Influence of Post Cracking Behaviour on the Response of Concrete Structures Under Thermal Gradients

P.D. Bhat
Ontario Hydro, Civil Design Dept., 700 University Ave., Toronto, Ontario M5G 1X6, Canada

Abstract

The factors influencing the behaviour of a cracked reinforced concrete structure subjected to thermal gradients is studied. The presently available approaches to consider these factors are first classified into three main categories and their relative merits are discussed.

The response of a frame structure subjected to thermal and nonthermal loads is predicted using the applicable methods. The frame structure studied analytically has been constructed and tests are currently being carried out to observe the behaviour under thermal gradients. Some preliminary results are shown and compared with analytical predictions.

The effect of considering post cracking behaviour on concrete nuclear structures is illustrated.

1. Introduction

The behaviour of reinforced concrete structures after the initiation of tensile cracking is greatly influenced by the bond between reinforcing bars and concrete, aggregate interlock, dowel action and tensile strain softening of concrete. These tensile stiffening effects provide a much larger stiffness for members compared to that assumed in conventional ultimate strength approaches. In reinforced concrete structures subjected to temperature gradients the evaluation of true stiffness gains special importance because of the direct dependency of moments and forces on the stiffness. Traditionally thermal stress analysis of nuclear containment structures has been carried out neglecting the contributions of the tensile concrete. This approach, although adequate to evaluate the ultimate strength, needs to be improved with the addition of tension stiffening effects to analyze service conditions and deformations of the structure.

In recent years a number of methods have been developed [1-5] to consider the various post cracking effects in reinforced concrete structures. However, most of these methods have been used for the analysis of structures under non thermal loads. The applicability of the methods to evaluate the response of structures under the stiffness dependent loads such as those produced by temperature gradients have not been fully studied.

The purpose of this paper is to study the applicability of various post cracking behaviour models of reinforced concrete to the prediction of structural response under thermal gradients. Temperature ranges encountered in service and accident conditions in a nuclear containment structure are of primary interest. The theoretical models are first classified according to the method of approach. Applicability of these approaches to thermal problems are discussed. Some typical methods are used to predict the behaviour of a frame structure which is currently being tested under thermal and mechanical loads. Preliminary test results are presented and compared with analytical predictions. The use of tension stiffening studies to determine the safety margins of nuclear structures is illustrated.

2. Post Cracking Behaviour Models

Depending on the analytical approaches used currently available models to consider post cracking effects could be classified into three categories as: (a) equivalent concrete stress strain models; (b) equivalent steel models; and (c) effective stiffness models.

In the equivalent concrete stress strain models the performance of concrete members after initiation of tensile cracking is idealized using an equivalent tensile stress strain curve for concrete. This equivalent curve is modelled to include the tension stiffening effects due to bond, aggregate interlock, dowel action and tensile strain softening. Some examples of such models are: the stepped response used by Scanlon [5], the gradual non linear unloading approach used by Vecchio and Collins [2] and the gradual linear unloading approach derived by Bazant and Oh [4]. The exact profiles of the curves were derived based on various experimental evidence. For example, Vecchio and Collins used test data from panels and Bazant and Oh used fracture test data. Derivation of a proper stress strain diagram with broad applicability is the main difficulty in this approach.

A comparison of some of the stress-strain curves are shown for a typical structural element in Figure 1. It is seen that considerable differences exist in the models which would affect the structural evaluations. The advantage of the equivalent concrete stress-strain approach is that they are adoptable in nonlinear analysis programs to trace the history of structural behaviour all the way up to failure. Such methods are ideally suited to analyze thermal response. The method proposed by Vecchio [6] specifically considers practical applications using micro computers.

In the equivalent steel models tension stiffening is modelled as an increase in the stiffness of the reinforcement [1,3]. This approach neglects the effect of progressive cracking with increasing load and hence is more pertinent when behaviour at ultimate load levels are of interest. In analyzing the behaviour under progressive cracking, such as required in the problem currently being studied this approach is not appropriate.

The effective stiffness approach is based on empirical derivation of effective moment of inertia such as those given by Branson [7]. Mentes et al [8] have shown that this approach is applicable for the analysis of thermal effects when load interactions and moment distributions are accounted. The method has the advantage of being simple to use and provides realistic predictions in the range of interest.

3. Analytical and Experimental Work

To confirm the validity of current understanding and to study the usefulness and reliability of simple design methods a combined analytical and experimental work has been undertaken.

As part of the analytical studies the response of a frame structure is analyzed using some of the representative methods. The frame structure chosen is an inverted portal frame shown in Figure 2. This frame will also be used in the experimental investigations. The structure has been analyzed using an equivalent concrete stress strain approach and the effective stiffness approach. In the equivalent concrete stress strain approach the tension stiffening model developed by Vecchio and Collins [2] has been used. For the effective stiffness approach the method formulated by Mentes et al [8] has been chosen. The equivalent steel approach has not been considered because it is thought to be inappropriate for this analysis. The response of the structure neglecting tension stiffening effects is also evaluated for comparison.

In the experimental investigation the frame structure shown in Figure 2 is tested for temperature gradients up to 80°C. The temperature is applied by heating the water inside the tank like structure. Restraint forces developed in the tie rod are measured to obtain the response of the structure. More details of the test model and test methods are given by Bhat and Vecchio [6]. A number of specimens will be tested in which member stiffnesses, loading patterns and material properties will be the variables.

Figure 3 shows the results of analytical and experimental studies. In all cases the initial hydraulic and dead load effects although small, have been included in the analysis but are not shown in the figures. The experimental response is obtained by applying a series of thermal loads. Each time the structure was allowed to cool prior to applying the next load. By doing this it is expected that the effect of creep is minimized. In further tests and analysis the effect of creep will be included.

The studies indicate that tension stiffening effects contribute significantly to the thermal moments developed. This is evident from Figure 3 where the difference between the moments predicted with and without tension stiffening is significant. It should be noted that the maximum moment created by the applied thermal gradients is about 50 percent of the ultimate capacity. In this range, experimental observations follow closely the theoretical predictions. In the testing completed so far it is interesting to note that the effective stiffness method provides fairly realistic results. This confirms that for most design purposes the simple approach of using effective moment of inertia for cracked members is adequate.

4. Application to Nuclear Structures

The post cracking effects discussed above have great influence on the determination of temperature limits in nuclear containment structures. To illustrate this a typical containment structure wall is analyzed by approximating it as a restrained beam. Results of using the effective stiffness method and the method neglecting tension stiffening are plotted as sensitivity curves in Figure 4 in which the permissible temperature gradient is given as a function of time duration after a postulated LOCA spillage. In both cases the rebar stresses are allowed to reach 0.9 times the yield strength.

The results show that if tension stiffening effects are neglected, a much higher temperature can be permitted. At this limit the structure will undergo heavy cracking and damage although it will be safe from ultimate strength point. Figure 4 also illustrates the procedure to obtain a measure of safety margin in the structure at various times over the postulated temperatures. In fact, a number of such sensitivity curves can be drawn using various tension stiffening models or considering various stress or deformation levels. These curves are helpful to select the permissible temperature limit based on the acceptable level of safety.

5. Summary and Conclusions

Applicability of the post cracking behaviour models of reinforced concrete for the prediction of structural response under thermal gradients has been studied. Analytical predictions using two different approaches are compared with experimental observations.

The study has shown that simple analytical approaches using effective stiffness method provides realistic results for practical design purposes. Inelastic analysis methods considering explicit tension stiffening models are useful in more rigorous analysis such as those which use nonlinear frame analysis programs or finite element methods.

An experimental program is underway to verify the theoretical prediction models. Preliminary results show that methods which include tension stiffening effects are able to realistically predict the structural response.

Sensitivity curves obtained by considering different degrees of tension stiffening effects are useful in assessing the safety margins of concrete nuclear structures.

6. References

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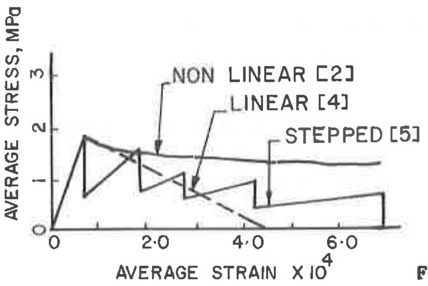

Figure 1 Equivalent Concrete Stress Strain Models

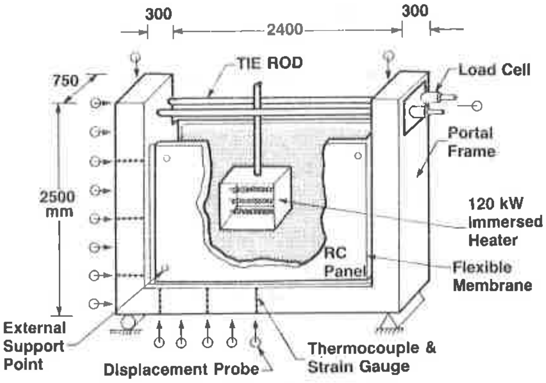

Figure 2 Portal Frame Model

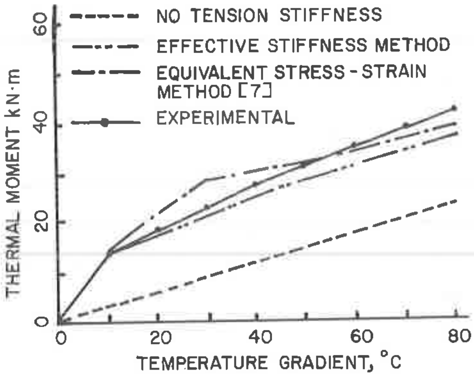

Figure 3 Response of Frame Structure

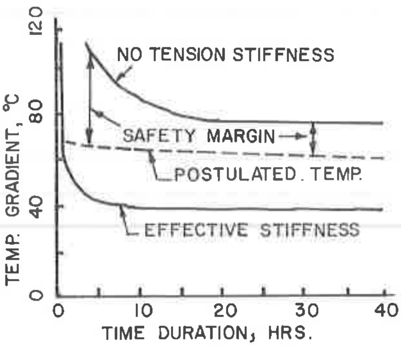

Figure 4 Sensitivity Curves