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A Study for the Improvement of Top End Piece Structural Strength

Kee-Nam Song and Dong-Seong Sohn
Korea Advanced Energy Research Institute
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상단고정체의 구조강도 개선을 위한 연구

송기남 · 손동성
한국에너지연구소
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Abstract

As a part of the design of the top end piece(TEP) for the 14×14 reload fuel, various models of top end piece structure were analysed, using the ANSYS code, under fuel assembly shipping and handling load conditions. The 3–dimensional isoparametric elements were used in each model. By rearrangement of slots and holes on the adapter plate, without violating the design requirements, and also by changing the enclosure attachment method used on the adapter plate from pin joints to through-weld, the load carrying capacity of the adapter plate was greatly strengthened. These concepts were adopted for the design of the 14×14 reload fuel.

요 약

14×14형 교체노심용 핵연료집합체 상단고정체 설계의 일환으로 핵연료집합체 운송 및 취급시의 하중조건하에서 여러 상단고정체 구조모델들에 대한 구조해석을 ANSYS code를 사용하여 수행하였다. 해석 모델에서는 3차원 등매개변수(isoparametric) 요소를 사용하였으며 설계조건들을 위배하지 않으면서 Adapter plate에 있는 구멍들의 배치를 조정하는 한편 Adapter plate에 부착되는 두름판(Enclosure)의 부착 방법을 개선함으로서 상단고정체의 구조적 강도를 증가시켰다. 이러한 개념들은 14×14 교체노심용 핵연료 설계에 채택되었다.

I. Introduction

As an upper structure of the fuel assembly the top end piece(TEP) consists of an adapter plate, with an array of holes and slots, an enclosure, a top plate, clamping pieces and pads as shown in Figure 1. The TEP should withstand all the expected loads throughout the fuel assembly life and accommodate the core components. It should also provide an interface for the fuel assembly handling tools attachment.

In order to maintain the above functions throughout the fuel assembly life, the TEP must be designed to be in structural integrity under all the expected loads throughout the fuel assembly life.

The general requirements for the structural integrity of the TEP are described in the FSAR of the relevant plant[1]. In the early years, mechanical tests using strain gauges were used to verify that the TEP met these requirements. But, the evaluation of the structural integrity by mechanical test is very expensive and also takes much time to prepare test equipment and specimens. For these reasons a numerical method using the FEM has recently been gradually introduced to facilitate the design procedure. In the beginning of the 1970's, certain vendors tried to evaluate the structural integrity of the TEP using the FEM, but with coarse meshes, they didn't get satisfactory results. However, as large capacity computers are developed and big computer codes become available, numerical methods are commonly used in the evaluation of the structural integrity.[2, 3]

The purpose of this paper is to investigate the way to increase the load carrying capacity of the TEP by improving the arrangement of slots and holes and also by changing the enclosure attachment method used on the TEP.

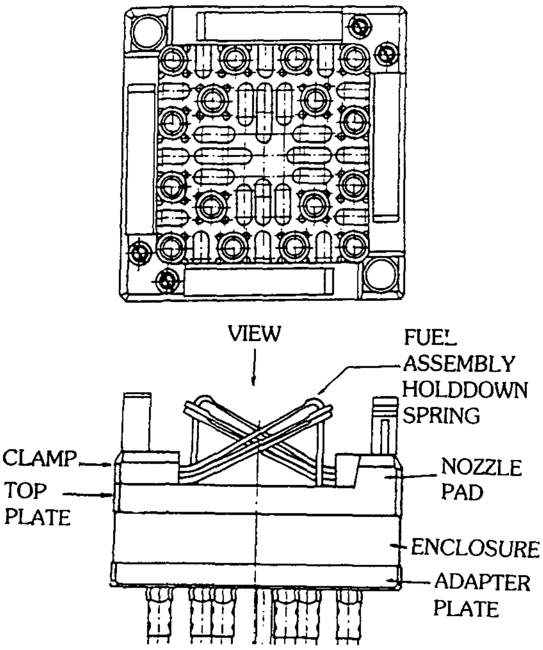


Fig. 1 Top End Piece

II. Finite Element Fomulation

II.1. Virtual Work Derivation for Stress Analysis in an Element

According to the principle of the virtual work[4], a virtual change of the internal strain energy must be offset by an identical change in external work due to the applied load, or:

$$\delta U = \delta V \quad \cdots\cdots (1)$$

where δU=virtual strain energy(internal work)

δV=virtual work(external work)

For the following equations, superscript T signifies the transpose of the vectors and matrices and subscript e signifies that the equation holds for a special element.

The virtual strain energy is:

$$\delta U = \int_{V^e} \{\delta \varepsilon\}^T \{\sigma\} d(vol) \quad \cdots\cdots (2)$$

where $\{\varepsilon\}$ =strain vector

$\{\sigma\}$ =stress vector

V^e=volume of an element

The stress is related to the strains by

$$\{\sigma\} = [D] (\{\varepsilon\} - \{\varepsilon^{th}\}) \quad \cdots\cdots (3)$$

where $[D]$ =material property matrix

$\{\varepsilon^{th}\}$ =thermal strain vector

The strain is related to the displacement at nodes

$$\{\varepsilon\}_e = [B] \{u\}_e \quad \cdots\cdots (4)$$

where $[B]$ =strain-displacement matrix based on the element shape functions.

$\{u\}_e$=displacement vector at nodes

Combining equation (2) with (3) and (4), and neglecting the thermal strain effect:

$$\delta U = \int_{V^e} \{\delta u\}_e^T [B]^T [D] [B] \{u\}_e d(vol) \quad \cdots (5)$$

The virtual work, δV, neglecting the body force, is

$$\delta V = \int_{V^e} \{\delta u\}^T \{f\} d(vol) \quad \cdots\cdots (6)$$

II.2. System Equation

From the principle of virtual work(equation (1)) we can derive the following force-displacement relation in an element.

$$[K]_e \{u\}_e = \{F\}_e \cdots\cdots (7)$$

where $[K]_e = \int_{V^e} [B]^T [D] [B] \, d(vol)$ is the element stiffness matrix.

$\{F\}_e = \int_{V^e} \{f\} \, d(vol)$

Assembling the force-displacement relation in total domain, the system equation is given as follows

$$[K] \{u\} = \{F\} \cdots\cdots (8)$$

where $[K] = \sum_{i=1}^{n} [K]_{ei}$

$\{F\} = \sum_{i=1}^{n} \{F\}_{ei}$

III. Formulation of the Problem

The TEP has the following main functions, which are derived from thermohydraulic, mechanical and engineering considerations.

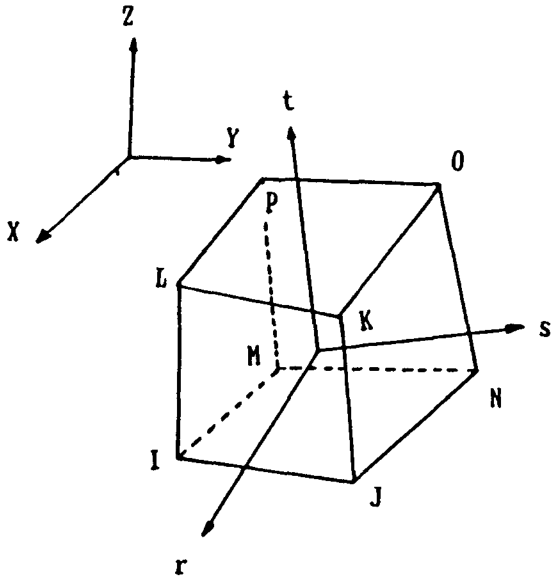
i) The TEP must position the upper ends of fuel assemblies so that they have the desired lateral spacing.
ii) The TEP must transmit holddown forces to the fuel assembly.
iii) The TEP must direct coolant flow to the upper core plate at an acceptable pressure drop.
iv) The TEP must provide an interface surface for fuel assembly handling tools attachment.
v) The TEP must prevent accidental ejection of the fuel rods through the adapter plate.
vi) The TEP is required to hold the fuel assembly guide thimbles and instrumentation tube in the desired locations and serve as the top structural member of the fuel assembly.
vii) The TEP must provide for guidance and protection of the fuel assembly during insertion and removal from the core, fuel handling equipment transfer baskets, or fuel storgae racks.

Therefore, so as not to violate the above functions, the TEP must be designed to maintain a structural integrity throughout the fuel assembly life.

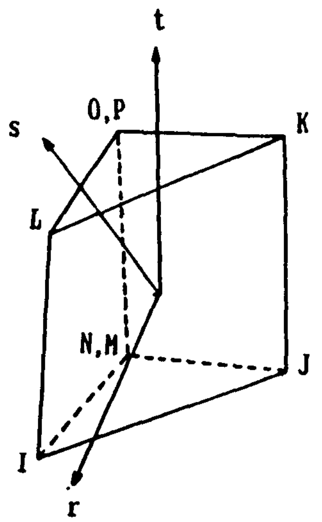
In designing the TEP the vertical load components are primarily considered because the effects of horizontial load components are negligible. Under the vertical load, the following two main factors affect the structural strength of the TEP.

i) positioning of holes and slots on the adapter plate
ii) boundary condition along the edge of the adapter plate

Since the thickness of the adapter plate is relatively thick compared with the side length of the plate, 3-dimensional analysis was performed with 8 node isoparametric brick elements and 6 node prism shaped elements[5] in some regions(STIF 45 in ANSYS code). Each node on the element has three independent displacement variables. Figure 2 shows the 3-dimensional isoparametric elements used in the analysis of the adapter plate.



8 nodes isoparametric brick element



6 nodes prism shaped element

Fig. 2 Finite Elements Used in Analyses

III.1. Basic Assumptions

To save cost and time, and also to simplify the adapter plate model the following assumptions have conservatively been made.

i) One of the weakest quarters of the adapter plate was selected to be the model since quarterly symmetric loads are acting on the TEP.

ii) All chamfers around the edge, holes, and slots were ignored.

iii) The strengthening effect on the TEP due to guide thimbles and correspoinding thread joints has been ignored.

iv) In the event that an enclosure was attached to the adapter plate by pin joints a simply supported boundary condition along the edge of the adapter plate was imposed on the model.

III.2. Design Load

The shipping and handling load of 4g due to the fuel assembly and the RCCA weight is a design value. The fuel assembly weight acts on the TEP guide thimble retention bores through the sleeves threaded to the adapter plate. The load due to RCCA weight acts at the central area of the adapter plate.

III.3. Imposition of Boundary Conditions

The following boundary conditions were imposed on the models

i) At symmetric edges.

Because of symmetry, all nodal displacements normal to the symmetric surfaces on the symmertric surface are zero, i.e.,

$u_{xi}=0$ along the vertical symmetric surface

$u_{yi}=0$ along the horizontal symmetric surface

ii) Along the edge of the adapter plate

Either of two kinds of boundary conditions were imposed depending on whether the enclosure was attached to the TEP by pin joints or through-weld.

First, in case of pin joints between the enclosure and the TEP, all nodal displacements which are normal to the plane of the adapter plate are zero along the edge of the adapter plate, i.e.,

$u_{zi}=0$ along the edge of the adapter plate.

Second, in case of through-weld attchment of the enclosure to the TEP all nodal displacements on the upper edge of the enclosure can be constrained because the stiffness of the adapter plate is much greater than that of the enclosure, i.e.,

$u_{xi}=u_{yi}=u_{zi}=0$ on upper edge of the enclosure

IV. Results and Discussion

Stress analyses on some adapter plate models have been performed to investigate the effect of the two main factors mentioned in Section III on TEP strength. The results of these analyses are as follows.

Adapter plate model I, in which most of the slots(or flow holes) in the central region are unidirectionally placed, is shown in Figure 3. Because enclosure was attached to the adapter plate by pin joints, contribution of enclosure to TEP strength was conservatively considered to be of no account. This adapter plate design had been used in the fuel assembly prepared previous to this study and the enclosure was attached to the TEP by pin joints. The stress calculation results with a simply supported boundary condition show that high stresses exceeding the minimum specified yield stress(δ_y) occurs on the shaded regions in Fig. 4. A maximum stress intensity which is about 50% higher than the minimum specified yield stress

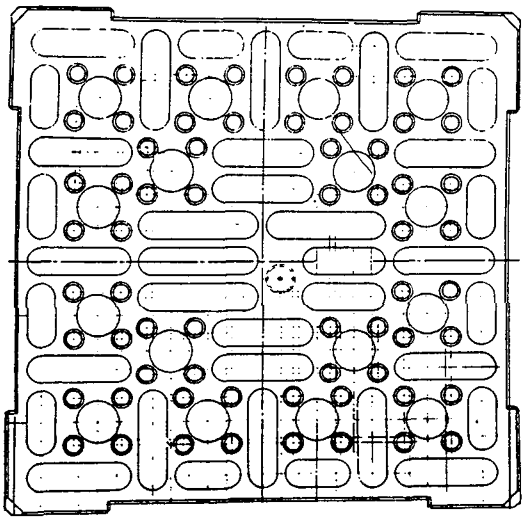


Fig. 3 Adapter Plate for Model I

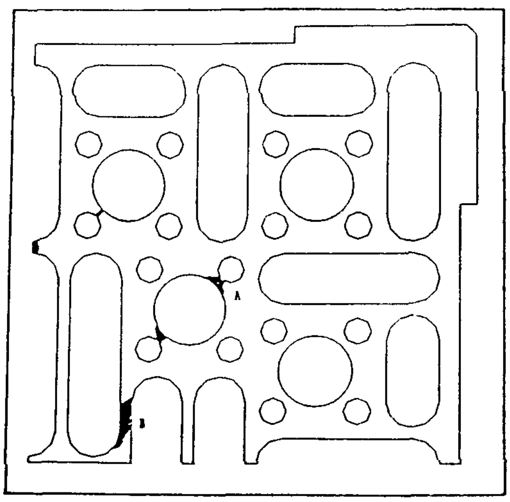


Fig. 4 Stress Distribution of Adapter Plate Model I

occurs in region A. The reason seems to be related to a narrow ligament width in this region and to the flow hole arrangement. In this model, slots in the central part of the adapter plate are aligned in the same direction and the load paths due to loads acting on the guide thimble retention bores(GTRB) are concentrated in these regions.

In order to reduce the concentration of load paths due to the un-optimised flow hole arrangement in Model I, slots in the central region are placed biaxially in Model II. The calculation result on Model II is shown in Figure 5. The shaded regions in Figure 5 denote highly stressed regions exceeding the minimum specified yield stress.

While the maximum stress intensity in region A is 9% lower than that in the identical region of Model I, stresses in regions B and C increased remarkably. It seems that the load paths formed by the loads on the GTRBs are concentrated in these regions.

In order to impoxve the flow hole arrangement further, slots were placed nearly radially in Model III. The calculation result on this model is shown in Figure 6. Calculated stress exceeded the minimum specified yield stress only in a small region, shown in Figure 6, and the maximum stress intensity in this region decreased by 21% from that in Model I. The radial arrangement of the flow holes seems to make the load paths due to both fuel assembly weight and RCCA weight evenly distributed on the ligaments in the central region of the adapter plate. The load carrying capacity of adapter plate Model III, in which flow holes are radially placed, is greatly increased over those of adapter plate Models I and II.

The effect of boundary condition on the strength of the adapter plate was investigated in adapter plate Model IV, in which through-weld attachment boundary condition was applied between the enclosure and adapter plate while the flow hole arrangement was kept the same as that of Model III.

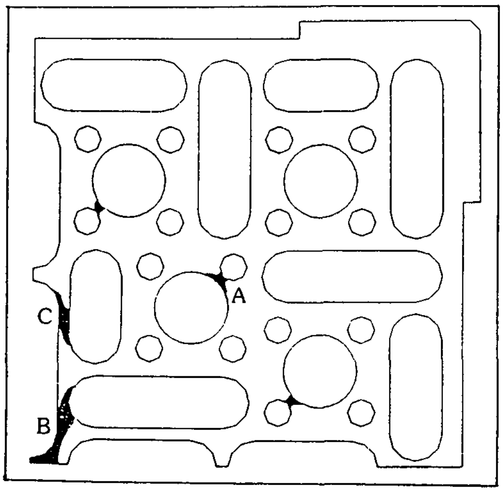


Fig. 5 Stress Distribution of Adapter Plate Model II

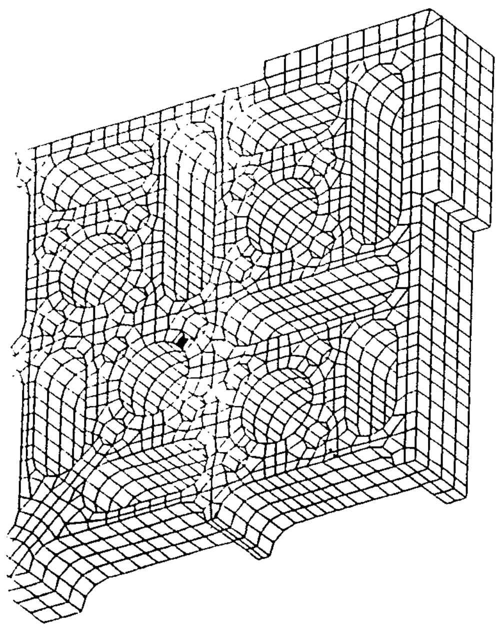


Fig. 6 Stress Distribution of Adapter Plate Model III

In Model IV, the clamped boundary condition, as mentioned in Section III.3, was imposed on along the upper part of the enclosure. The results of the stress calculation, as shown in Figure 7, revealed that the region where the minimum specified yield stress had been exceeded was significantly reduced, and the maximum stress intensity of this region decreased about 13% from that in Model III. The reason the stresses in the adapter plate Model IV are smaller than those in the adapter plate Model III seems to be that the enclosure not only shares the strain energy but also constrains, to some extent, the deformation along the edge of the adapter plate.

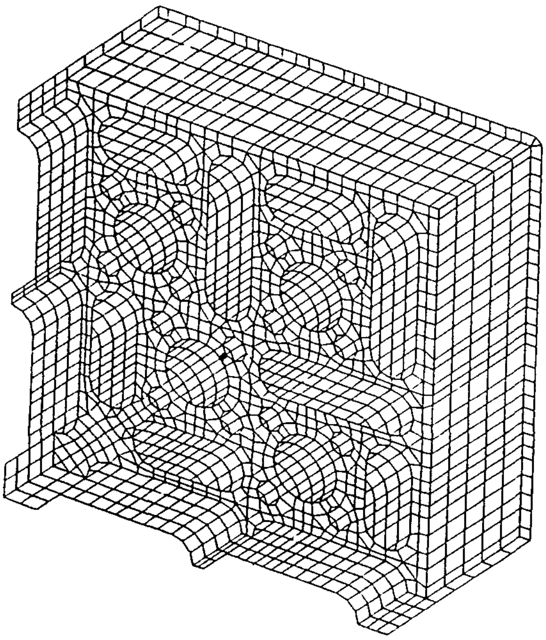


Fig. 7 Stress Distribution of Adapter Plate Model IV

Even though the improvements in flow hole arrangements in Model III and IV produced marked reduction in calculated stress, the model is a slightly unsatisfactory for the TEP for the 14×14 reload fuel because there is still a high stress region with a value above the minimum specified yield stress. Finally, the width of the ligament between the GTRBs and the small holes around them was slightly increased in the adapter plate design for the 14×14 reload fuel as shown in Figure 8. This model yielded a maximum stress below the minimum specified yield stress and satisfied all the other requirements, considered in the mechanical design and thermal-hydraulic design including the constraints mentioned in Section III

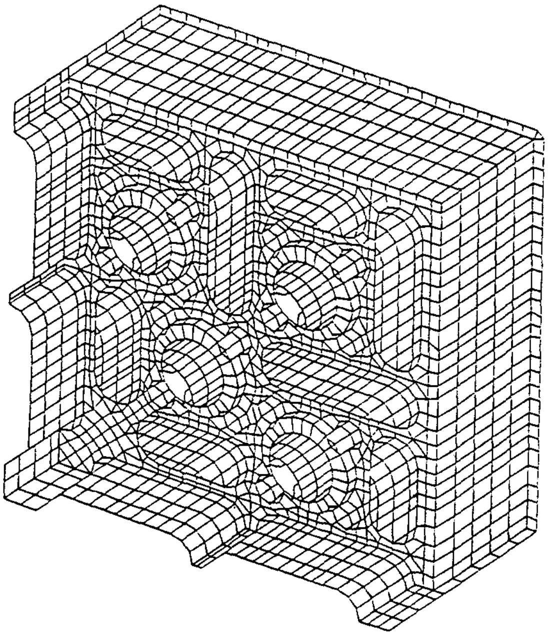


Fig. 8 Adapter Plate Model for the 14$\times$14 Reload Fuel

V. Conclusions

Structural analysis and design improvements of a TEP for 14$\times$14 reload fuel has been performed under the fuel assembly shipping and handling load. The results can be summarized as follows.

1. Optimizing the flow hole arrangements in the adapter plate in a nearly radial configuration, the load carrying capacity of the adapter plate was greatly increased. The maximum stress intensity was reduced by 21% from the reference design.
2. Through-weld attachment of the enclosure to the adapter plate considerably strengthens the load carrying capacity of the TEP. The maximum stress intensity was reduced by 13% from the pin-joint type of attachment.
3. The structural integrity of the TEP for 14$\times$14 reload fuel is maintained under the fuel assembly shipping and handling conditions.

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