Computer Aided Analysis of Reactor Containment Building

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Abstract

The paper presents a computerized, structural analysis of the Reactor Containment Building (RCB) of a liquid metal nuclear power plant. Emphasis is placed on developing techniques for large 3-Dimensional, structural models using interactive computer graphics, analyzing the structure by NASTRAN and a simplified analytical approach to account for non-linear, temperature-dependent, material properties at elevated temperatures caused by a sodium spill from a Design Basis Accident (DBA).

1. Description of Reactor Containment Building (RCB) Structures:

The RCB consists of a steel containment vessel surrounding internal concrete structures (Figure 1) which are supported on a foundation mat common to all buildings of the Nuclear Island.

The internal structures of the RCB consist of several interconnected, reinforced concrete cells. These cells are enclosed by, and are connected with, a peripheral concrete cylindrical wall. The peripheral wall is constructed against the inner face of the vessel and extends from the foundation mat to the operating floor. Butting against the outer face of the steel vessel, another concrete wall is constructed from the mat to the operating floor. A detailed discussion on the structural concept of the sandwiched steel vessel below the operating floor is given in Reference [1].

There are several cells in the RCB containing liquid sodium components. These cells are lined with carbon steel plate and thermal insulation is provided to control heatup of the structural concrete.

2. Mathematical Model

Most of the structural configuration for the RCB model was developed on interactive computer graphics by using UNISTRUC [2]. The model was translated into MSC/NASTRAN [3] input file. Special features not available in UNISTRUC were added into the NASTRAN input file by developing pre-processor computer programs.

The model consists of walls, slabs, steel vessel, solid concrete block and the numerous openings (Figures 2 and 3). Quadrilateral (QUAD4) and triangular plate elements (TRIA3) of NASTRAN were used to model walls and slabs. Solid elements were used in areas where the thickness of a slab was excessively high in proportion to its span. Figure 2 shows several concrete walls including the inner peripheral wall. All floor slabs and some walls are excluded in Figure 2 for clarity. Figure 3 shows various floor slabs and some of the concrete walls. It is apparent from these two figures that the structural configuration of the model is large and complex requiring several thousand degrees-of-freedom with very large semi-band width of the stiffness matrix.

Further details on the development of the model are provided below.

2.1 Computer Graphics Application

A structural configuration can be developed for a complex structure using interactive computer graphics. Following are the characteristics for developing the RCB structural configuration at a graphic terminal operating in a time-sharing mode.

1) When part of a slab or a wall shares common features with other slabs or walls, the part can be modelled once and the model can be incorporated repetitively in several other slabs or walls resulting in significant saving of time in developing the model. The technique was used for four out of the six slabs (Figure 3).

2) Computer graphics facilitates modelling near openings, particularly when several of them are closely spaced since the model can be almost instantly updated and viewed.

3) Errors, such as connectivity between different structural elements, undesirable size or shape and skewness of elements are easily detected and can be immediately corrected by zooming and viewing complex parts of a model from different angles.

4) Computer graphics that uses on-line facility in a time-sharing mode tends to be expensive. Moreover, a computer graphics program may not provide all the features of a general purpose structural analysis program. if so, additional cost occurs to update the neutral input file generated by the computer graphics program.

2.2 NASTRAN Application

The following considerations were given in developing the model:

1) Several slabs had relatively short spans compared to its thickness. It was therefore considered desirable to account for shear deformation in the analysis.

2) A parametric study on simplified models was performed in order to achieve an omptimum mesh size for the RCB model. Stresses in the simplified models were about 95% of the theoretical values.

3) The sandwiched steel containment vessel has no mechanical connections between the vessel and the concrete walls. Since the steel vessel is not anchored to the concrete walls, the sandwiched plate elements cannot be used as this allows shear transfer between the inter-surfaces of the steel and concrete walls. Hence the three cylindrical walls were modelled separately and connected by axial elements. This allows interaction between the three cylinders without shear transfer.

It is more appropriate to use interface friction elements rather than the axial elements which permit contact or break between two surfaces, depending upon the normal force exerted on the surfaces and the coefficient of friction between the surfaces. However, such an analysis is nonlinear, requires several iterations, and very expensive for a large structure. Reference [1] provides further details on the nonlinear model.

3.0 Analysis: The analysis described in this paper is due to the loads caused by the Containment Design Basis Accident (DBA). The DBA is related to a postulated sodium spill in a steel lined cell (Cell 102A in Figure 1) causing a sodium fire in the cell. The accident poses pressure and significant thermal loads on the RCB structures and the Containment Vessel. The analytical method utilized to calculate stresses imposed by the DBA is described below. There are other accidents due to sodium spills in several other cells, but are not described in this paper.

3.1 Methodology

The following steps are recommended for the structural analysis of a complex concrete structure when thermal loads are a major contributory factor in the load combinations. It is further assumed that the reinforcing bars are effective and crushing or gross deterioration of concrete caused by elevated temperatures is precluded. Concrete temperatures should preferably be less than 500°F; however, temperatures higher than 500°F are permissible provided that concrete is not degraded to such an extent that the reinforcing bars are ineffective.

The steps below are based on a detailed evaluation of the RCB model (Figures 2 and 3) using NASTRAN. However, other general purpose finite element programs in lieu of NASTRAN can also be used. The method is presented in a generic way so that it can be used for other complex structures under the conditions described earlier.

1. Prepare the structural model using appropriate finite elements. Perform finite element structural analysis for each load case separately. Use Young's modulus (E) of concrete as a function of temperature for each element. As a simplification, several elements can be grouped together using weighted average temperatures. Consider an uncracked concrete section. The rigidity of each element is defined as EI where I is its moment of inertia.

2. In step 1, the surface temperature for the concrete walls and slabs are used as determined from the accident analysis. Such surface temperatures are generally nonlinear due to sodium spill accidents and should not be linearized. Temperature distributions through the thickness of elements are also nonlinear and could be linearized by the method prescribed in Appendix A of ACI-349 [4] but should preferably be considered nonlinear.

3. Calculate moments (M), axial forces (N), strains (e) and curvatures (ϕ) for each element in NASTRAN.

4. Perform sectional analysis for each element using strains and curvatures from NASTRAN as further described in (a) to (f) below. In the sectional analysis, nonlinear temperature distribution through the concrete thickness and nonlinear temperature dependent material properties are used. From this sectional analysis, new values of moment (M'), axial force (N') and section rigidity (E'I') are determined.

Details of sectional analysis for a concrete section are as below:

(a) Divide the concrete section into a number of segments (Figure 4). Find free thermal strains (e_{T_i}) at every node, i, which is given by:

$$e_{T_i} = (T_i - T_o) \times \alpha_{T_i}$$

where, T_i = Temperature at ith node point, T_o = Reference temperature, and α_{T_i} = Average coefficient of thermal expansion at T_i

(b) Compute top and bottom strains (e_a and e_b in Figure 4c) using strains and curvatures from NASTRAN (Step 3). Strain, e_i, at any node is given as:

$$e_i = \frac{(e_a - e_b)}{H} \times h_i + e_b,$$ where H and h_i are shown in Figure 4.

(c) Calculate net strains (e_{oi}) at every node point, i, which is given as:

$e_{oi} = e_{T_i} - e_i$ at node i, of the section.

(d) For each net strain, corresponding stress is determined from the temperature-dependent stress-strain curves of the concrete and reinforcing bars (Figures 5 and 6).

(e) Knowing stresses at all points of the concrete section, force (F') and moment (M') of the element can be calculated from statics.

(f) A concrete segment of the section may be cracked or uncracked depending upon the net tensile strain of the segment. Section rigidity (E'I') is calculated, where E' is temperature-dependent Young's modulus and I' is the moment of inertia of the cracked section.

5. If moments and axial force from Step (4) differ from those calculated in Step (3), calculate equivalent Young's Modulus (E_{eq}) by equating new rigidity (E'I') from Step 4f to the assumed rigidity (EI) in Step 1.

6. Use E_{eq} in the finite element analysis. Iterate Steps 1, 3, 4 and 5 until convergence.

3.2 Discussion on the Methodology

A brief discussion of the method presented above is as follows:

(1) For biaxial state of stress, the orthotropic option of NASTRAN should be used. Section rigidity (E'I') should be calculated in the two orthogonal directions. Poisson's effects may need to be accounted for.

(2) It was observed in the DBA analysis, that many critical areas (sections subjected to the maximum moment or axial force) were uncracked. The thermal stresses could not have been relieved using conventional linear analysis, since cracking did not occur. The linear analysis, uses the secant modulus which leads to very conservative results for high thermal strains. In the nonlinear analysis, due to reduction in the concrete modulus at high strains (.001 and above), thermal stresses can significantly be reduced. In summary, the proposed method relieves thermal stresses for both the conditions (a) section is cracked and (b) section is uncracked and subjected to high strains.

4.0 Results of Analysis

The table below provides typical results of the analysis for the part of a slab which did not crack due to high axial compression. The table shows that there is a significant reduction in the moments and forces as a result of the nonlinear analysis.

Element No.	Initial (I) or Final (F) Value	N_x kip/ft	M_x kip ft/ft	N_y kip/ft	M_y kip ft/ft
35	I	1632	211	1708	223
	F	1205	118	1245	121
36	I	1750	202	1340	180
	F	1267	106	1038	110

5.0 Conclusions

Computer graphics applications and its relative merits for a large and complex structure are discussed in the paper. It is concluded that, in general, computer graphics application significantly increases reliability of the model and reduces its development time but at increased computer cost. Moreover, computer graphics programs need to be carefully evaluated for their applicability to the model and their compatability to the general purpose finite element programs.

The paper also provides methodology for the thermal stress analysis of complex structures when thermal strains are high and are a major contributory factor in the load combinations. It was found that a simplified nonlinear analysis can reduce conservatism for both cracked and uncracked concrete sections without substantially increasing computer cost.

References

/1/ C. B. Abhat and G. B. Sigal "Steel Containment Vessel for LMFBR Nuclear Power Plants" 7th SMiRT Conference, Chicago, Illinois, 1983

/2/ UNISTRUC, Control Data Corporation, Minneapolis, Minnesota, 1978

/3/ MSC/NASTRAN "User's Manual", C. W. McCormick, MacNeal-Schwendler Corp., California, 1978

/4/ AC1-349 Code and Commentary, "Code Requirements for Nuclear Safety Related Concrete Structures", American Concrete Institute, Detroit, Michigan, 1980

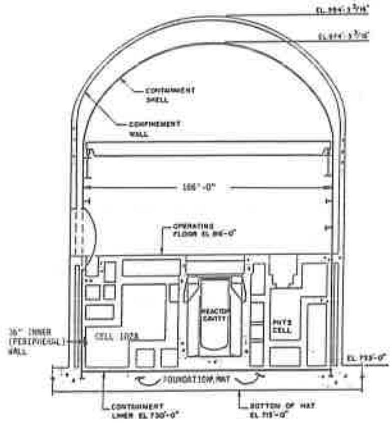

FIGURE 1 REACTOR CONTAINMENT BUILDING SECTION

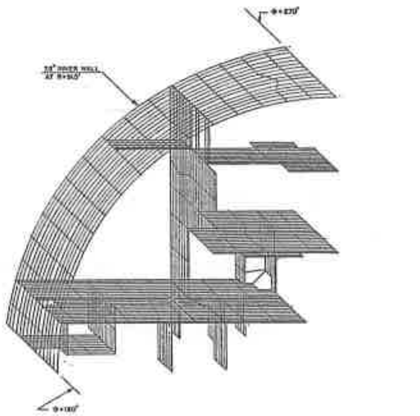

FIGURE 2 NASTRAN MODEL FOR RCB INTERNAL STRUCTURES

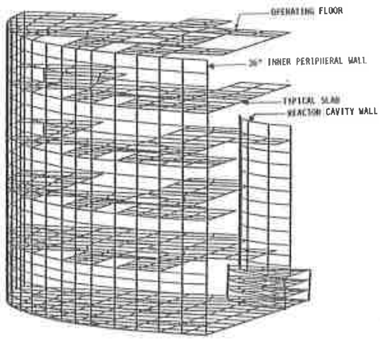

FIGURE 3 NASTRAN MODEL

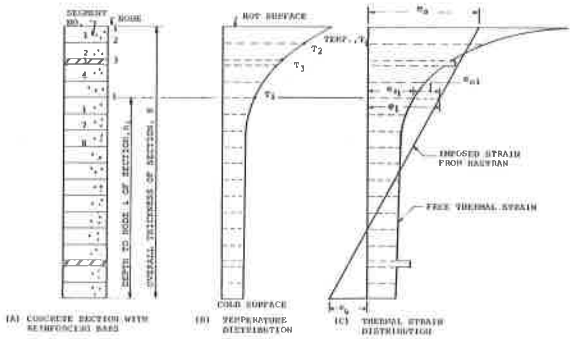

FIGURE 4 THERMAL STRAINS FOR A CONCRETE SECTION

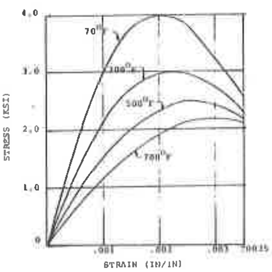

FIGURE 5 TYPICAL STRESS-STRAIN CURVES FOR CONCRETE

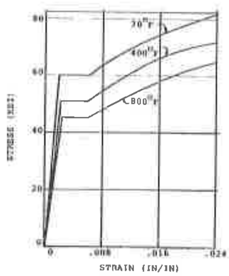

FIGURE 6 TYPICAL STRESS-STRAIN CURVES FOR REINFORCING STEEL BARS