrinkage cracks were caused to reinforcement stressed in unexpected manner before the structure meets any design load like earthquake. Thus, appropriate overall structural behavior would never be achieved. If shrinkage effect does not included during design process especially the structures containing large and thick members restrained more rigid once, unfortunately even collapse would be likely occurs induced by shrinkage during earthquake.

REFERENCES

Mokarem D. W., Meyerson R. M., Weyers R. E., 2003,Development of Concrete Shrinkage Performance Specifications, Final Contract Report, VTRC04-CR1

Bentz D. P., and Jensen O. M., 2004, Mitigation strategies for autogenous shrinkage cracking, Cement and Concrete Composites, 26, 677-685

Holt E. E., 2001, Early age autogenous shrinkage of concrete, VVT Building and Transport Publications, 446

Nejadi S., 2005, Time-Dependent Cracking and Crack Control in Reinforced Concrete Structures, PhD Thesis, The University of New South Wales, Sydney, Australia

Ah-Sha H. H., Sanders D. H., Saiidi M. S., 2001, Early Age Shrinkage and Cracking of Nevada Concrete Bridge Decks, NDOT Research Report, RDT 01-010

Transportation Research Board, 2006, Control of Cracking in Concrete – State of the Art, TRANSPORTATION RESEARCH CIRCULAR E-C107