Brick Cladding on Reinforced Concrete Structures: Deformations and Stresses

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Abstract

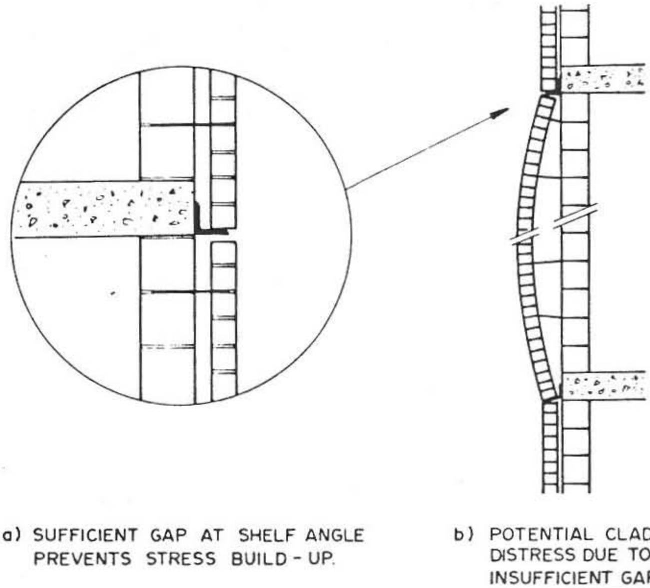
Use of clay brick and concrete block in conjunction with reinforced concrete in highrise construction has been common practice in North America for about two decades. While the clay brick often provides the outer skin of the structure and is supported on shelf angles, concrete block is used as back-up and is built between slabs and columns of the reinforced concrete frame. If properly detailed, constructed and maintained, this system has shown to be extremely durable. Yet cracking and failure of clay brick cladding have become a frequent and often serious occurrence. The problem stems from the deformations that both the reinforced concrete structure and the cladding undergo with time.

The paper deals with the deformations affecting reinforced concrete as well as brick and block masonry. Since some of the deformations are time and load dependent, a computer program was developed that performs the iterative steps required to arrive at deformations and possible stresses in the clay brick cladding when free movement is restrained due to the shelf angle detail. The computer program covers various time intervals up to a maximum of twenty years. The paper concludes with a discussion of the capabilities and limitations of the computer program.

1. INTRODUCTION

Reinforced concrete structures with brick masonry cladding are widely used in the construction of highrise commercial and residential buildings. The selection of brick masonry as the cladding material is based on architectural, structural, environmental and economic factors. It provides an outer skin to the structure which is weather and fire resistant, aesthetically appealing and, if properly designed, constructed and maintained, extremely durable. Yet durability has been a problem of late as cracking and failure of brick masonry cladding has become a serious and all too frequent occurrence. The problem stems from the deformations that both the reinforced concrete structure and the cladding undergo with time. The cladding, normally supported at each storey by a shelf angle as seen in Fig. 1, will not develop distress if a gap of sufficient size is provided below the shelf angle so that all differential deformations between structure and cladding can be accommodated as free veneer movements. Where the gap is of insufficient size or is mortared-in altogether, stresses are set up in the cladding which may lead to serious distress. The basic design information required to prevent such problems are the types and magnitudes of deformations to be considered.

The paper deals first with the key deformations that affect reinforced concrete as well as brick and block masonry. Block masonry is included here because in Canada and the USA it frequently serves as back-up for brick veneer. Once relations for each key deformation have been presented, the paper then outlines a computer program which was developed to arrive at deformations and possible stresses in the brick cladding if free veneer movement is restrained due to the shelf angle detail. For particular information beyond the scope of this paper the reader is referred to Ref. 1 on which this paper is based.



a) SUFFICIENT GAP AT SHELF ANGLE PREVENTS STRESS BUILD - UP.

b) POTENTIAL CLADDING DISTRESS DUE TO INSUFFICIENT GAP AT SHELF ANGLE.

Fig. 1. Typical Shelf Angle Cladding Support

2. ELASTIC SHORTENING

Elastic shortening occurs mainly during the time of construction. The magnitude of elastic shortening of the i^{th} storey for concrete columns, and brick or block masonry can be calculated from:

$$\delta_{el,i} = \frac{P\ h_i}{E_i\ A_{tr,i}} \qquad (1)$$

where

$\delta_{el,i}$: elastic shortening of the i^{th} storey

P : applied load

h_i : height of the i^{th} storey

$A_{tr,i}$: transformed cross sectional area at the i^{th} storey

E_i : modulus of elasticity at the i^{th} storey

In case of reinforced concrete columns, the applied load P is the summation of floor loads and cladding loads. However, as there is a time difference between construction of the concrete columns and construction of the cladding, only the deformations occurring after cladding construction will be considered. Hence the elastic shortening of the concrete columns is calculated from:

$$\delta_{el,i} = \frac{h_i}{E_i\ A_{tr,i}} [\sum_{J=K}^{N} P_{f,J} + \sum_{J=i}^{N} P_{b,J}] \qquad (2)$$

where

P_f, P_b : floor and cladding loads, respectively

K : $i + NOSL + 1$

NOSL : number of storeys lagging between the construction of concrete columns and cladding

N : total number of storeys

For the determination of modulus of elasticity of brick and block masonry the authors utilized empirical formulas given in Refs. 2 and 3.

3. MOISTURE MOVEMENT

Moisture absorption produces expansion in brick masonry made of clay or shale products [4]*; on the other hand, loss of moisture produces contraction

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* Numbers in parentheses refer to references cited at the end of this paper.

or shrinkage in reinforced concrete and concrete block masonry [5]. Moisture expansion of clay brick depends on material composition, the firing process, exposure conditions and the time of exposure. Grimm [6] has estimated the moisture expansion of brick walls after 60 years by the equation:

$$\delta_{me} = 0.6\ e_b\ [3.24 - \ln(T' + 2.3)] \qquad (3)$$

δ_{me} : in-wall moisture expansion after 60 years (%)

e_b : moisture expansion of 2-day old brick after 4 hours exposure to steam at 100°C (%)

T' : kiln to wall time lapse in months

Values of e_b do not appear to be available for Canada and United States brick, but assuming reasonable values of T'(7-30 days) and ∂_{me}(0.02% - 0.04%), the factor e_b can be estimated. According to McDowall and Birtwistle [7], moisture expansion of brick units can be calculated from the equation:

$$\delta_{br} = e_b\ [-0.1929 + 0.6013\ \ln(T_e + 2.2977)] \qquad (4)$$

where

T_e : time of exposure in months

This equation can be applied for any time up to 5 years. By assuming a reasonable ratio between wall expansion and brick unit expansion of 0.6 to 1.10 [4], the moisture expansion of walls can be calculated at any time up to 5 years. To predict the moisture expansion at any time between 5 to 60 years, the authors have assumed a linear relation between moisture expansion and time.

Shrinkage of concrete and concrete blocks depends on the composition of the concrete mix, curing, storage conditions and the size and shape of the member . The magnitude of shrinkage strain of a concrete column can be calculated from Fig. 2 [1].

For a concrete block wall, the maximum shrinkage strain varies between 0.02% to 0.06% for a normal weight concrete and 0.02% to 0.07% for light weight concrete according to the above mentioned factors [8]. For the calculations in this paper an equation has been fitted to the test results given in Ref. 9. This equation, which gives the magnitude of shrinkage after any time with a maximum value of 0.02% after 20 years, is as follows:

$$\epsilon_{sb\ell} = [0.713 - 1.455 \log T + 1.029(\log T)^2 - 0.277(\log T)^3 + 0.025(\log T)^4]/1000 \qquad (5)$$

where

$\epsilon_{sb\ell}$: % shrinkage strain in block masonry

T : time in days

As the relation between shrinkage and log-time is the same irrespective of the maximum shrinkage value, this equation was modified by the authors for other maximum values at 20 years.

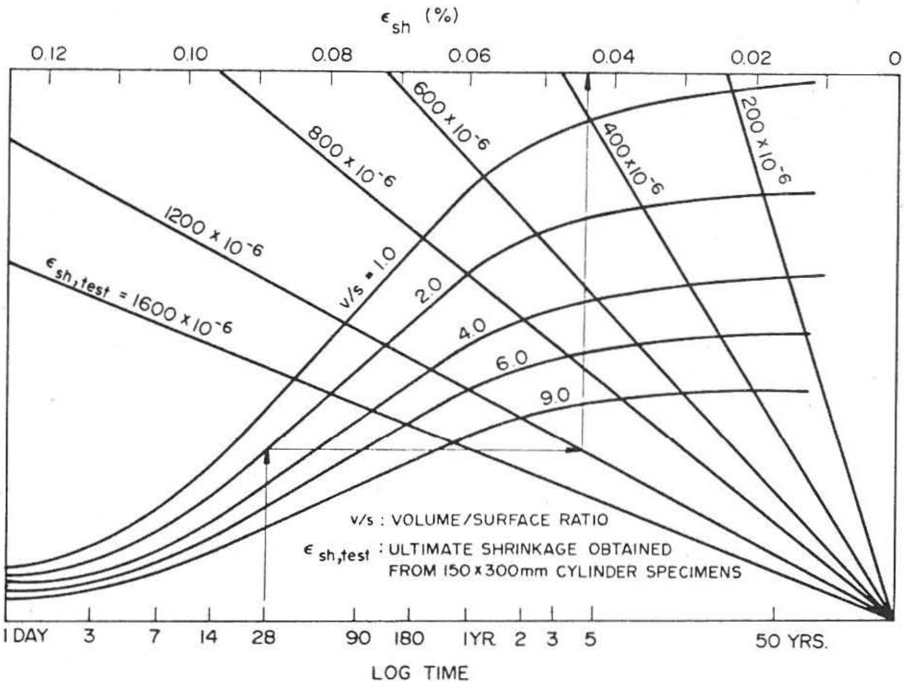

Fig. 2. Relation between Time and Shrinkage Strain

4. CREEP

Creep can be defined as the increase in strain under sustained stress. The magnitude of creep depends on the applied stress, material strength, size of specimen, age at loading and time under sustained load.

For reinforced concrete columns, it is convenient to utilize specific creep, SC, in creep calculations. Specific creep can be determined experimentally or predicted from the modulus of elasticity. As there is a difference in time between the application of floor loads and cladding loads, the specific creep will be different for each load. Hence the magnitude of creep of the

i^{th} storey [10] can be calculated from:

$$\delta_{cr} = \sum_{J=i}^{N} a_{v/s,i}\, a_{age,i}\, h[f_{cf_{J,i}}\, SCF_{J,i} + f_{cb_{J,i}}\, SCB_{J,i}] \qquad (6)$$

where

δ_{cr} : creep deformation of a column at the i^{th} storey

f_{cf}, f_{cb} : stresses due to floor and cladding loading, respectively

SCF,SCB : specific creep at 28 days for loading periods of the floor and the cladding loads, respectively, as given in Fig. 3.

$a_{v/s}$: coefficient to consider the effects of column size on creep as given in Fig. 4.

a_{age} : coefficient to consider effect of age of the column at loading for each load increment as given in Fig. 5.

Curves have been developed to calculate creep directly for the case of columns loaded with equal load increments at equal time intervals, a situation which applies to most highrise buildings. Fig. 6 gives creep deformations after 30 days under loading; other curves for 1, 5 and 20 years under loading are available in Ref. 1.

For brick and block masonry different procedures have been suggested to predict creep deformations. Based on the analysis of a great number of experimental curves, Poljakov [11] suggested the following equation for brick masonry creep:

$$\epsilon_{cbr} = A \frac{f_m}{f'_m} [0.1 + 1.82e^{-0.3 \sqrt[4]{T_L}}](T_o - T_L)^{1/7} \qquad (7)$$

where

ϵ_{cbr} : creep strain of brick masonry wall

T_L, T_o: age of brickwork (in days) at time of loading and time of observation, respectively

A : coefficient depending on the types of brickwork [1]

f_m : stress

f'_m : strength

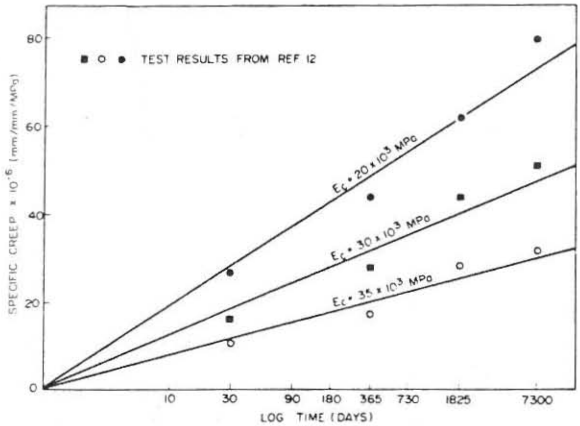

Fig. 3 Relation between Time and Specific Creep

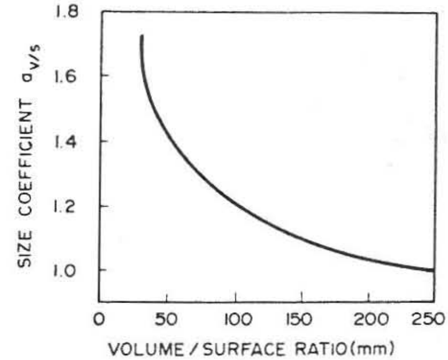

Fig. 4 Effect of Volume to Surface Ratio on Creep

Recent research by the National Concrete Masonry Association [9] has shown that the same method used for predicting creep deformations of concrete can be applied to non-reinforced ungrouted block masonry. The suggested equation is:

$$\epsilon_{cb\ell} = \frac{T_d^{0.6}}{10 + T_d^{0.6}} C_u \tag{8}$$

where

$\epsilon_{cb\ell}$: creep strain of a block masonry wall at any time T

T_d : time under loading in days

C_u : ultimate creep coefficient defined as the ratio of creep to initial elastic strain

C_u- values of 2.33 and 2.39 are suggested for lightweight and normal weight concrete block, respectively [9].

5. EFFECT OF REINFORCEMENT ON CREEP AND SHRINKAGE

The amount of vertical reinforcement has a pronounced restraining effect on the creep and shrinkage of a concrete column. The reductions of creep or shrinkage strains result from a gradual transfer of part of the column

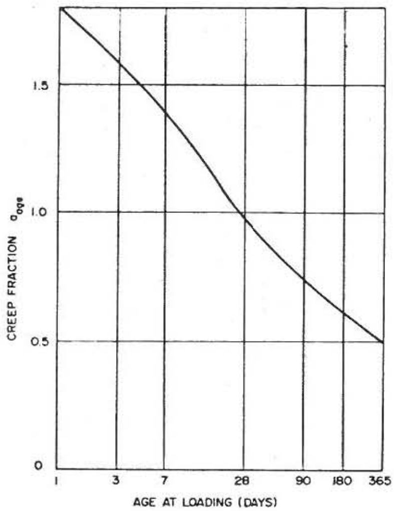

Fig. 5 Effect of Age of Loading on Creep as Fraction of Creep for Loading at 28 Days [12]

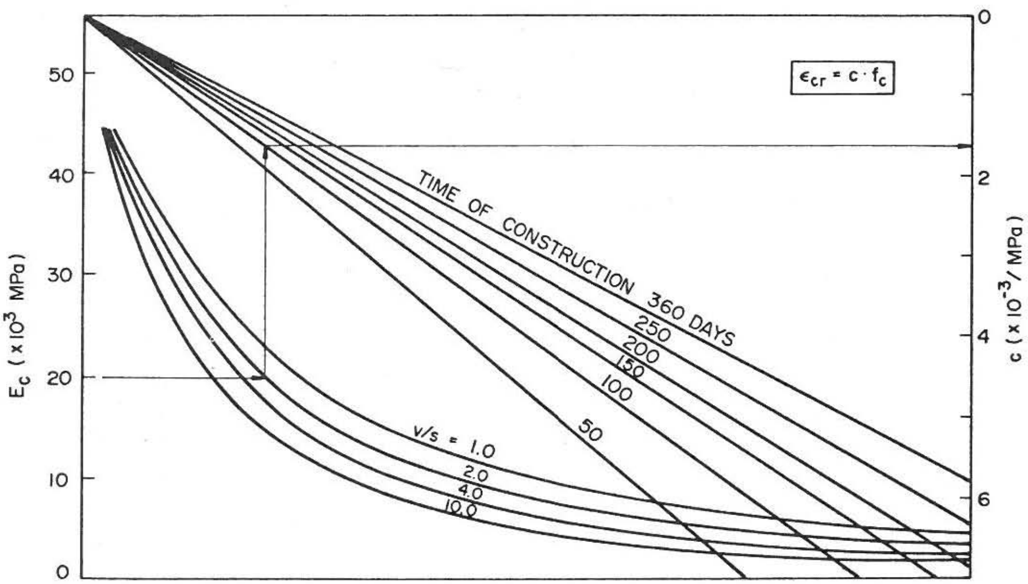

Fig. 6 Creep Strain after 30 Days under Loading

load from the concrete to the steel. The residual creep and shrinkage strains of a reinforced concrete column are equal to the additional strain of the reinforcement and therefore can be calculated from the change in steel stress [12]:

$$\Delta f_s = \frac{\epsilon}{\rho SC'} \left(1 - e^{-(\rho n/1+\rho n)SC'E_c}\right) \tag{9}$$

where

Δf_s : change in steel stress due to creep or shrinkage strains

ϵ : total creep or shrinkage strain of plain concrete

SC': ultimate specific creep of plain concrete

ρ : reinforcement ratio of the section

E_c : modulus of elasticity of concrete

n : modular ratio = E_s/E_c

The residual strain then is equal to $\Delta f_s/E_s$. If it is assumed that the relation between time and the change in steel stress is the same relation as between time and specific creep, Δf_s at any time can be calculated by substituting in Eq. 9 the value of the specific creep at that time instead of the ultimate specific creep.

6. THERMAL MOVEMENT

Thermal movement is a short term deformation due to change of temperature of the material. The magnitude of thermal movement depends on the coefficient of thermal expansion and on the initial and final temperatures which in turn depend on the following: Temperature inside and outside the building at the time of construction and at the time under consideration; location and type of insulation material; width of air cavity; coefficient of thermal conductivity of concrete, insulation and cladding material. These factors control the heat flow through the building section and in turn control the initial and final temperature of each element of the section [13]. The thermal movement of concrete columns and brick or block masonry in the i^{th} storey can be calculated from:

$$\delta_{t,i} = \alpha(t_1 - t_2)h_i \tag{10}$$

where

$\delta_{t,i}$: thermal movement at the i^{th} storey

α : coefficient of thermal expansion

t_1, t_2 : initial and final temperature, respectively

7. STRESSES DUE TO DIFFERENTIAL DEFORMATION

Based on the stated procedure for each type of deformation, the free deformation that will take place in each of the structural elements consisting of

reinforced concrete columns, brick cladding and block masonry backup can be calculated. Unless a gap of sufficient size is provided under the shelf angle at each floor to accommodate differential deformations between concrete columns, cladding and backup, stresses will be developed in the cladding. The magnitude of these stresses depends mainly on the magnitude of the differential deformation, the width of the joint provided and the rigidity of the shelf angle connection.

In order to calculate resultant stresses in the cladding, final unrestrained deformations of the three elements are equated at each floor level and residual strains are determined assuming a linear stress-strain relation. Because some of the deformations are time and load dependent, a computer program was developed that performs iterative steps to arrive at deformations and possible stresses in the brick cladding if free veneer movement is restrained due to the shelf angle detail. Capabilities and limitations of the computer program, which enables a designer to determine deformations and possible stresses for various time intervals up to twenty years, are outlined in the last section of this paper.

8. COMPUTER PROGRAM

The computer program is written in FORTRAN language. It calculates the deformations that take place in the reinforced concrete columns, brick veneer, and block masonry backup. It also determines resulting stresses due to differential deformations if free veneer movement is prevented by the shelf angle detail. The program has the following capabilities and limitations:

- It calculates the magnitude of differential deformations and possible resulting stresses at each storey and after any chosen period of time between 14 days and 20 years. Selected time intervals are 14, 20, 90, 180 days and 1, 5 and 20 years. In each interval, the stresses calculated from the previous one are used to calculate the new deformations.

- Stresses due to restrained differential deformations are assumed to be axial and to vary linearly with strain.

- The maximum number of storeys is 30.

- It calculates deformations and possible stresses for any assumed value of support rigidity and horizontal joint width.

- Deformations and stresses can be calculated in cases where cladding supports are provided at intervals of more than one storey.

The computer program has been applied to four case studies involving brick cladding distress in Canada. Details of the four case studies are presented at this conference in a second paper entitled "Brick Cladding Distress in Reinforced Concrete Structures: Four Case Studies " [14].

9. CONCLUSIONS

Key deformations affecting reinforced concrete as well as brick and block masonry have been identified as elastic, moisture, creep and thermal movements. Procedures are suggested to determine the magnitude of each deformation under unrestrained conditions. Subsequently a computer program was developed to estimate at any period of time the deformations and possible stresses imposed on the brick cladding when free veneer movement is restrained due to an inadequate shelf angle detail.

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