ON BS 8007 RECOMMENDATIONS FOR REINFORCEMENT TO CONTROL THERMAL AND SHRINKAGE CRACKING

by

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Abstract

The fall in temperature of the concrete mass *(T_1)* between the hydration peak and the ambient temperature is an important parameter in deciding the reinforcement area required to control cracking due to thermal and shrinkage effects. Proper controlling of these cracks is paramount in water retaining structures and hence BS 8007 has given due consideration for this aspect. However, due to various constraints involved, accurate computation of T_1 is difficult and the calculation is usually based on an approximate value. This paper discusses the implications of uncertainty in determining T_1 on the reinforcement area computed by code recommendations, by considering the influence of the restraint factor *(R)* in BS 8007.

1.0 Introduction

In designing reinforced concrete water retaining structures, it is important to ensure that the concrete has a low permeability to satisfy the durability requirements. This can be achieved at the design stage by techniques such as controlling the cement content in the mix, specifying an appropriate aggregate type and controlling the free water/cement ratio. At the construction stage, proper compaction and curing will ensure adequate durability in the concrete mix. However, the durability of a concrete element will be substantially impaired if cracks of excessive width appear in the structure, although there is considerable disagreement on the manner in which crack widths relate to performance and durability[1] . Hence to ascertain proper service of the structure, due care should be taken by the designer to control cracks in concrete, both in hardened (mature) concrete and in fresh (immature) concrete. In the past, there had been numerous occasions (both in Sri Lanka and in other countries) where water retaining structures failed to provide the intended service due to leaking of water. One cause for these leakages is the cracking of the structure beyond maximum widths stipulated in design guides.

Cracks that appear in concrete structures can either be structural or non-structural. Non-structural cracks are generated due to intrinsic properties of concrete and its constituent materials[2] and they are not caused by external forces. Cracks due to thermal movement and shrinkage fall into the category of non-structural cracks and if not properly considered in design, it can give rise to serious problems with the performance of the structure. Out of the parameters influencing these cracks, the fall in temperature of concrete mass between hydration peak and ambient temperature (referred to as T_1 here after) is an important factor to be considered in controlling these cracks.

Different design codes of practice adopt various techniques in controlling shrinkage and thermal movement cracks. The Australian code of practice AS 3735[3] specifies reinforcement to control these cracks in a collective manner. Explicit consideration is not given for temperature and other factors, and the required steel ratio is given for a particular range of bar diameters (see (B) in the appendix). General requirements of the Indian code of practice states that stresses due to temperature and shrinkage effects may be ignored, provided that (i) permissible stresses in steel are not exceeded (ii) adequate precautions are taken to avoid cracking of concrete during the construction period until the reservoir is put into use and (iii) recommendations regarding movement joints and a suitable sliding layer at the base are complied accordingly[4]. However, these are general recommendations and the designer should take into account special situations that need further attention. The British code of practice BS 8007[5] gives an explicit formula to compute the necessary reinforcement percentage and all contributory parameters should be known in using this formula.

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In Sri Lanka, British codes of practice are used in reinforced concrete design (both normal and water retaining) and the discussion in this paper is focussed on the method stipulated in BS 8007 in controlling cracks due to shrinkage and thermal movement. However, BS 5337[6], the predecessor of BS 8007, is still being used in Sri Lanka and hence the specification in this code of practice is also considered for comparison. Comments from the Australian code of practice[3] are also highlighted for a wider perception.

2.0 BS 8007 method in controlling thermal movement and shrinkage cracks

2.1 BS 8007 Design Philosophy

A reinforced concrete structure designed to retain water (or any aqueous substance) should be free from excessive cracking and deflection, in addition to possessing adequate strength to withstand the action of loads. The aspect of careful controlling of cracking and deflection (known as serviceability conditions) is not very critical in normal reinforced concrete structures and these structures are usually *designed* for strength and *checked* for serviceability conditions. However, in water retaining structures, the structure should be *designed* for cracking (deflection is not normally critical) and a structure designed in such a manner possesses more than adequate strength, practically in all cases. The BS 8007 design procedure is established on this viewpoint.

BS 8007 is based on the limit state philosophy, which is widely used throughout the world for normal structural design[7] since it was found to be more economical than methods based on elastic theory. Elastic deign methods used in previous codes of practice led to the use of thick concrete sections with large quantities of mild steel reinforcement, and there was no proper method to consider cracking due to shrinkage and thermal movement. In these codes, a nominal reinforcement percentage was specified to control cracking. As mentioned in the preceding paragraph, BS 8007 clearly emphasises the importance in designing the concrete section for cracking (Cl 2.6 & Cl 3.2.2), both in mature concrete (Cl 3.2.2 (b) & Cl 3.2.2(c)) and in immature concrete (Cl 3.2.2(a) & Cl 2.6.2.3). Cracking due to thermal movement and shrinkage is classified as direct tensile cracks in immature concrete arising from *restrained shrinkage* and *heat of hydration movement*.

2.2 Reinforcement to control thermal movement and shrinkage cracks

2.2.1 Early thermal movement

When concrete begins to set, temperature of the concrete mass increases due to heat of hydration of cement. Duration and magnitude of the temperature rise are not constants and they will depend on factors like the type of formwork used, thickness of the section and quantity of cement in the mix. Later the temperature reduces gradually to the ambient temperature due to cooling. Normally the rise in temperature does not cause any problem, as stresses in the concrete at this stage are compressive. However, when the temperature drops from hydration peak to ambient, the concrete contracts, thus inducing tensile stresses if the contraction is restrained, either completely or partially. These tensile stresses give rise to cracks and these cracks are defined as early thermal movement cracks. From the mechanism, it is clear that the fall in temperature between hydration peak and ambient (T_1) and the restraint to contraction are important factors in the formation of cracks.

Restraints can either be external or internal. External restraints are due to physical end and surface conditions. Internal restraints are usually present in thick sections where the cooler outer surface acts as a restraint to the core of the section.

2.2.2 Drying shrinkage

When concrete hardens and dries, it starts to shrink. This shrinkage of concrete is resisted by the reinforcement and therefore the reinforcement bar will be in compression and the concrete in tension. In controlling cracks due to shrinkage, the bond strength between the reinforcement bar and concrete plays an important role.

2.2.3 Late Thermal Movement

There is a possibility of late thermal contraction in hardened or semi-hardened concrete resulting from the temperature change due to seasonal variation (T_2). The effect of this seasonal variation is incorporated with the effects of early thermal movement and drying shrinkage of immature concrete in calculating reinforcement.

2.2.4 Calculation of reinforcement

Appendix A of BS 8007 gives the procedure in calculating reinforcement area required to control cracking due to shrinkage and thermal movement.

The minimum steel ratio is given by the formula[5];

$$\rho_{crit} = \frac{f_{ct}}{f_y} \qquad (1)$$

f_{ct} = direct tensile stress in immature concrete
f_y = characteristic strength of reinforcement

The maximum crack spacing (s_{max}) is given by[5];

$$S_{max} = \frac{f_{ct}}{f_b} \times \frac{\phi}{2\rho} \qquad (2)$$

f_{ct}/f_b = ratio of tensile strength of the concrete to average bond strength
ϕ = size of reinforcing bar
ρ = steel ratio

The maximum crack width is related to the maximum crack spacing by the following formula[7].

$$\frac{W_{max}}{S_{max}} = \varepsilon_{te} + \varepsilon_{cs} - \frac{1}{2}\varepsilon_{ult} \qquad (3)$$

w_{max} = maximum crack width
s_{max} = maximum crack spacing
ε_{te} = early thermal contraction from hydration peak
ε_{cs} = total shrinkage strain
ε_{ult} = ultimate concrete tensile strain = 200×10^{-6}

The value of shrinkage strain (ε_{cs}) is approximately equal to 100×10^{-6} after allowing for creep strain. Hence equation (3) can be reduced as shown below.

$$\frac{W_{max}}{S_{max}} = \varepsilon_{te} = \frac{1}{2}\alpha\, T_1 \qquad (4)$$

α = coefficient of thermal contraction in concrete

Making allowance for the high creep strain in immature concrete, the effective value of ε_{te} is taken as half the actual value. If there is any subsequent thermal contraction in hardened concrete due to seasonal variation (ε_{tl}), this thermal contraction strain can be expressed as;

$$\varepsilon_{tl} = \alpha_{eff}\, T_2 \qquad (5)$$

T_2 = temperature difference due to seasonal variation

In mature concrete, the tensile strength of the concrete is lower in comparison to the bond strength[7] and hence the effective contraction may be assumed as half the contraction given by the actual value of α. Hence the effect of seasonal variation can be expressed as;

$$\frac{W_{max}}{S_{max}} = \varepsilon_{tl} = \frac{1}{2}\alpha\, T_2 \qquad (6)$$

The combined effect of early thermal contraction, shrinkage and seasonal variation is given by the following formula[5,7].

$$W_{max} = S_{max}\,\frac{1}{2}\,\alpha\,(T_1 + T_2) \qquad (7)$$

The factor (1/2) is expressed by a general symbol R, where R is defined as the *Restraint Factor*[5]. It is obvious that the maximum value of R is (1/2).

Hence;

$$W_{max} = S_{max}\, R\, \alpha\, (T_1 + T_2) \qquad (8)$$

This is a remarkable difference between the formulae given in BS 8007 and BS 5337[6], the predecessor of BS 8007. In BS 5337, the factor R is not defined and the equation is similar to equation (7) above. Hence, in designs based on BS 5337, the factor is taken as 0.5 and no reduction is allowed.

Combining equations (2) and (8), the reinforcement ratio required can be obtained as follows.

$$\rho = \frac{f_{ct}}{f_b}\,\frac{\phi}{2W_{max}}\,R\,\alpha\,(T_1 + T_2) \qquad (9)$$

Careful investigation of the rationale of restraint factor (R) leads to the effects of uncertainty of parameters, such as T_1, in computation of the reinforcement area.

3.0 Effects of Restraint Factor (R) and Temperature (T_1) on reinforcement to control thermal movement and shrinkage cracks

The correct computation of ρ in equation (9) is dependent on the accuracy of contributory parameters. Out of these parameters, the most difficult parameter to evaluate is the temperature T_1. Analysis of the parameters influencing T_1 indicates that it is practically difficult, if not impossible, to compute T_1 accurately[8]. As seen from (A) in the appendix, the temperature T_1 depends on a variety of conditions such as (i) section thickness (ii) type of element (iii) type of cement used and cement content (iv) type of formwork (v) thickness of formwork (vi) concrete placing temperature and (vii) mean daily temperature. Values in (A) of the appendix are given as typical values for OPC concrete when more particular information is not available, and furthermore they are applicable for UK conditions. Even under UK conditions, reference should be made to CIRIA report no. 91, when other types of cement are used. Values given in this table are not directly applicable to Sri Lankan conditions, mainly due to the difference in mean daily temperature. However, there are approximate methods to obtain equivalent T_1 for Sri Lankan conditions. One method is to add half the difference between local mean daily temperature and 15° C to values of T_1, provided that the difference between mean daily temperature and concrete placing temperature is 5° C.

From the discussion in the preceding paragraph, it is evident that T_1 cannot be estimated accurately, and a certain degree of uncertainty exists in the value obtained even after giving every possible attention to controlling parameters. Now one has to think of the question, *"What is the effect of this error of estimation of T_1 on reinforcement ratio (ρ) obtained?"* The answer to the question can be examined by investigating the restraint factor R in equation (9).

BS 8007[5] suggests that R can be reduced from the maximum of 0.5, depending on the degree of restraint in the concrete element. Figure A3[5] gives some examples where R can be reduced further in certain locations of elements. A value of 0.5 is used at locations where the element is fully restrained. However, BS 5337[6] does not allow this reduction and the value is taken as 0.5 in all cases, irrespective of the degree of restraint. Hence it can be clearly seen that BS 8007 tries to provide a more economical design. Practically, the argument in BS 8007 is valid since, virtually in all elements, there is *some* freedom of movement resulting from precautions taken by the designer/contractor to reduce restraint to expansion & contraction and from physical boundary conditions of the element. BS 8007 exploits this aspect in its design.

Hence, in most concrete elements, it is logical to assume that the average restraint factor (R) is less than 0.5. But, once again, it is difficult to find a reasonable value for R, due to the unpredicted nature of restraints in the element. Therefore, it is worth in investigating the implications in using the maximum value of 0.5 (in all cases) on the error induced due to approximate estimation of T_1.

The effect of T_1 is critical if T_1 is under estimated. If T_{10} is the estimated value of T_1 and ΔT_{10} is the error in estimation, then the probable value of T_1 would be T_{10} + ΔT_{10}. Take the adopted value of R as 0.5, and the probable value of R would be 0.5 - ΔR^0, where ΔR^0 is the allowance possible due to reduced restraint to contraction.

Then from equation (9);

$$\rho_{req} = \frac{f_{ct}}{f_b}\,\frac{\phi}{2W_{max}}\,(0.5 - \Delta R^0)\,\alpha\,(T_{10} + \Delta T_{10} + T_2) \qquad (10)$$

Now the same value of ρ should be obtained by using the adopted value of R and the estimated value of T_1.

$$\rho_{req} = \frac{f_{ct}}{f_b}\,\frac{\phi}{2W_{max}}\quad 0.5\,\alpha\,(T_{10} + T_2) \qquad (11)$$

Equation (11) shows that using the estimated value of T_1 will not change the required reinforcement ratio, if a reduction of ΔR^0 is possible in the restraint factor (equation 10). Conversely, an error of ΔT_{10} can be negated (either partially or completely) by <u>not incorporating</u> the reduction possible for the Restraint factor (R). That is a value of 0.5 is used in all designs.

Equations (10) and (11) yield the following relationship between ΔT_{10} and ΔR^0.

$$\Delta R^0 = \frac{0.5\,\dfrac{\Delta T_{10}}{T_{10}}}{1 + \dfrac{T_2}{T_{10}}\,\dfrac{\Delta T_{10}}{T_{10}}} \qquad (12)$$

Equation (12) shows the relationship between unit error of T_1 (ΔT_{10} / T_{10}) and the required ΔR^0 to nullify the effect of this error on the value of ρ computed. The necessary ΔR^0 value is dependent on absolute values of T_1 and T_2. The value of T_2 is usually obtained from meteorological data available. It should be noted that the equation (12) has no intrinsic value since ΔT_{10} is not deterministic (if ΔT_{10} is known, T_1 can be estimated accurately). However, the relationship in equation (12) can be exploited to formulate guidelines to eliminate (or reduce) errors induced due to improper estimation of T_1 (see example in section 4.0). It is imperative to note that the equation (12) *does not depict* any physical relationship between T_1 and R. In actual fact, they are two *independent* factors. The equation (12) shows only the "delta" variation in R required to compensate the error of estimation of T_1 <u>on the reinforcement area</u> computed.

Figure 1 illustrates the variation of ΔR^0 versus $\Delta T_{10}/T_{10}$ for several values of ΔT_{10}. According to these graphs, for error in T_1 up to 30% the required reduction in R is less than 0.12, which gives an effective R value of minimum 0.38 (=0.5-0.12). This is a reasonable value for R in many situations. Also, the effect of error in T_1 diminishes as T_2 increases. The influence of T_{10} is minimal on ΔP^0 when the error is less than 50%, and usually, it is possible to estimate T_1 to this accuracy. On the upper limit, a 100% error in T_1 demands only a reduction of 0.25 in the restraint factor, and this is an unlikely situation.

4.0 Illustrative Example

A part of a concrete wall of a rectangular sump is shown in figure 2. Due to a planned series of construction, the wall is cast in alternate panels and hence 3 edges of the wall panel (two vertical sides and the top) are free edges. The bottom edge is reckoned as a fixed edge. Restraint factors at various locations are estimated using figure A3 in BS 8007.

For the design, following information is used.

$T_1 = T_{10} = 30^0$ C (estimated from available data)
$T_2 = 10^0$ C (obtained from meteorological data)
Bar diameter = 12 mm
W_{max} = 0.2 mm

$\alpha = 10 \times 10^{-6} / C^0$
$f_{ct}/f_b = 0.67$

Average restraint factor for the panel
= $(0.5 + 0.25 + 0.25)/3$
= 0.33 *(approximately)*
Adopted restraint factor in design = 0.5

Design :

Since the adopted restraint factor is 0.5;

$\Delta R = 0.5 - 0.33 = 0.17$

From equation (11);

$\rho_{req} = 0.67 \times 12/(2 \times 0.2) \times 0.5 \times 10 \times 10^{-6} \times (30+10)$
$= 0.00402$

ρ_{req} = **0.00402**

From chart (3) in figure 1;

$\Delta T_1 0 / T_1 0 = 0.7$
$\Delta T_1 0 = 21^\circ C$

Hence adopting the maximum value of 0.5 for the restraint factor in the design, an error of 21° C in T_1 can be nullified.

[Check : $\rho_{req} = 0.67 \times 12/(2 \times 0.2) \times 0.33 \times 10 \times 10^{-6} \times (30+10+21) = 0.00405$
(decimal difference is due to numerical errors)]

However, the values of ΔR^0 and/or $\Delta T_1 0$ are not available for the designer. The above example is an illustrative one which shows the implications of using the maximum restraint factor (0.5) in a design where T_1 cannot be accurately computed. From this example, the designer can obtain an idea on relative magnitudes of errors involved, which he can effectively use in design to minimise ill effects due to improper estimation of the temperature T_1. However, using the maximum value of R (0.5) in all cases will, obviously, not allow the reduction in reinforcement which is possible in locations where R is less than 0.5[5]. Thus the design will be less economical. This is an advantage which has to be foregone, if errors in estimation of T_1 are to be compensated by using the maximum value of R.

(The above example can be worked out using the Australian Code of Practice AS 3735[3]. The table in (B) of the appendix gives the reinforcement ratio as 0.0048x(0.15/0.2) = 0.0036. This answer is less than the answer obtained using BS 8007. However, AS 3735 does not explicitly consider parameters such as T_1 and R for a particular design, and reinforcement ratios are given only as functions of bar diameters).

5.0 Closure

The discussion in this paper ensues in following points on the computation of reinforcement to control shrinkage and thermal movement cracks in reinforced concrete water retaining structures using BS 8007.

- As stated in BS 8007, it is practically possible to reduce the restraint factor (R) from a maximum of 0.5 depending on the degree of restraint to expansion and contraction.

- It is difficult to estimate the correct value of T_1 in designs due to numerous factors influencing its variation. Only an approximate value can be computed using available data such as cement content, formwork type, element type, and section thickness.

- Using a higher value for the restraint factor (R), the effect of error in estimation of T_1 can be negated, either partially or completely. However, this is not applicable to a structural element, where the restraint factor is actually 0.5 (maximum) at all locations. In such a case, no compensation can be achieved.

- The effect of error in T_1 is relatively reduced as the value of T_2 increases while other parameters remain constant.

In conclusion, it can be stated that it is reasonable to adopt a restraint factor of 0.5 in designs when reinforcement to control thermal and shrinkage cracks is computed, although it may be possible to reduce it. This approach will substantially, if not completely, reduce the effect of error in estimation in T_1 and this is particularly applicable to Sri Lankan conditions where relevant information to compute T_1 is not readily available.

6.0 References

1. AS 3735 Suppl - 1991 Concrete structures for retaining liquids - Commentary (Supplement to AS 3735 - 1991) *Standards Association of Australia*

2. Intrinsic cracks in concrete storage structures *CD Turner*, Concrete Society conference on "Design, construction & maintenance of concrete storage structures", New Castle Upon Tyne, 3-4 December 1984

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4. Civil Engineering Handbook, Vol II, *VN Vazirani,SP Chandola*, Khanna Publishes, Delhi, India

5. BS 8007 : 1987 Design of concrete structures for retaining aqueous liquids *British Standards Institution*

6. BS 5337 : 1976 The Structural use of concrete for retaining aqueous liquids *British Standards Institution*

7. Design of liquid retaining concrete structures, *RD Anchor*, 2 nd Edition, Edward Arnold, England

8. Early-age temperature rises in concrete sections with reference to BS 5337:1976 *TA Harrison, Interim Technical Note, ITN 5 - November 1978, Cement and Concrete* Association.

Figure 1 - Charts showing the variation of ΔR^{o} against $\Delta T_1^{o} / T_1^{o}$

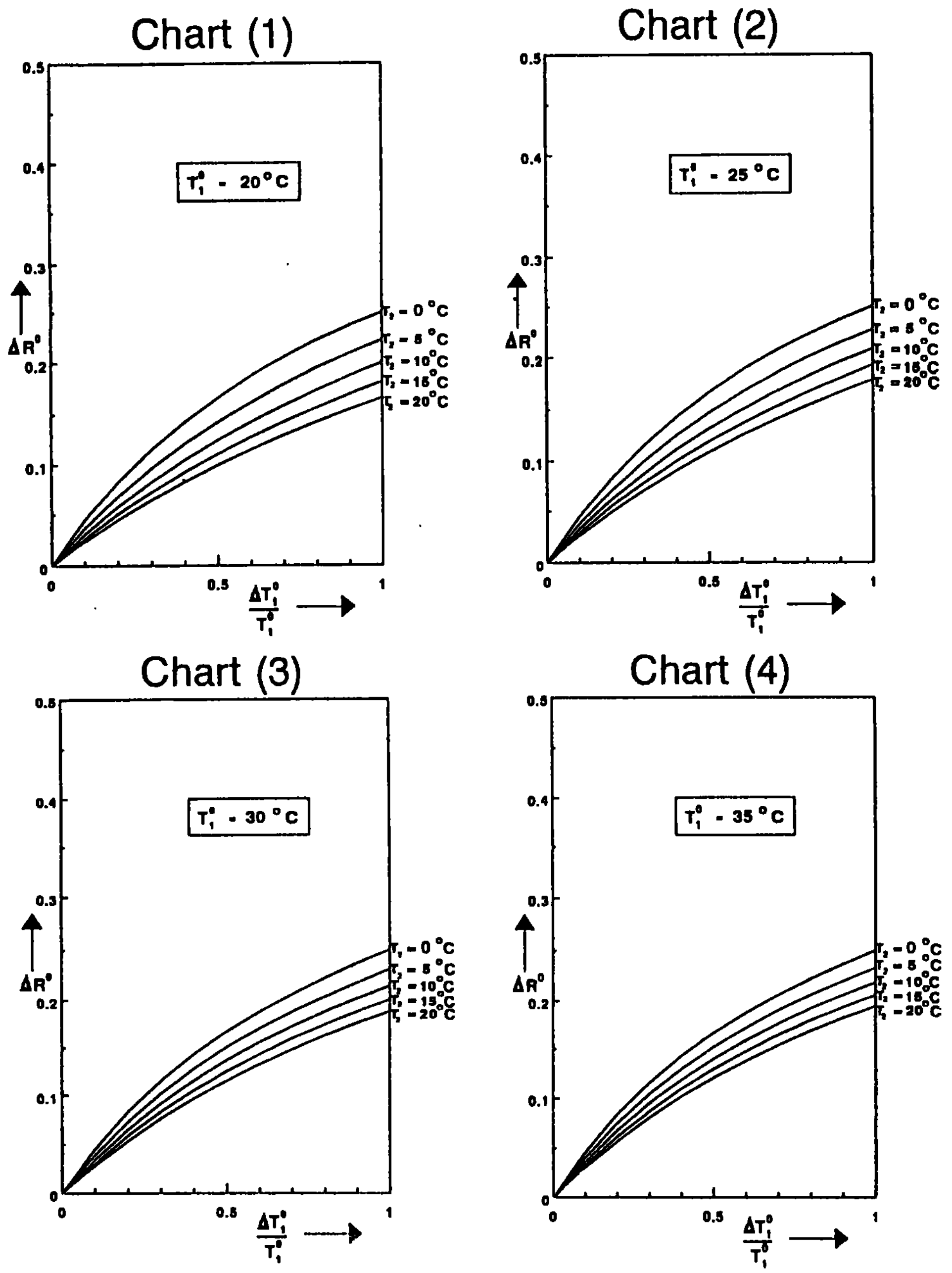
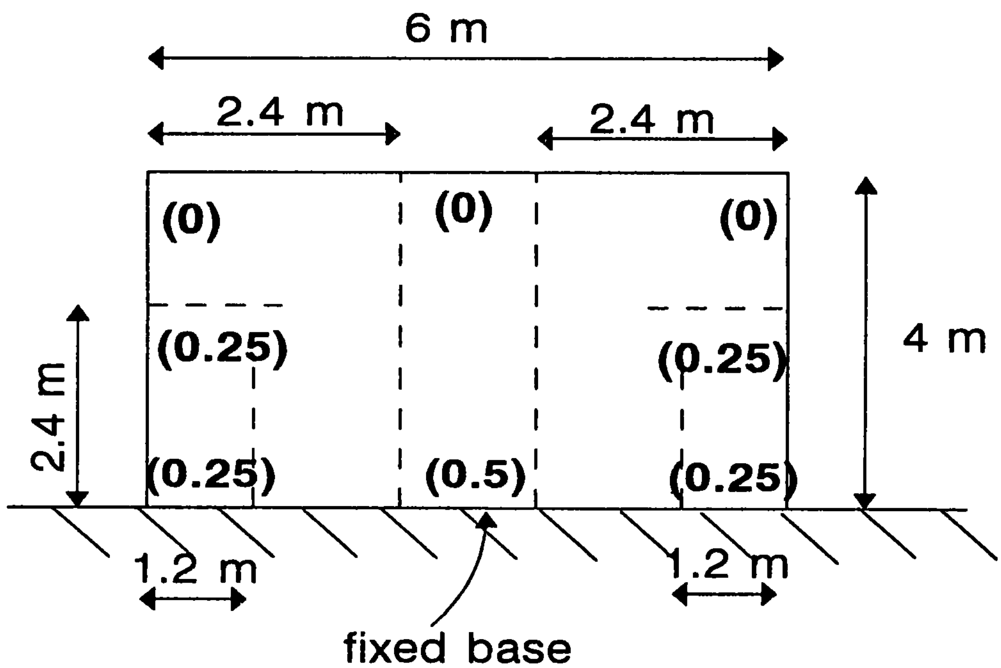


Figure 2 - Restraint Factors at various locations in a wall panel where top and sides are free [5]



(Restraint factors are shown in brackets)

APPENDIX

(A) Typical values of T_1 for OPC concrete when more particular information is not available[5].

1	2		3				4		
Section thickness	Walls						Ground slabs: OPC content, kg/m³		
	Steel formwork: OPC content, kg/m³			18 mm plywood formwork: OPC content kg/m³					
	325	350	400	325	350	400	325	350	400
mm	°C	°C	°C	°C	°C	°C	°C	°C	°C
300	11	13	15	23	25	31	15	17	21
500	20	22	27	32	35	43	25	28	34
700	28	32	39	38	42	49	-	-	-
1000	38	42	49	42	47	56	-	-	-

(B) Minimum reinforcement percentage for fully restrained in-situ concrete - deformed bars (for a mean crack width of 0.15 mm)[1,3]

d_b (mm)	8-12	16	20	24	28	32
ρ (min) %	0.48	0.64	0.80	0.96	1.12	1.28