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Design of Top Closures of Concrete Reactor Vessels with Very High Energy Absorption Capability

A.H. Marchertas, R.W. Seidensticker
Argonne National Laboratory,
9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.

Z.P. Bazant
The Technological Institute, Northwestern University,
Evanston, Illinois 60201, U.S.A.

SUMMARY

Reported are preliminary results of a study at the Argonne National Laboratory, the objective of which is to find a design which substantially increases the energy absorption capability of the top slab of a prestressed concrete reactor vessel for liquid-metal cooled fast-breeder reactor (LMFBR). Investigated is a novel design in which the lining in the opening in the top closure of the vessel for the main rotatable plug is strengthened into a heavy steel ring which is then anchored into the PCRV by prestressing tendons deflected from the barrel section. Although no final conclusions can yet be reached, this design appears to endow the PCRV with a consistently high and uniform energy absorption capability, due to eliminating the weakening effect of the large opening on the top closure of the PCRV.

1. Introduction

Recent studies at the Argonne National Laboratory have clearly demonstrated that a prestressed concrete reactor vessel (PCRV) for an LMFBR can easily contain energy releases expected in a hypothetical core-disruptive accident the magnitude of which is far greater than currently prescribed. A potential weakness of the PCRV exists, however, in the opening required for the large rotatable plugs in the top closure of the PCRV. Early concerns about the design of top closures have been expressed, for example, by Andersen and Ottosen [1]. The existing designs apparently cannot provide equal energy absorption capability as does the PCRV. The present paper gives preliminary information on a design scheme that eliminates this problem and results in a PCRV of a uniformly high energy absorption capability.

2. Principal Design Features

The weakness of the top closure of the PCRV is apparently two-fold:

(1) The conventional design of the bolts or holddowns of the large-diameter plug in the top closure appears to have inadequate capacity for these very high energy releases; in other words, the attachment of the plug (both the primary plug as well as the secondary plug within the plug) to the lining of the plug opening needs to be strengthened.

(2) The anchorage of the plug (particularly the lining of the opening in the top closure of the PCRV which holds the bolts or holddowns) into the reinforced and prestressed concrete of the top slab appears to be relatively weak.

The first problem, namely the attachment of the plug itself, is present whether a PCRV is used or not, and will not be discussed further in this paper. (It should be noted that numerous successful design solutions have been provided for this problem area.) The second problem, on the other hand, is particular to a PCRV. Work on this problem includes a recent paper by F. K. Garas [2]. Addressing the second problem, three novel design features are being considered in this study:

(a) The steel lining of the large diameter opening for the top plug is substantially strengthened, transforming it into a heavy steel ring which in itself has a sufficient stiffness even without the support of the surrounding concrete (10 in Fig. 1);

(b) The steel ring is anchored to the concrete of the top slab by prestressing tendons (9 in Fig. 1); and

(c) The tendons that anchor the steel ring also serve as the main prestressing tendons for the top slab and as a large part of the vertical tendons required for the barrel section of the PCRV.

3. Discussion of the Proposed Design Features

In a preliminary design, the number of the prestressing tendons anchored in the steel ring was determined from the condition that it should resist the maximum dynamic pressure on the plug without the aid of concrete. The prestressing tendons consist of 170 wires each, with wires of a 0.635 cm diameter and a tensile strength 1.52 MPa (resulting in a 53.77 cm^2 cross-section area of the tendon). The calculation results in 192 prestressing tendons to be anchored to the steel ring. The reaction pressure upon the steel ring from the underlying concrete, caused by the loads from tendon anchors, is estimated from the condition that the radial expansion displacement of the ring due to the sum of the tendon loads and the opposing pressure from concrete must be equal to the expansion of the opening in the top slab considered as a concrete cylinder with a hole and subjected to uniform pressure from the hole. This calculation gives the total hoop forces within the ring, as well as the bending moments due to the span between the tendon reactions. The calculation yields a thickness of 8.1 cm for the steel ring. The radially inclined tendons (9 in Fig. 1) provide adequate radial prestress in the top slab, but they do not provide sufficient circumferental prestress; for this reason further prestress is added on the top slab by circumferential prestressing wires wound around the cylindrical outer surface of the PCRV and supported in steel clad channels, as has been used in several recent designs.

To assure that the anchorage tendons of the steel ring have a sufficient vertical reaction component, these tendons must have significant inclination (Fig. 1). Therefore, unless the top slab would be extremely thick, it is necessary to terminate the top slab at its outer boundary with a large conical haunch. The openings for the internal heat exchanger and pumps must pass through this inclined haunch. At the same time, the radially inclined anchorage tendons (9 in Fig. 1) must bypass these openings. An arrangement which does that is possible; see Section A-A in Fig. 1. The haunches in the top slab limit the available internal space of the PCRV, but only slightly. They also somewhat complicate the shape and suspension of the primary steel vessel in the conventional design (left side of vertical section in Fig. 1), as well as the shape of the liner in the design alternate in which a primary steel vessel serves as a liner of the concrete vessel. (This alternate is considered in a parallel paper of this conference [3].)

The inclination of the radial tendons anchoring the steel ring allows them to be deflected vertically and continued through the barrel section. Thus, most of these radially inclined anchorage tendons can at the same time serve as the main vertical prestressing tendons of the barrel section, thus contributing to the integrity of the vessel. The friction loss of the prestressing force as well as radial reaction due to the 45° change in direction of the tendons (Fig. 1) appears to be acceptable.

The inclined radial anchorage tendons which pass through the top slab substantially strengthen the slab against inclined cracking near its boundary. In conventional design such inclined cracking in concrete is known to result in a punching failure of the top slab due to internal pressure, which occurs in a mode called crypto-dome failure. The possibility of such failure, which is distinguished by a brittle character (i.e., a rapid decline of the resisting force with increasing deformation) is essentially eliminated by the inclined anchorage tendons. Thus the safety margin of failure modes of the PCRV design seems to be significantly enhanced by this design feature.

There is still another advantage of this prestressing system, namely, that the direct anchorage of the vertical tendons into the steel ring enveloping the plug, along with the use of additional wound circumferential prestressing wires around this top slab, permits the elimination of horizontal transverse tendons crossing the top slab. There are thus fewer separate tendons, which improves the integrity of the vessel and diminishes the congestion of reinforcement in the top slab (as compared, for example, to the design considered in previous papers [4,5,6]). This aspect would also reduce the burden of in-service inspection of the tendons.

The cost of the steel to be used for the heavy steel ring around the plug is partly offset by the saving of the anchorages in the arrangement of prestressing tendons. Fewer anchorages are necessary since the vertical prestressing tendons of the barrel serve at the same time as the tendons that prestress the top slab.

To resist possible local impact and other local forces, the ring is also anchored into the surrounding concrete by welded studs or ribs, as is usual with liners.

4. Preliminary Results of Dynamic Finite Element Analysis

The energy absorption capability of the foregoing design of the top closure is being evaluated by a dynamic finite element analysis using the program and mathematical formulation already described in previous works [4,6]. The preliminary results of this analysis are as follows.

The loading on the inside wall of the PCRV is derived from the hypothetical core expansion, where at time zero 4800°K hot fuel vapor is assumed to exist in a 10 m^3 volume. This energy source corresponds to 2720 MW-s when expanded to a volume corresponding to 1 atm. The pressure history on the rigid PCRV boundaries is analytically modeled by the ICECO code using the same assumptions as described in Ref. [4]. The results of the ICECO solutions provide a pressure surge at the initial phase of the excursion, with the slug impact on the top closure starting at about 0.09 s and terminating impact at about 0.13 s. This derived pressure loading is permanently stored for future use on the PCRV model.

Dimensions of the PCRV model are shown in Fig. 2a. Since the bottom of the plug is of little concern in this study, the analytical model was simplified by eliminating the bottom slab altogether. The material properties used in the PCRV model are given in Table I.

The prestressing of PCRV head-cover model to specified prestress values in the circumferential and axial-radial tendons is first simulated by means of the DYNAPCON code. Because an axisymmetric geometry is assumed, equivalent thickneeses for the rows of tendons are used. The effect of the plug is neglected in the prestressing operation. After the prestressing is done, the plug is connected at one nodal point to the rest of the PCRV model, and then the previously derived internal loading is applied.

Figure 2b shows the calculated cracking pattern at the start of the slug impact on the top closure (time 0.14 s). The number of cracks at 0.25 s, shown in Fig. 2c, is seen to have increased somewhat, but not very extensively; this is essentially the time when steady state conditions become predominant.

During the excursion the maximum stresses in the tendons and the retaining ring remain elastic. This means that the indicated cracks in the PCRV would tend to close after removal of the internal load.

By contrast, analysis of a similar PCRV configuration, but with no haunch, subjected to the same source expansion [6], resulted in some permanent deformation in the tendons. Since the tendons and the reinforcement are the main load-carrying members of the PCRV, it appears that the present design may actually be too conservative: either the number of tendons or the percentage of reinforcement could be reduced to carry the ultimate load.

5. Concluding Remarks

Designing the top plug and closure as a heavy steel ring directly anchored by the main prestressing tendons of the barrel section of the PCRV appears to offer the possibility of a very large energy absorption capability, not only for the PCRV as a whole but also for the large diameter plug. The results reported herein must, however, be still considered as preliminary.

6. Acknowledgement

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