Design of Reinforced Concrete Containment Structures for Thermal Gradients Effects

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SUMMARY

The need for more accurate prediction of structural behaviour, particularly under extreme load conditions, has made the consideration of thermal gradient effects an increasingly important part of the design of reinforced concrete structures for nuclear applications. While the thermal effects phenomenon itself has been qualitatively well understood, the analytical complications involved in theoretical analysis have made it necessary to resort to major simplifications for practical design application. A number of methods utilizing different variations in approach have been developed and are in use today, including one by Ontario Hydro which uses an empirical relationship for determining an effective moment of inertia for cracked members.

Depending on the nature of the simplifications, the existing methods can yield substantially different results. This paper describes an evaluation of the different approaches, based on a sensitivity study which has been carried out to assess the degree of effect of changes in the various assumptions. It confirms that the results are primarily dependent on the assumptions regarding the extent, distributon and behaviour of concrete cracking, which, in turn, is influenced by concrete tensile strength, tension stiffening, mechanical load interaction and axial load effects.

Reliable quantitative values for many of these parameters are either not available or are limited to the range of operating temperatures. Predictions of performance, particularly in the range approaching the yield limits of reinforcing or the initiation of localized cracking, is difficult and requires the use of appropriate conservatism in designs. Data on the post yield effects of thermal gradient is non-existent, as is experimental confirmation of many aspects of practical performance such as crack recoverability, leakage, etc.

As a step toward confirming the design approaches and improving design precision and economy, a major test program is being initiated at Ontario Hydro. This paper describes the specific objectives of the program and some of the experiemental arrangements prepared.

1.0 INTRODUCTION

Thermal gradient effects are an important consideration in the design of reinforced concrete structures for nuclear applications. The various factors which influence the response of a structure to thermal loadings have been extensively studied in the past, but analytical models for accurately predicting their effects have been too complex for practical design applications. As a result, most existing methods utilize varying types and degrees of simplification, which, in turn, necessarily affect the accuracy of their results. A further problem in current analyses is the lack of reliable quantitative data on the variation of individual parameters, particularly when approaching the limits of elastic behaviour and the onset of significant localized cracking.

While current designs for nuclear structures can adequately cover these shortcomings by appropriate conservatism in design, accurate prediction of structural safety margins is very difficult. Current methods of analyses are, moreover, limited to behaviour within the elastic limits of reinforcing. Experimental data on behaviour in the inelastic range is rather minimal.

A sensitivity study was undertaken to gain a better understanding of the simplifications inherent in the major design approaches, and to determine which of these might warrant closer analytical and experimental investigations. This study compares the results of different simplified design approaches with those of a more rigorous analysis. An experimental program is being undertaken at Ontario Hydro to confirm present analytical assumptions and to obtain further data on thermal effects in the inelastic range.

2.0 DESIGN APPROACHES

The major differences in current design approaches lie in the assumptions and simplifications used to model the cracked member stiffness. Most of the design approaches presently available can be generalized into the following three categories:

(a) fully cracked members;

(b) cracked section as determined by mechanical moment distribution;

(c) cracked sections as per effective moment of inertia.

The "fully cracked members" approach assumes that the entire tensile region of the member is fully cracked in all loading cases. As an example in the case of frame analysis, this approach will result in all members cracked over their full length. Methods suggested by Gurfinkel [1] and Pajuhesh [2] belong to this category. In this study, Gurfinkel's method is used as a representative approach.

The "cracked section as determined by mechanical moment distribution" approach recognizes that uncracked lengths might exist in a member near the regions of contraflexure. The cracked and uncracked regions are determined on the basis of mechanical moments alone and thermal moment distribution is carried out considering this variation in stiffness along the member. At any cracked section, the stiffness evaluated is the fully cracked stiffness. This approach is suggested by ACI Committee 349 [3].

The "cracked sections as per effective moment of inertia" approach assumes that the effect of cracked and uncracked lengths in a member is equivalent to an effective moment of inertia when the complete member is considered. This effective moment of inertia is calculated considering the stiffness contributions of tensile strength of concrete, tension stiffening and crack progression. Three distinct approaches are available to evaluate the effective stiffness as suggested by Kar [4], Macchi and Sangalli [5] and Mentes, Bhat and Ranni [6]. In this study, the "I_e Method" suggested by Mentes, et. al., has been used, and the effective moment of inertia is evaluated based on the empirical relation suggested in the American and Canadian codes for calculating deflection of continuous beams. The cracking is due to combined mechanical and thermal loads and the stresses are evaluated by characterizing the tension effects in terms of an equivalent area of steel with its centroid coinciding with the centroid of tension steel.

3.0 SENSITIVITY STUDY

In this investigation, a sensitivity study has been carried out by analyzing a typical restrained section by each of the representative design approaches outlined above and comparing the results with those of a more rigorous numerical analysis.

The rigorous analysis is carried out by adopting the procedure used by Bazant and Bhat [7] for mechanical load analysis. In this procedure, a section is divided into layers and discrete rebar positions with perfect bond assumed between them, and an equilibrium analysis is performed to obtain moment-curvature relations considering the time history of load application. The constitutive behaviour of concrete is modelled using Endochronic Theory. The method takes into account the confining effect of stirrups, constant shear strains and the elastic-plastic-strain hardening behaviour of reinforcing steel.

Cracking of concrete is modelled by assuming that each layer cracks when the principal stress in the layer exceeds the theoretical tensile strength of concrete. The stiffness of the cracked concrete layer is re-evaluated assuming that the tensile stress across each crack is zero. The shear stress transferred across the crack is considered in an approximate way by the use of a constant shear transfer factor ($\alpha = 0.5$) in the material stiffness matrix.

4.0 DISCUSSION OF RESULTS

The typical fully restrained beam section shown in Figure 1 was analyzed using assumed linear thermal gradients. The calculated moments and rebar stresses for various load conditions are shown in Figures 1 to 3.

Results show that at operating temperature gradients or for load combinations producing rebar stresses less than approximately 0.5 times yield strength fy, the calculated thermal moments are greatly influenced by the type of model used for concrete tension and tension stiffening effects. Depending on the assumption used, the discrepancy in thermal moments can be as much as 75 percent compared to the more rigorous layered analysis (see Figure 1a). As the yield limit is approached, this disparity is gradually reduced (see Figure 1b). The deformations predicted by the simplified methods at rebar yield limit are less than that of rigorous analysis. This indicates that if these methods are used to estimate the remaining inelastic rotations, they will be overestimated. The effective moment of inertia method provides the closest approximation at all load stages compared to the rigorous analysis. It is expected that the disparity could be reduced further with better modelling of aggregate interlock, dowel action and tensile strength of concrete.

From Figure 2, it is apparent that the approach taken in considering axial loads also has a significant bearing on the calculated thermal moments. If the effects of axial compression are not considered when evaluating cracked section properties, then thermal moments will be underestimated.

Figure 3 shows the rebar stresses calculated using the different design approaches. Results indicate that consideration of tension stiffening effects appreciably reduce average rebar stresses, particularly at service load levels. Even near ultimate load levels, the differences in calculated stresses are not negligible.

5.0 PROPOSED EXPERIMENTAL RESEARCH

The sensitivity study has shown that improvements can be made in the present thermal analysis methods and further information is needed to investigate the possible additional safety available in the range of inelastic behaviour, which could result in improved and more economical designs. To this end, a major test program will be carried out at Ontario Hydro's Research facilities over the next three years. Several large scale reinforced concrete models will be subjected to combined thermal and mechanical loads as part of the proposed study.

The prototype test specimen proposed is an inverted portal frame with suspended side panels as shown in Figure 4. Preliminary details call for the frame to be constructed of three reinforced concrete members each approximately 0.3 m thick, 1.0 m wide and 2.5 m long. The columns of the frame will be tied by two post-tensioning rods, and two 0.10 m thick reinforced concrete panels will complete the tank-like model. The panels are to be structurally independent of the frame, connected only by a flexible membrane or bellow, and hence will not affect the frame's stiffness or deformation. Both the frame and the side panels will be extensively instrumented with thermocouples, strain gauges and displacement transducers. Also, the post-tensioning rods and panel support rods will be fitted with load cells, giving positive readings of compatibility-induced thermal forces.

Thermal load will be applied to the test model by heating the contained water up to temperatures of 100°C. Under such conditions, the structure will tend to distort outwardly, but will be restrained by the tie-rods, thus inducing moments within the frame. The bottom member will be subjected to a uniform moment along its entire length; the vertical members will be under linearly varying moments. In subsequent tests, externally applied mechanical loads will also be superimposed. Thus, the test models should provide important data relating to the stiffness of cracked members, the magnitude of stresses induced, development of thermal gradients, formation and progression of cracks, load interaction effects, inelastic rotation capacity at failure, and other pertinent behaviour characteristics.

6.0 CONCLUSIONS

While current methods for calculating thermal gradient effects are satisfactory provided adequate conservatism is employed in the design, significant improvements could be made to permit more precise evaluation of safety margins.

The design approach, using an effective moment of inertia, provides the closest approximation of moments, stresses and deformations at all load levels compared to those derived by rigorous analysis, and can be considered to be the most realistic approach available at this time.

At operating temperature levels when rebar stresses are well below their yield limits (less than approximately 0.5 fy), the effect of tension stiffening and tensile strength of concrete greatly influence the calculated thermal moments and stresses.

The actual rotation capacity and available amount of redistribution appear to be less than that estimated by simplified design methods. Further investigation regarding these aspects is required to establish the margins of safety under extreme loads.

Additional experimental evaluation would be necessary to provide definitive information for the more precise prediction of gradient effects. Investigation of behaviour under limiting conditions and in the inelastic range could be particulary helpful.

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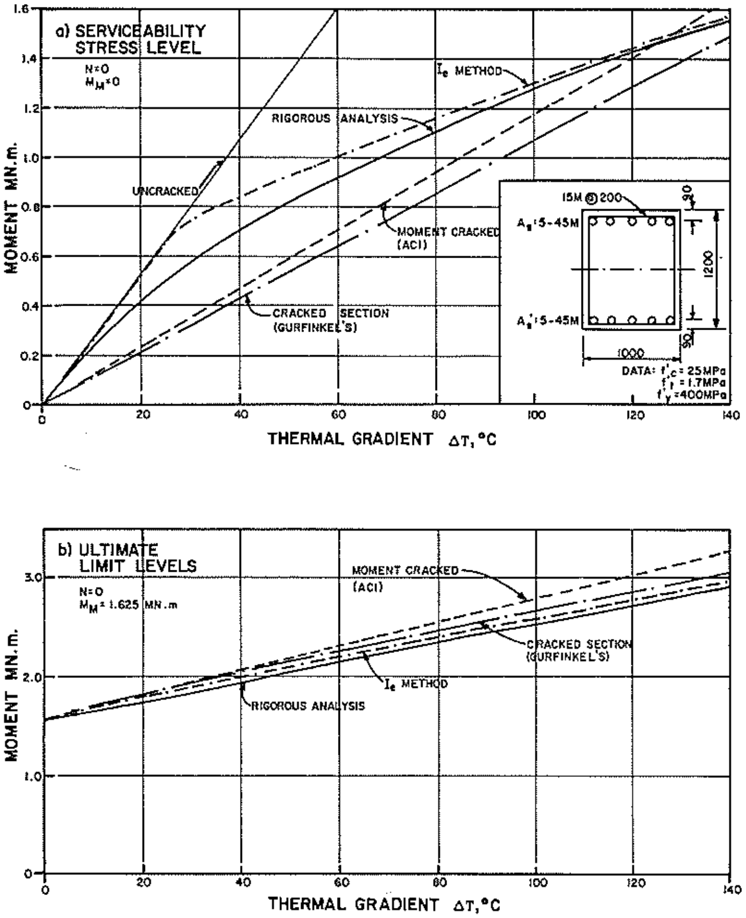

Figure 1 Comparison of Moments

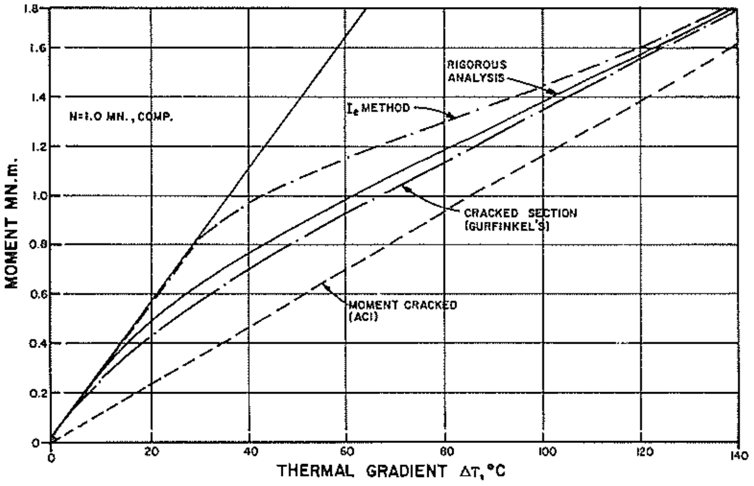

Figure 2 Effect of Axial Force

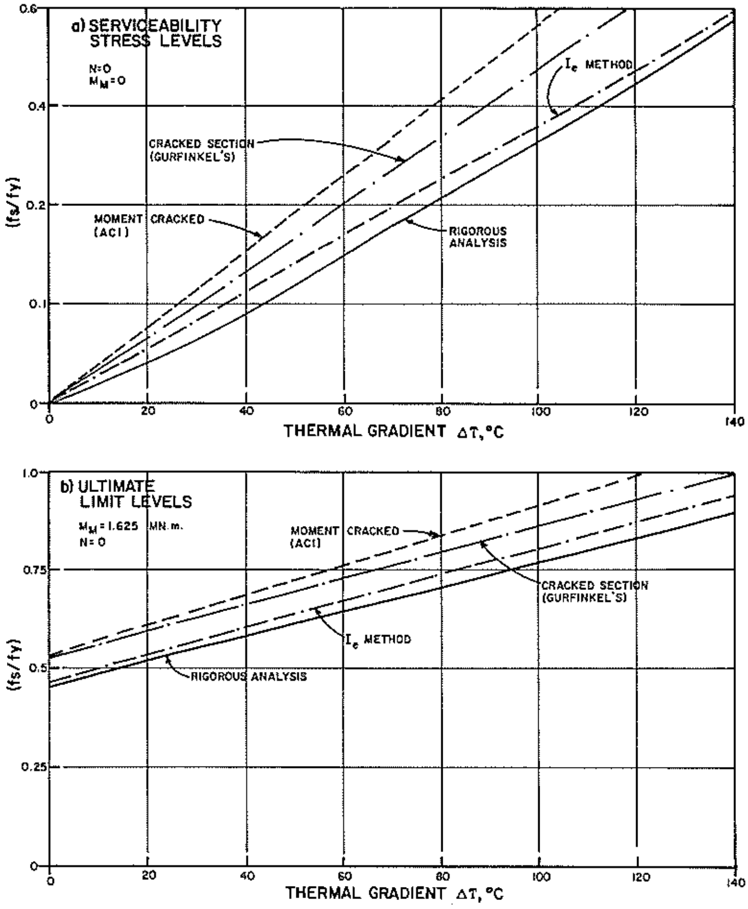

Figure 3 Comparison of Rebar Stresses

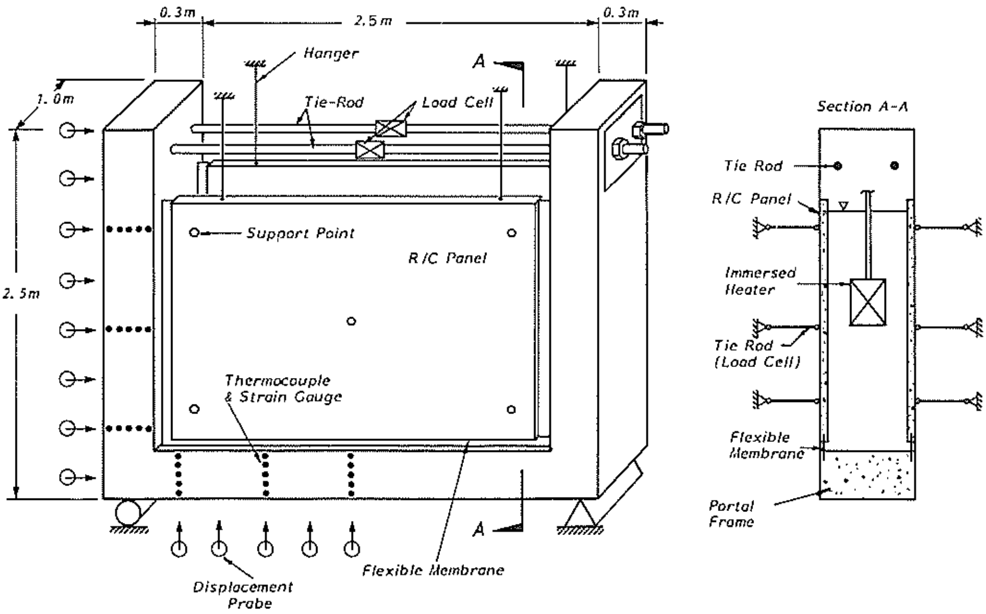

Figure 4 Portal Frame Test Model