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論 文

[2015] Evaluation of Thermal Stresses in Concrete Liquid Storage Tanks

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1. INTRODUCTION

Concrete liquid storage tanks are used for many purposes particularly in water-supply and waste-water treatment schemes and also as industrial liquid retaining structures. In the past, hydrostatic pressure from the retained liquid was considered to be the dominant loading condition. However, in recent Codes of practice [1,2], the designers are required to incorporate thermally induced stresses in the design process. Similar requirements have been introduced in concrete bridge design practices [3].

The available design aids and recommendations are however limited in this regard [4,5,6]. The early deterioration of many concrete liquid storage tanks has been attributed to the lack of guidelines and recommendations based on rational approaches for the evaluation of thermally induced stresses [6].

In this paper, the significance of thermal stresses and their evaluation are discussed. A simplified non-linear analysis methodology for the analysis of cylindrical concrete reservoirs subjected to rotationally symmetric loading, is also described.

2. PROVISIONS OF THE CODES OF PRACTICE

Thermal gradients across the wall thickness develop mainly due to the solar radiation and ambient temperature changes as well as due to the storage of hot or cold liquids depending on the functional requirements. The nature and magnitude of the induced temperature gradients depend on many factors such as material properties and local meteorological factors.

Based on few measured data [7], typical linear temperature gradients have been specified in few design standards [1,2] for different conditions: summer and winter for tank full and empty conditions, Fig. 1. It is assumed in Fig. 1 that the temperature of the inside face of the reservoir wall does not change. Other standards and design practices have left the evaluation of temperature gradients to the designer, and this has led to the improper treatment of this loading condition [6,8].

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The significance of cracking on the relaxation of thermal stresses has been treated rather cursorily in [1,2] by specifying constant stress reduction factors, Fig. 2. The need for research on the relaxation of thermal stresses has been however recognised [1,2].

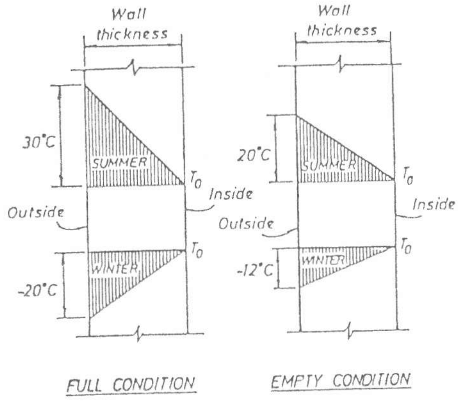

Fig. 1 Recommended temperature gradients [1,2]

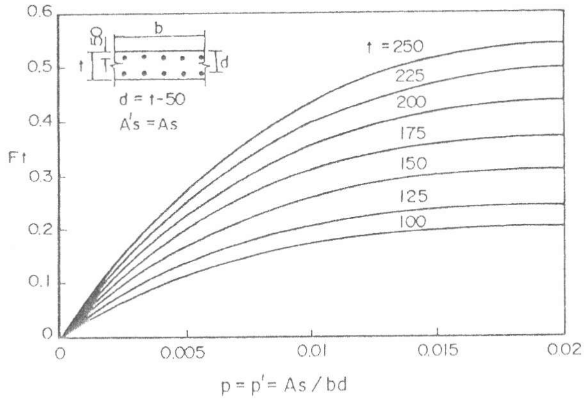

Fig. 2 Stiffness reduction factors F_t [1,2]

3. THE SIGNIFICANCE OF THERMAL STRESSES

Thermal stresses are caused by induced strains and they hence directly depend on the stiffness of the member (load-deformation response). Cracking of the member would therefore relax thermal stresses significantly.

Under service loading conditions, the magnitude of thermal strains is significant in comparison with the elastic strains caused by the applied loadings such as the hydrostatic pressure. Therefore, thermal stresses are generally significant only under the service loading conditions.

The design of liquid retaining structures is mainly governed by the limited crack width criterion under service conditions [1,2,9]. The incorporation of thermal stresses is therefore of particular importance in the design of liquid retaining structures.

4. DETAILS OF THE RESEARCH

4.1 BACKGROUND

Analysis methods and design aids are well established for the determination of flexural moments and hoop forces on reservoir walls subjected to common loadings such as hydrostatic and gas pressures [10]. These also have limitations in their applicability such as uniform wall thickness and typical loading patterns.

The combined applied and thermal stresses usually exceed the cracking strength of the section. Cracking not only reduces the magnitude of thermal stresses but also redistributes the moments and forces throughout the reservoir wall. The analysis using the uncracked section properties is therefore an incompatibility. This could result in a gross overestimate of the thermal stresses [11]. The use of constant stress reduction factors to account for cracking, Fig. 2, does not represent the actual behaviour of the wall. To predict the stress relaxation due to cracking, the actual load-deformation response of the wall elements should be incorporated in the analysis.

4.2 NON-LINEAR BEHAVIOUR OF WALL ELEMENTS

Before attempting to develop sophisticated analysis methods, the load-deformation response of the wall elements has to be established. There are various methods proposed in the literature [12] to estimate the "tension stiffening" effect. These are mainly based on the test results on beam members subjected to applied loadings. Therefore, an experimental study [11] was carried out on typical reinforced concrete wall elements subjected to applied and thermal flexural moments with and without simultaneous inplane tensile forces. Both unidirectional and bidirectional behaviours were investigated.

These experimental results [11] showed that the Branson formulation [13] for calculating the effective flexural stiffness would be a suitable model for predicting the non-linear behaviour of wall elements, (Eq. 1).

$$I_e = (M_{cr}/M)^3 \ I_{tg} + [1 - (M_{cr}/M)^3] \ I_{cr} \qquad (1)$$

where I_e is the effective moment of inertia, M is the moment at which I_e is calculated, M_{cr} is the cracking moment, I_{tg} is transformed uncracked section moment of inertia, and I_{cr} is the cracked section moment of inertia.

As the Branson formulation was originally developed for members subjected to flexural moments only, a modification was done to include the high level of inplane tensile force [11], representing the hoop forces imposed by the hydrostatic pressure on a reservoir wall. The ACI Committee 224 Report on "Cracking of Concrete Members in Direct Tension" [14] recommends a formulation analogous to the Branson formulation for predicting the axial force-strain response of concrete elements.

4.3 DETAILS OF THE NON-LINEAR ANALYSIS

4.3.1 Assumptions and limitations

The assumptions and limitations are; (a) imposed loadings are rotationally symmetric, ie, do not vary around the tank's circumference (b) linear temperature gradients across the wall thickness (c) creep effects of concrete can be neglected and (d) non-linear behaviour of wall elements can be represented by the Branson formulations as outlined in Section 4.2.

4.3.2 Structural simulation

The loadings imposed on cylindrical reservoirs are resisted by the vertical beam and the hoop (inplane) actions. This wall action is similar to that of a beam on an elastic foundation (BEF) [15]. The wall hoop action is represented by the sub-grade reaction equal to Et/R^2 where E is Young's modulus of the wall material, t is the wall thickness, and R is the reservoir radius.

In a more generalised approach, this behaviour can be simulated by beam members on discrete struts or springs (frame analogy) with beam members representing the wall flexural action and struts representing the wall hoop action, Fig. 3. The axial stiffness of each horizontal strut represents the radial hoop stiffness of the wall contributory area.

In the nonlinear range beyond cracking, an incremental analysis was carried out with the wall stiffness values modified at the end of each load or temperature increment. The hydrostatic pressure is applied as equivalent nodal forces. The total temperature gradient is considered incrementally as shown in Fig. 4. A full description of the method can be found in Ref [11].

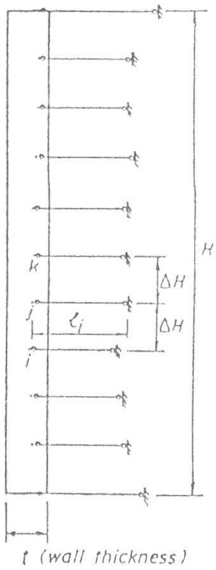

Fig. 3 Frame analogy simulation

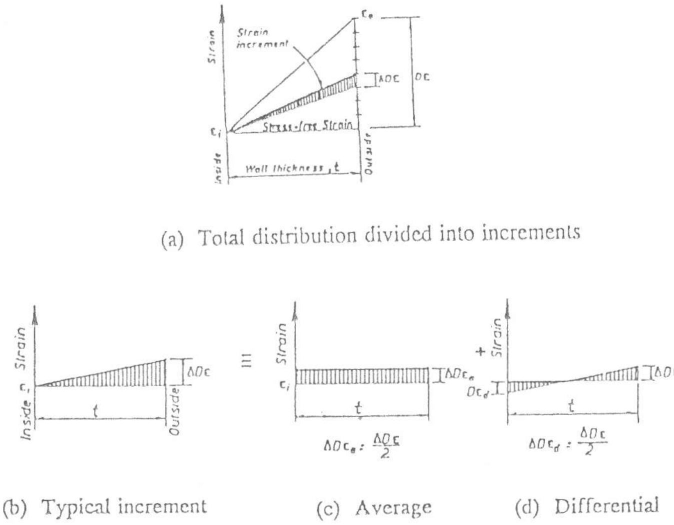

Fig. 4 Thermal strain distribution across wall thickness

5. ANALYSIS OF A TYPICAL RESERVOIR

5.1 DETAILS

A typical reservoir is analysed to compare the results predicted by the non-linear analysis method developed (Section 4.) and the values obtained using the constant stiffness reduction factors shown in Fig. 2.

This example would represent reinforced concrete reservoirs constructed in New Zealand and Australia. The reservoir capacity is 5000 m^3 with height H = 8.0 m, radius R = 14.0 m and uniform wall thickness t = 300 mm. The wall is doubly-reinforced with equal reinforcing steel ratios on each face. The steel ratio p (= A_s/bd, where t=d-c) in each face in each direction are; vertical = .005 and circumferential = .013 up to the mid-height (= H/2) and .009 up to the wall top. The concrete cover to steel c is 45 mm (vertical) and 60 mm (circumferential). The reservoir wall is assumed to be pinned at the base (no sliding but rotation permitted) and free at the top.

The typical values assumed for the material properties were; Young's modulus of concrete and steel E_c = 27,800 MPa and E_s = 200,000 MPa, and concrete coefficient of thermal expansion α = 10×10^{-6}/°C. Two values were used for the tensile strength of concrete f_t = 1.75 and 3.00 MPa to represent the range of tensile strength values found for concrete wall elements [11]. These f_t values would correspond to C_t = 0.3 and 0.5 for concrete compressive strength f'_c = 35 MPa ($f_t = C_t\sqrt{f'_c}$).

5.2 RESPONSES OF THE RESERVOIR WALL

Figure 5 shows the analysis results for the reservoir "full summer" temperature gradient shown in Fig. 1. The responses shown include the combined effect of hydrostatic pressure and temperature loadings.

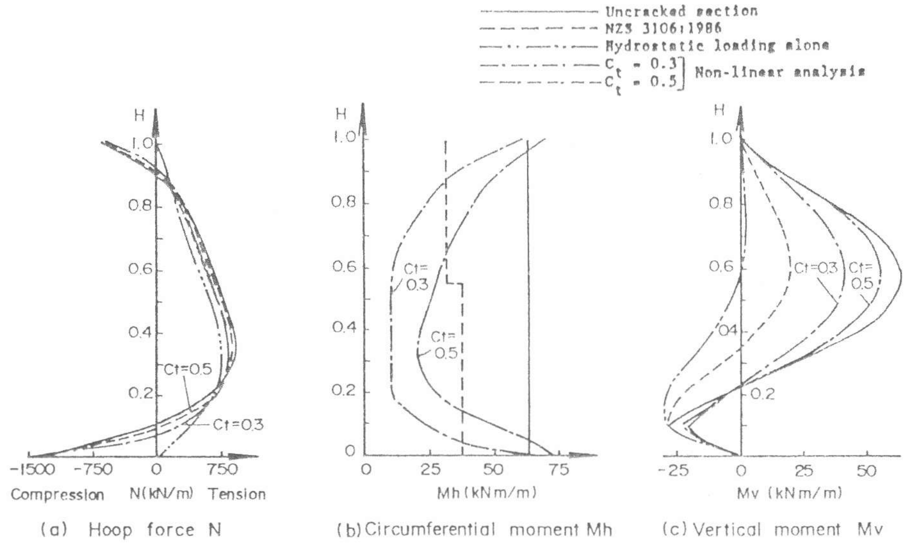

Fig. 5 Moments and hoop force for reservoir "full summer" temperature gradient

From the distributions of hoop force N, circumferential and vertical moments M_h and M_v shown, it can be seen that significant differences exist between the Code recommended values and the predicted values. The following brief observations can be made for this particular example;

(a) Combined hoop forces N are not much different from the hydrostatically induced hoop forces, except close to the base and the top.

(b) Circumferential moments M_h are much less than Code values with a maximum reduction of upto 70%.

(c) Vertical moments M_v are much higher than the Code values due to the fact that the degree of cracking in this direction is not high.

6. CONCLUSIONS

As shown by a typical example, the use of constant stiffness reduction factors does not represent the actual behaviour of the reservoir wall. Similar analyses for a wide range of reservoirs showed that the differences are inconsistent. While the approach taken by [1,2] to incorporate temperature effects is to be appreciated, there is an urgent need for more research in this area.

ACKNOWLEDGEMENT

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