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Structural Integrity Evaluation of CANFLEX Fuel Bundle by Hydraulic Drag Load

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Abstract

The CANFLEX fuel bundle has been developed by KAERI/AECL jointly to facilitate the use of various fuel cycles in CANDU-6 reactor. The structural analysis of the fuel bundles by hydraulic drag force is performed to evaluate the fuel integrity during the refuelling service. The present analysis method is newly developed for the structural integrity evaluation by studing FEM modelling for the fuel bundles in a fuel channel. As compared the results of the mechanical strength test, the displacement value of endplate given by analysis results shows to be good agreement within 15% under the maximum design drag load. As the results of analysis, it is shown to keep the structural integrity of CANFLEX fuel bundles under hydraulic drag load during the refuelling service.

1. Introduction

The CANFLEX fuel bundle has been developed by KAERI and AECL jointly to facilitate the use of various fuel cycles in CANDU-6 reactor[1-9]. The CANDU-6 calandria contains 380 horizontal fuel channels. The heavy water coolant passes through the fuel bundle string contained in the pressure tube. During the normal operation, the fuel bundles are randomly loaded into the fuel channel under the on-power reactor condition. The mechanical loads in the fuel channel are presented in static hydraulic drag force, flow-induced vibration and dynamic impact load. As one of the fuel design evaluations, the structural analysis on CANFLEX fuel bundles with the hydraulic drag load would be an interesting subjects. The hydraulic drag load is generated due to the pressure drop in channel. For the newly design bundle several hydraulic tests such as pressure drop, cross-flow, strength, impact and endurance tests are required to verify the fuel design. In general, the tests require more time, investment and manpower compared with the analysis. However, both the tests and the analysis are desirable to compare between the test and analysis results for further design improvement.

The present structural analysis is considered in static load due to the hydraulic drag force during the refueling. The drag force is caused mainly by the flow blockage in the cross section of fuel bundle components and by the flow on the friction of fuel element surface. This force can be varied with the number of fuel bundles, alignment of bundles and flow rate in channel. The pressure drop data measured in the test can be applicable to predict the drag force, respectively. In this work, the structure analysis is carried out with the ANSYS code[10]. A reliability of

FEM modeling for CANFLEX bundle string is also studied under several load and constraint conditions. The structure analysis method is established by an appropriate FEM modelling for the complicated CANFLEX fuel bundle string in the fuel channel. And it shows the stress, force and displacement behavior on fuel bundle components which can not be obtained easily by the tests. In order to conform the fuel structural integrity, the mechanical strength test of fuel bundles have been carried out so far. The present paper shows that the integrity for CANDU-6 fuel bundle is evaluated by the analysis method. This analysis method can be easily obtained the overall data which could not cover at the strength tests.

2. Load and Structural Matrices

2.1. Hydraulic Drag Load

The pressure drop through the fuel string in a CANDU-6 channel occurs mainly along the inner surface of pressure tube and fuel bundles. It is composed of the skin friction loss $\triangle P_{Friction}$ and form loss $\triangle P_{Form}$. The skin friction is caused by the surfaces of pressure tube and fuel elements. And the form loss is caused by the bearing pads, spacers, buttons and endplates. The total pressure loss along the fuel string in the channel is given as,

$$\Delta P_{Total} = \Delta P_{Form} + \Delta P_{Friction}$$

$$\Delta P_{Friction} = (c \cdot \frac{f \cdot L}{D_{eq}})\rho\frac{v^2}{2},\ \Delta P_{Form} = K \cdot \frac{\rho v^2}{2}$$

where, c is skin friction correction factor, L, total fuel bundle length, f, friction factor, K, total form loss factor in channel, D_{eq}, equivalent hydraulic diameter. The hydraulic drag load is mainly due to the pressure drop through the fuel bundle string in channel.

This load affects on reaction force at the side-stops which supports the fuel bundle at channel flow outlet during refueling service. Fig. 1 shows an overview of the fuel bundles contacted to side-stops in a fuel channel during the refuelling. The double side-stops contact the eight outer elements of the last downstream bundle. Since the upstream ram control system is designed to reduce the force to zero when the side-stops are activated, the load on the side-stops is normally equivalent to the hydraulic drag. The hydraulic drag force depend on the flow rate and the number of bundles in channel flow.

2.2. Structural Matrices

The principle of virtual work states that a virtual (very small) change of the internal strain energy must be offset by an identical change in external work due to the applied loads,

$$\delta U = \delta V \tag{1}$$

where, U = strain energy(internal work) = U1 + U2

V = external work = V1 + V2 + V3

The virtual strain energy is

$$\delta U_1 = \int_{vol} \{\delta\varepsilon\}^T \{\sigma\}\, d(vol) \tag{2}$$

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

$\{\sigma\}$ = stress vector

Continuing the derivation assuming linear materials and geometry, Eq.(1) and Eq.(2) are combined to give

$$\{\sigma\} = [D](\{\varepsilon\} - \{\varepsilon^{th}\}),\quad [D] = elasticity\ matrice \tag{3}$$

$$\delta U_1 = \int_{vol}(\{\delta\varepsilon\}^T[D]\{\varepsilon\} - \{\delta\varepsilon\}^T[D]\{\varepsilon^{th}\})d(vol) \tag{4}$$

The strains may be related to the nodal displacements by,

$$\{\varepsilon\} = [B]\{u\} \tag{5}$$

where, {B} = strain-displacement matrix based on the element shape functions

{u} = nodal displacement vector

It will be assumed that all effects are in the global Cartesian system. Combining equation(5) with equa-

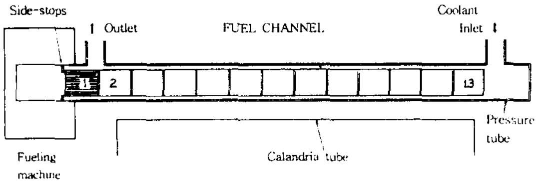

Fig. 1. Load Configuration in the Fuel Channel During Refueling

tion(4), and noting that {u} does not vary over the volume,

$$\delta U_1 = \{\delta u\}^T \int_{vol} [B][D][B]\, d(vol)\{u\} - \{\delta u\}^T \int_{vol} [B][D]\{\varepsilon^{th}\}\, d(vol) \quad (6)$$

Another form of virtual strain energy is when a surface moves against a distributed resistance, as in a foundation stiffness. Next, the external virtual work (inertial effects, pressure, nodal forces) will be considered. The equilibrium equation represented with matrices and load vector as a one element basis become generally,

$$([K_e] + [K_e^f])\{u\} - \{F_e^{th}\} = [M_e]\{\ddot{u}\} + \{F_e^{pr}\} + \{F_e^{nd}\} \quad (7)$$

where,

$[K_e] = \int_{vol}[B]^T[D][B]d(vol)$ = *element stiffness matrix*

$[K_e^f] = k\int_{area}[N_n]^T[N_n]d(area_f)$ = *element foundation stiffness matrix*

$[F_e^{th}] = \int_{vol}[B]^T[D]\{\varepsilon^{th}\}\, d(vol)$ = element thermal load vector

$[M_e] = \rho\int_{vol}[N]^T[N]d(vol)$ = *element mass matrix*

$\{\ddot{u}\} = \frac{\partial^2}{\partial t^2}\{u\}$ = *acceleration vector(such as gravity effects)*

$[F_e^{pr}] = \int_{area_p}[N_n]^T\{P\}d(area_p)$ = *element pressure vector*

3. Structural Analysis

3.1. Analysis Modeling

(1) Beam model (13 bundles in channel)

The fuel bundle string in the channel shall be modelled to investigate its structure response and behavior in the hydraulic drag condition. The fuel string in the present condition is consisted of 13 fuel bundles in channel. The hydraulic drag force is assumed to be applied uniformly on each bundle spacer pad location as an axial load. The bundles are assumed to be located horizontally in same line which the rod elements(string) are collinear. The endplate of adjacent bundles are in full contact. The fuel string is allowed to move in axial direction only and buckling under the drag load is restrained.

The finite element model of CANFLEX 43 elements fuel string is a beam model. Endplates, fuel rods and side-stops are modelled as beam elements, using different material properties. The endplates of all the bundles are modelled with 3-D elastic beam element. The weld of endplate to fuel element(rod) is modelled the same 3-D elastic beams with rigid properties given by higher Young's modulus than that of endplate material. Fuel bundle elements are modelled as 3-D elastic beams with element properties included in sheath and meat. The length of each element is divided into six segments. This fine elements is expected to obtain proper displacement. And the spacer pads and inter bundle elements are modelled as rigid truss elements with 3 translational degrees of freedom. The adjacent endplates of two fuel bundles are interconnected with rigid beams. These inter bundle connecting elements between the bundles are rigid truss element and transfer the axial forces only.

The downstream bundle #1 contacted to the side-stops have axial displacement restrained so that the Uz translation is fixed. The centre node on each of the two endplates of all fuel bundles have their transverse displacements(Ux, Uy) restrained to fix these nodes in spacers. The hydraulic drag force is applied uniformly as a point axial force on the 43 nodes representing the spacer pad of each bundle. The 13 bundles beam model located in 3 dimensional geometry(x,y,z) in a fuel channel.

(2) Shell/Beam model (Single bundle)

Single bundle for downstream #1 bundle is modelled by combined shell and beam element. Both endplate of the bundle is assumed to be 3-D shell element and 43 fuel rods is considered as 3-D beam element. The shell model for endplate is necessary to calculate the plastic shell element.

3.2. Structural Analysis for CANFLEX Bundles

In order to choose an appropriate modelling for the fuel bundle string in the channel, the analyses were performed by using the various elements and constraint conditions. To verify the modelling simulation of CANFLEX bundles, the analysis results were compared with that of KAERI mechanical strength test[11]. Both the maximum displacements at endplate are founded to agree less than 0.5mm. As compared the results of the mechanical strength test, the displacement value of endplate given by analysis results shows to be good agreement within 15% under the maximum design drag load, Fmax. Therefore, it is enough to study the structural integrity evaluation by using the developed modelling. The overall analysis method and procedure is shown in Fig. 2. The structure analysis model I for 13 bundles consists of 8,450 nodes and 11,085 elements for ANSYS code. The each endplate shell for single bundle model compose of approximately 550 nodes. The static analysis was calculated first so as to find the drag forces and displacements behavior on 13 fuel bundles modelled as 3-D beam and truss elements. The present analysis is considered normally to withstand hydraulic load against double side-stops contacted with 8 fuel elements. The hydraulic load for double side-stops is considered to be 1.6 time higher than the maximum operation load.

In addition, the downstream bundle #1 should be conformed to the structural integrity for the higher drag force load. The elastic and 2-step plastic analyses for single bundle model were performed by modelling the endplate shell into the fine segments and by using the drag forces which had been obtained in previous 3-D beam analysis. It is predicted that a large force is given at the endplate of the last bundle. Several plastic analysis under various drag loads were performed to obtain the displacement values.

4. Results and Discussions

The important source of static load in the bundles is the axial drag force generated by coolant flow. As one of the structural analysis results of 13 fuel bundles model, Fig. 3 shows the drag load distribution through 13 bundles. The drag forces of fuel bundle were obtained by load response through 13 bundles which is given the initial load condition. The initial drag load is assumed to be applied uniformly on each bundle spacer pad location as an axial load.

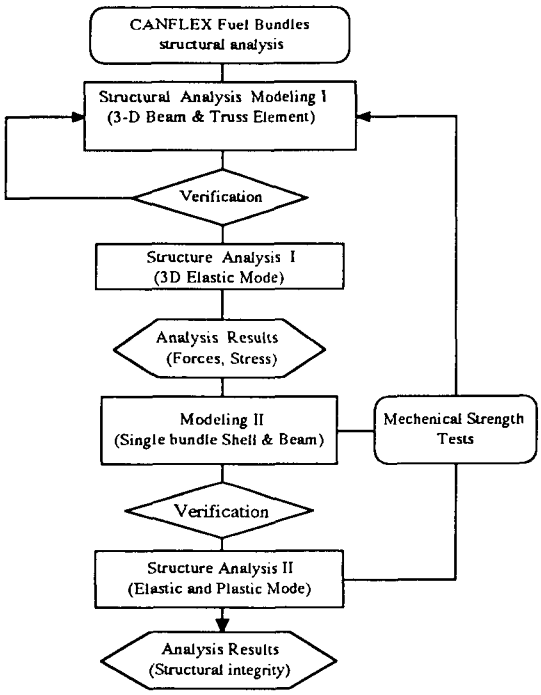

Fig. 2. Flow Chart of Structure Analysis for CANFLEX Fuel Bondles

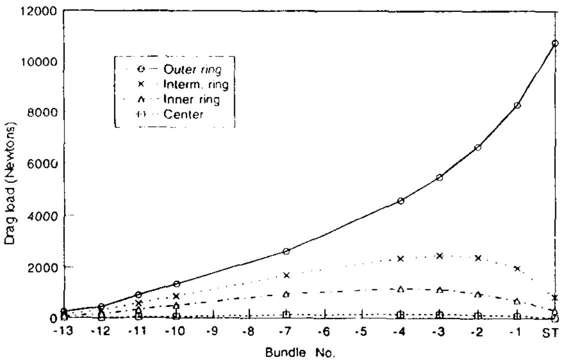

Fig. 3. Drag Load Carried by Outer, Interm. & Inner Ring Elements (Double Side-stop)

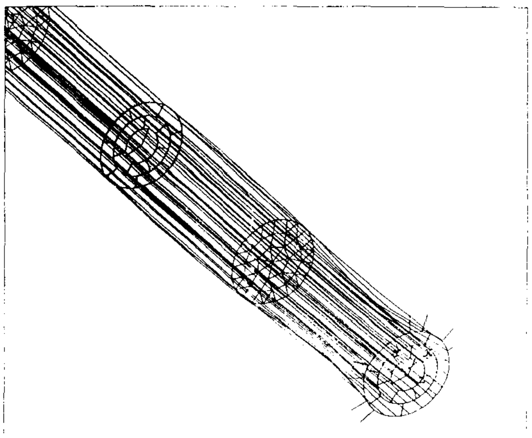

Fig. 4. Deformed Shape Around Downstream Bundle No. 1

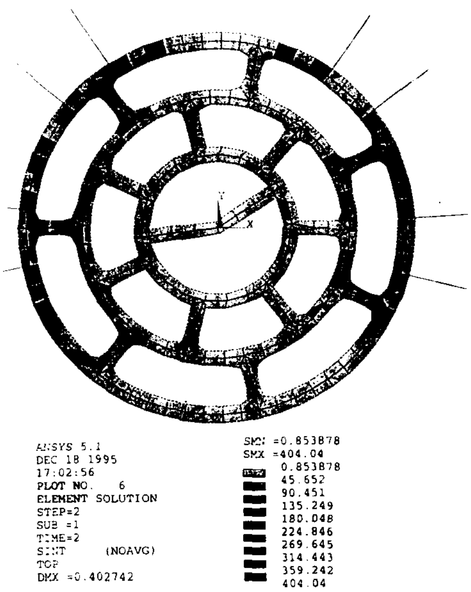

Fig. 5. Stress Contour on the Endplate at Double Side-stops

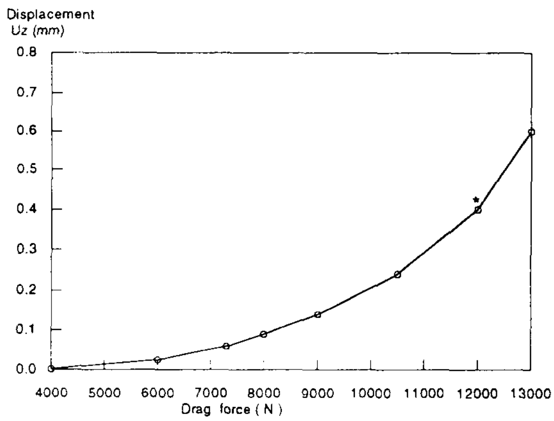

Fig. 6. Endplate Displacement Profile Versus Drag Forces

The outer ring elements of bundle in the downstream bundle #1 carry higher load values, while the intermediate ring and inner rings have lower load values. This indicates a load transfer of 90% from the inner and intermediate rings to the outer ring, because the load transfer the inner and intermediate ring elements are not supported at double side-stops.

Fig. 4 shows the slightly deformed configuration of bundle #2 and #1 downstream near to 8 side-stops nodes under maximum drag load. The displaced shape of bundle #1 looks more deformed than that of bundle #2, because the drag load given in bundle #1 is much higher than that of bundle #2. The stress intensity contour on the endplate are given in Fig. 5 under double side-stops boundary condition. As shown in Fig. 5, the deep dark region is presented as higher stress intensity concentration distribution around the double side-stops. The displacement value of endplate after the plastic analysis is important to evaluate the structural integrity of fuel bundle.

Fig. 6 shows the displacement profile according to the various drag load condition. Under the Fmax load, the endplate was shown to be slightly displaced shape less than 0.5mm. As compared the measured value(*) of the mechanical strength test in Fig. 6, the displacement value of endplate given by analysis results shows to be good agreement within 15% under the maximum design drag load, Fmax. The deformed shape within 0.5mm displacements is negligible to affect on the overall endplate structure. Therefore, it is enough to keep its structural integrity for CANFLEX bundle under hydraulic drag load during the refuelling.

5. Conclusions

The structural analysis model for complicated CANFLEX fuel bundles in the fuel channel was newly developed by the various analysis method. The analysis results were obtained by 13 bundles model I and model II for single bundle due to hydraulic load in channel. The calculated displacements value for downstream #1 bundle endplate is compared with the that of the mechanical strength test under the maximum design load Fmax . The plastic analysis shows that the displacement value is slightly low less than 5mm which is well agreed to the experimental value within 15% difference. However, no significant effect of the overall endplate structure was observed. Therefore, the structure integrity of CANFLEX fuel bundles would be concluded to be safe under the maximum hydraulic drag load. The structural analysis will be continued for further study to improve and optimize the fuel design.

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