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# Effect of Modeling of Super-structure on the Behaviour of Reactor Building Raft

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## ABSTRACT

*The finite element idealisation of a rector building raft is important for proper prediction of design forces/moments for economical design. This paper discusses the various issues related to FE modelling of the RB raft and their effect on the behaviour of the RB raft. The effect of the stiffness of the super structural elements on the loss contact as well as on the design forces/moments have been addressed.*

**KEY WORDS:** Modeling, Super-structure, reactor building, raft, PHWR, seismic, loads, accident

## INTRODUCTION

The raft of the Reactor Building of typical Indian PHWR supports both the containment structures along with the reactor internals. The Reactor Building raft is a solid circular reinforced concrete structure with a continuous stressing gallery near the periphery to facilitate the prestressing of the cables for the inner containment structure. The major loads considered in the design of the raft are dead load, live load in normal operating, construction and shutdown conditions, thermal loads in normal operating and accidental situations, effect of accident pressure, suppression pool water load, seismic load etc. All static loads on the raft are estimated using a load run-down method. In conventional method of design, the raft is normally idealised as plates supported on vertical Winkler's springs and is subjected to all the applicable loads coming from the super structure. The stiffness of the super structural elements is ignored while computing the element forces and moments of the raft. Similarly, since the raft is very rigid in its own plane and since the horizontal stability of the raft is ensured during design, the degrees of freedom in horizontal direction are constrained.

This paper addresses the behaviour of the RB raft when the stiffness of the super-structural elements are considered in the analysis as compared to the results of conventional analysis without the stiffness of the super-structural elements. The effect of the stiffness of the super-structures on the loss of contact of the raft under seismic environment has also been studied. In order to study the effect of horizontal springs on the behaviour of the raft particularly near the stressing gallery under seismic environment, a separate study has been carried out considering a 3D model consisting of solid elements supported on both horizontal and vertical springs. This model has been analysed for all the forces applied at the top of the raft and the analysis results have been compared with those of shell model. Based on detailed studies, it has been concluded that consideration of the effect of stiffness of the super-structures on the behaviour of the raft is necessary from point of view of economical design. It is also concluded that shell model is adequate for the purpose of raft design.

## GEOMETRY OF RAFT

The Reactor Building raft of a typical Indian 220MWe PHWR, which is considered for the present study, is shown in Fig.1. The top of the raft is located about 12.1m below ground level and the raft is cast on competent rock strata. The raft is 52 m in diameter and 3.5m thick in general except that the outer periphery is thickened to 5.5 m in order to accommodate the stressing gallery. The raft is constructed with M45 (cube) grade of concrete having 28 days compressive cube strength of 45 MPa.

## LOADING & LOAD COMBINATIONS

The raft of the Reactor Building supports both inner and outer containment along with internal structures. The major loads considered in the design of the raft are

(i) Dead load due to self-weight of the raft and that of the super-structures.
(ii) Live load consisting of imposed load acting in the raft as well as load transferred from super-structure in different situations such as normal operating, construction and shutdown conditions.
(iii) Temperature load during normal operating condition in summer and winter.

(iv) Test pressure loads during testing of inner containment structure.

(v) Accident pressure due to postulated design basis accident viz. Loss of coolant accident (LOCA), main steam line break (MSLB). Loads acting on ICW and OCW under accidental conditions are transferred to the raft. Pressure load acting on the surface of the raft within ICW is applied directly on FE model of the raft. Hydro-dynamic effect in the suppression pool water due to post accidental scenario such as Vent Clearing, Pool Swell, Steam/Air flow and Chugging loads are considered and effects of these loads are transferred to the raft. Thermal loads due to accident condition are also considered.

(vi) Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) due to three component earthquake motions are also considered. Forces / moments due to one each along East-West and North-South axes and one in vertical direction transferred from the super-structure are obtained from a separate 3D stick model and are applied on the top of the raft.

(vii) External water pressure due to ground water table is considered.

(viii) Active earth pressure and dynamic increment considered on the OCW and the reactions are transferred to the raft.

(ix) Wind load transferred from OCW to the raft. However, the effect of wind load is much smaller than that due to seismic loads

(x) Prestressing forces from ICW and rock anchors are also considered.

The design of the raft has been carried out as per the provisions of the French Code RCC-G for both the load combinations i.e. limit state of serviceability and limit state of strength.

## MATHEMATICAL MODELING OF THE RAFT

The raft has been idealized using 4-noded 3D shell elements supported on Winkler's springs for all load combinations. The shell element used for Finite Element idealization has six degrees of freedom per node. The effect of shear deformation has been included in the formulation of the shell elements.

The foundation medium has been idealised as a Winkler medium with a uniform modulus of sub-grade reaction. The spring stiffness underneath the raft has been computed using a uniform modulus of sub-grade reaction, obtained using Vasic's Equation as indicated below:

$$k_s B = 0.65 * \left( \frac{E_r}{1-\mu^2} \right) * \sqrt[12]{\frac{E_r B^4}{E_f I_f}}$$

where,

| | | |
|---|---|---|
| $k_s$ | = | Modulus of subgrade reaction |
| B | = | Least width of footing in metre |
| | = | Diameter of raft for the present case |
| $E_r$ | = | Average Deformation modulus of rock |
| $E_f$ | = | Elastic modulus of concrete |
| $I_f$ | = | Moment of inertia of footing in cross-section |
| $\mu$ | = | Poisson's ratio for rock |

The stiffness of spring connected to the nodes of the shell elements is obtained based on the influence area of the nodes.

In order to study the effect of the stiffness of the super structure on the behaviour of raft, two FE models have been considered. These FE models are described below.

(i) **Model-1:** In this approach of mathematical idealization, only the raft has been modeled using 4-noded 3D general shell elements supported on vertical soil springs. The effect of the stiffness of the super-structure on the raft has been neglected. Only the forces transferred from the super-structure are applied on the FE model. The FE discritisation is shown in Fig. 2.

(ii) **Model-2:** In order to consider the stiffness of the super structure, the inner containment structure, outer containment structure and the internal structures are modeled using shell elements along with the raft. However loads transferred from the super-structure are applied on the top of the raft. The same discritisation of the raft portion as considered in Model-1 is retained in Model-2. The FE model is shown in Fig. 3.

## ANALYSIS PROCEDURE

The loss of contact underneath the raft is different for different load cases. The forces/moments in the raft is dependent on the deformation pattern, which is mainly controlled by loss of contact. As a result, the forces/moments obtained from individual load cases can not be combined directly to obtain the forces/moments for a particular load combination.

Hence, the raft has been analysed for all the load combinations separately. The analysis has been carried out in an iterative manner for each load combinations. The springs under tension have been deleted in each step and analysis is repeated with the new set of springs. The process is continued till all the vertical springs are found to be under compression. The forces / moments corresponding to this converged stage is considered for design.

## LOSS OF CONTACT

One of the important aspects of the design of the raft is the loss of contact of the raft under seismic environment. The typical loss of contact of the RB raft of the 220 MWe PHWR under load combinations pertaining to Safe Shutdown Earthquake (SSE) is 72% of base area, if the prestress rock anchors are not considered. In view of the uncertainties of the side soil/rock properties, the effect of the side soil/ rock resistance has been neglected in the computation of loss of contact.

The French Code RCC-G / BAEL adopted in the design of the raft does not specify any limit on the loss of contact. Based on the review of other international codes, it has been decided to limit the loss of contact of the raft to 33.33% of the total base area. In order to control the loss of contact, prestressed rock anchors have been provided in the raft.

The loss of contact under various load combinations has been computed using the FE analysis considering the effect of prestressed rock anchors using both Model-1 and Model-2. A comparison of loss of contact under various load combinations pertaining to SSE using both models has been presented in Table-1. It may be observed from Table-1, that the maximum loss of contact underneath the raft is 31% of the base area when the stiffness of the super-structure is accounted for and the same is 34% of the base area when the effect of super structure is neglected.

## FORCES AND MOMENTS:

Since raft is primarily flexural member, the bending moment obtained from both the models have been compared in Table-2 at various locations under different load combinations. Typical variation of moment along the diameter of raft for a load combination pertaining to SSE is shown in Fig. 5.

## EFFECT OF HORIZONTAL SPRINGS

In the analysis of raft presented above, the raft was idealized on thick plate founded on vertical winkler's springs. The stability of the raft was checked separately and adequate factor of safety against sliding and overturning was ensured. A separate local analysis using solid element was also carried out for detailed investigation of stress pattern around stressing gallery. In all these analysis, the horizontal degrees of freedom in the raft were restrained.

In order to study the effect of horizontal springs on the behaviour of the raft particularly near the stressing gallery under seismic environment, a separate study has been carried out considering a 3D model consisting of solid elements supported on both horizontal and vertical springs. The FE model of raft developed using Brick element is shown in Fig. 4. The stiffness of the super-structure has also been considered in this approach. Super-structure such as Inner Containment, Outer Containment, Internal structures etc is modelled using general shell elements. Appropriate boundary condition using kinematic constraint equation is applied at shell-solid junction. All the forces considered in shell model have been applied at the top of the raft in the solid model.

## ANALYSIS RESULTS

The analysis of the raft using the solid model has been carried out considering an interactive process in a same line as mentioned above. The springs under tension have been removed externally till the process converged. Analysis result for one typical load combination, which yields maximum loss of contact, has been presented in this paper.

The stresses across the thickness obtained at different locations are integrated to compute the total axial force and bending moment acting at different sections. The forces/moments thus obtained are compared in Table-2 with those from the analysis using shell model without horizontal springs. It may be observed from Table-2 that the bending moments obtained from shell model and solid model with horizontal springs are very close.

The maximum loss of contact obtained from the solid model is 36% whereas the same is 31% in the shell model for the corresponding load combination. Typical pattern of loss of contact under RB Raft is shown in Fig. 6. The shell model idealizes the mid-plane of the raft whereas the solid model represents the actual geometry. Since the effective forces/moments at the base of the solid model is higher as compared to those at the mid-plane of the raft, the solid model shows slightly higher loss of contact.

## CONCLUSION

Based on the study presented above, the following conclusions are drawn:

(i) Idealisation of the reactor building raft using shell elements is adequate for estimating the design forces/moments on the raft. The design forces/moments obtained from FE model consisting of solid elements closely matches with those obtained from FE model with shell elements. Idealisation of the RB raft using shell elements will also reduce the problem size and the related computational efforts.

(ii) The stiffness of the super-structure has significant effect on the behaviour of the raft. Consideration of the stiffness of the super structure reduces the design forces/moments significantly and hence, modelling of the stiffness of the super structure is necessary for economical design.

(iii) Modelling of horizontal stiffness of the raft in terms of horizontal springs at the interface of the raft and the rock does not have significant effect on the behaviour of the raft and as such, is not required to be considered in the FE model. However, it is necessary to ensure adequate factor of safety against the overall stability of the raft.

## REFERENCES

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| Table:1 **Loss of contact and Bearing Pressure under RB Raft for Different Load Combinations pertaining to SSE** | | | | | |
|---|---|---|---|---|---|
| Load comb. No. | Description | **Shell Model with Super-structure** | | **Shell Model without Super-structure** | |
| | | %Loss of Contact | Maximum Bearing Pressure (T/m$^2$) | %Loss of Contact | Maximum Bearing Pressure (T/m$^2$) |
| **Load combination Type: EXTREME ENVIRONMENT (SSE)** | | | | | |
| 25 | DL+PS+Top+0.4Esz+1.0Esy+0.4Esx+UL | 21.0 | 152.1 | 22.0 | 152.2 |
| 26 | DL+PS+Top+0.4Esz+0.4Esy+1.0Esx+UL | 26.0 | 173.6 | 29.0 | 184.8 |
| 27 | DL+PS+Top-1.0Esz+0.4Esy+0.4Esx | 0.0 | 157.4 | 0.0 | 168.0 |
| 28 | DL+PS+Top-0.4Esz+0.4Esy+1.0Esx | 0.0 | 196.0 | 0.3 | 209.9 |
| 29 | DL+PS+Top-1.0Esz+0.4Esy+0.4Esx+OPLL | 0.0 | 158.3 | 0.0 | 169.0 |
| 30 | DL+PS+Top-0.4Esz+0.4Esy+1.0Esx+OPLL | 0.0 | 196.9 | 0.0 | 210.9 |
| **Load combination Type: ABNORMAL+EXTREME ENVIRONMENT (MSLB+SSE)** | | | | | |
| 31 | DL+PS+Pa+Ta+1.0Esz+0.4Esy+0.4Esx+UL | 0.0 | 109.6 | 0.0 | 118.0 |
| 32 | DL+PS+Pa+Ta+1.0Esz+0.4Esy-0.4Esx+UL | 2.0 | 112.8 | 4.0 | 116.7 |
| 33 | DL+PS+Pa+Ta+1.0Esz-0.4Esy+0.4Esx+UL | 0.0 | 92.7 | 0.0 | 101.2 |
| 34 | DL+PS+Pa+Ta+1.0Esz-0.4Esy-0.4Esx+UL | 2.1 | 110.7 | 2.1 | 114.9 |
| 35 | DL+PS+Pa+Ta+0.4Esz+1.0Esy+0.4Esx+UL | 19.0 | 137.3 | 20.0 | 137.5 |
| 36 | DL+PS+Pa+Ta+0.4Esz+1.0Esy-0.4Esx+UL | 21.0 | 138.1 | 24.0 | 135.4 |
| 37 | DL+PS+Pa+Ta+0.4Esz-1.0Esy+0.4Esx+UL | 22.0 | 123.4 | 24.0 | 128.7 |
| 38 | DL+PS+Pa+Ta+0.4Esz-1.0Esy-0.4Esx+UL | 26.0 | 143.8 | 30.0 | 144.9 |
| 39 | DL+PS+Pa+Ta+0.4Esz+0.4Esy+1.0Esx+UL | 25.0 | 163.6 | 30.0 | 169.8 |
| 40 | DL+PS+Pa+Ta+0.4Esz+0.4Esy-1.0Esx+UL | 28.0 | 165.1 | 32.0 | 167.7 |
| 41 | DL+PS+Pa+Ta+0.4Esz-0.4Esy+1.0Esx+UL | 22.0 | 143.0 | 28.0 | 151.6 |
| 42 | DL+PS+Pa+Ta+0.4Esz-0.4Esy-1.0Esx+UL | 31.0 | 165.7 | 34.0 | 165.5 |

Note: DL : Dead Load
PS : Prestress Load (Rock Achor Forces)
Top: Operating Temperature
Esz:SSE Forces along Z-axis (Vertical Direction)
Esy:SSE Forces along Y-axis (Horizontal West-East Direction)
Esx:SSE Forces along X-axis (Horizontal North-South Direction)
UL:Uplift Load (Buoyancy Pressure due to rise of Ground water Table)
OPLL:Live Load during Normal Operating condition
Pa: Pressure during Accidental situations
Ta: Temperature during Accidental situations

**Table:2 Comparison of Analysis Results of RB Raft with Different Models**

| **Model adopted for the Analysis** | **Portion of Raft** | **Maximum Principal Moment (T-m/m)** | **Minimum Principal Moment (T-m/m)** |
|---|---|---|---|
| Thick Plate Bending Element founded on vertical Winkler spring (without Super-structure) | Outer | 1197.3 | -1905.1 |
| | Central | 129.1 | -893.1 |
| Thick Plate Bending Element founded on vertical Winkler spring (with Super-structure) | Outer | 455.9 | -1141.1 |
| | Central | 40.0 | -676.7 |
| Brick Element founded on vertical Winkler spring with horizontal Spring (with Super-structure) | Outer | 602.8 | -1072.8 |
| | Central | 112.3 | -723.5 |

Note:Moment Causing Top Tension is +ve

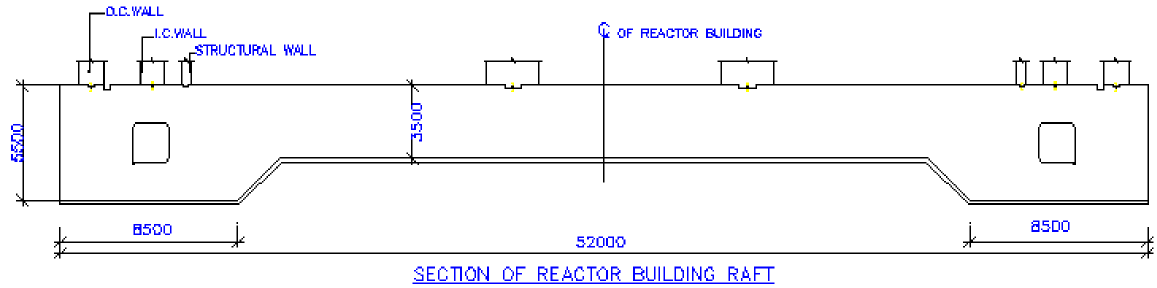


**Fig. 1: Section of Reactor Building Raft**

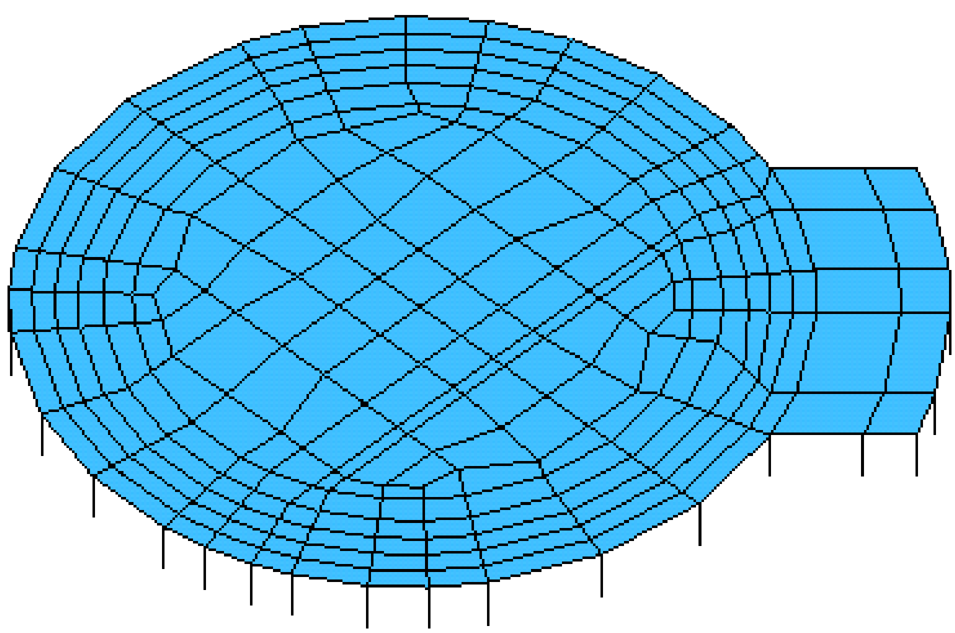

**Fig. 2: FE Model of RB Raft (Without Super Structure)**

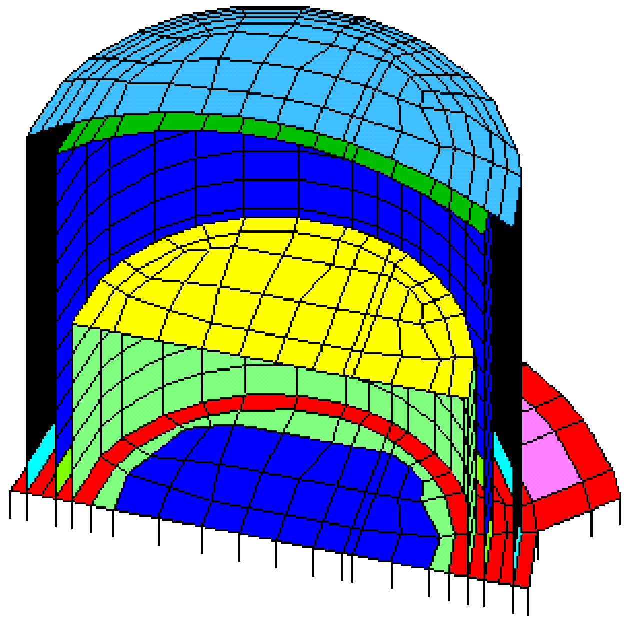

**Fig. 3: FE Model (With Super Structure)**

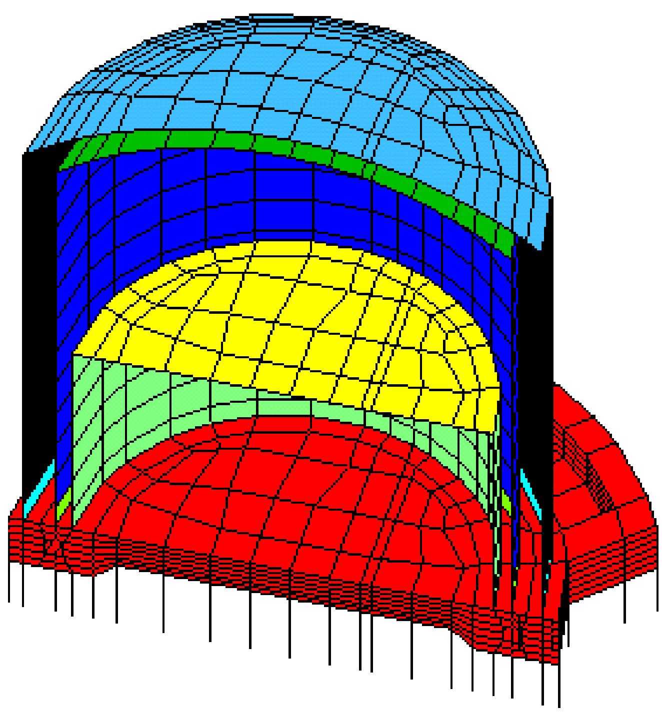

**Fig. 4 : 3-D Solid Model of Raft**

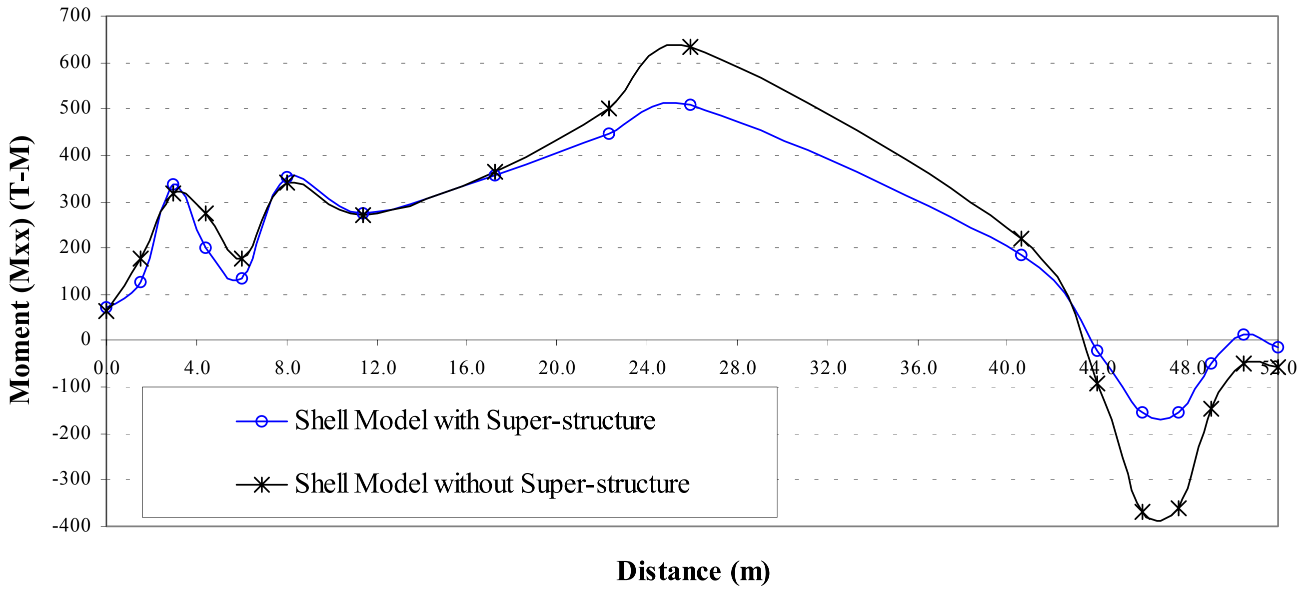


**Fig. 5: Variation of Moment (Mxx) along the diameter of the raft**

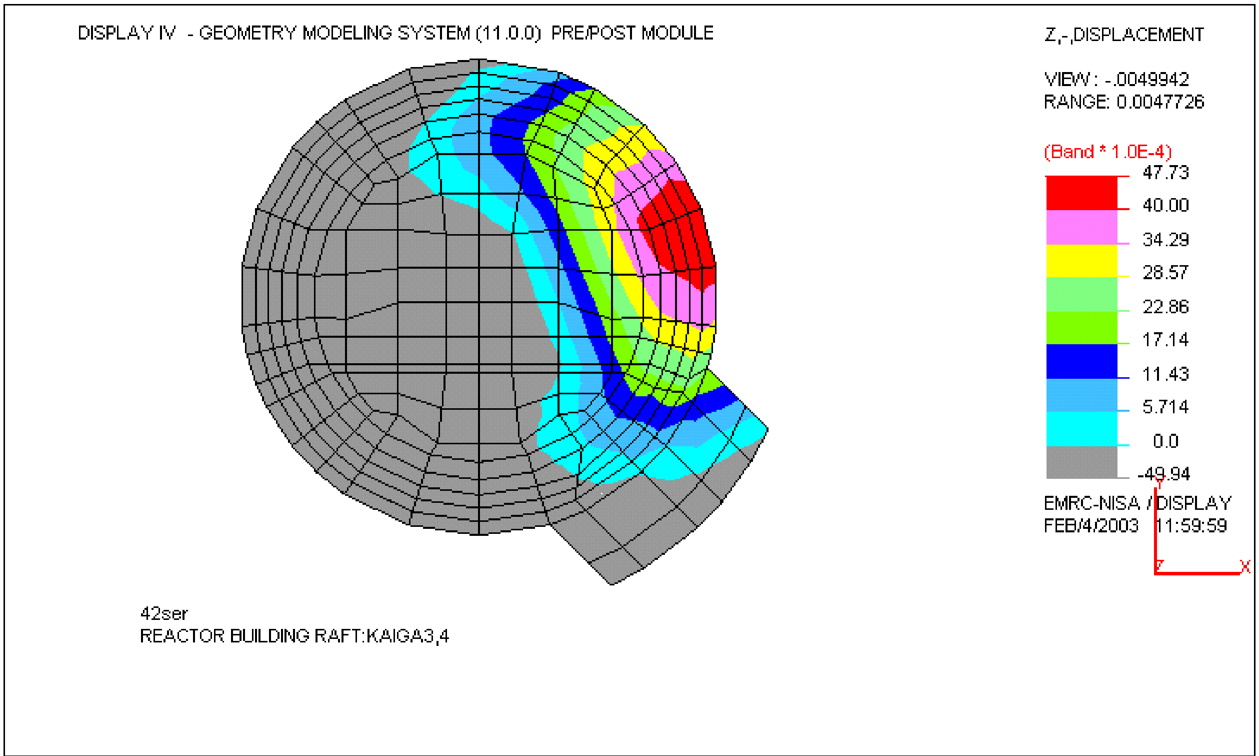


**Fig. 6 : Typical pattern of loss of Contact under RB Raft**