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Structural Analysis of CANFLEX Fuel Bundles

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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. As one of the design evaluations, the structural analysis of the fuel bundles by hydraulic drag force is performed to evaluate the the fuel integrity in the period of the refuelling in CANDU-6. The structural integrity is evaluated by FEM modelling for the complicated bundles configuration in channel. It is noted that the present analysis method is newly developed for the structural integrity evaluation. The analysis results show that the fuel bundle is shown to keep its structural integrity during the refuelling.

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]. 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 refueled in the on-power reactor is refueled in accordance with a refueling scheme. In order to evaluate the fuel design, the structural analysis on CANFLEX fuel bundles due to hydraulic drag load would be one of the interesting subjects in CANDU fuel evaluations. The hydraulic drag load is generated due to the pressure drop in channel. For the newly design bundles, several hydraulic tests such as pressure drop, vibration, impact and endurance are also performed to verify the fuel design. In general, the tests require more time, investment and manpower compared with the analysis. However, both the tests and analysis is 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[2]. 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. And it shows the stress, force and displacement behavior on fuel bundle components which can not be obtained easily by the tests.

2. Load and Structural Matrices

2.1 Hydraulic drag load

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

$$\Delta P_{Total} = \Delta P_{Form} + \Delta P_{Friction} \qquad (1)$$

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

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

This load effects on reaction force at the side-stops which supports the fuel bundle at channel flow outlet during refueling period. The 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 equilibrium equation represented with matrices and load vector as a one element basis become generally,

$$([K_e] + [K_e^f])\{u\} - \{F_e^{th}\} = [M_e]\{\ddot{u}\} + \{F_e^{pr}\} + \{F_e^{nd}\} \qquad (3)$$

where, $[K_e]$, $[K_e^f]$ =element stiffness and foundation stiffness matrix

$\{u\}$, $\{F_e^{th}\}$ =nodal displacement vector and element thermal load vector

$[M_e]$ =*element mass matrix*, $\{\ddot{u}\}$ =*acceleration vector*

$\{F_e^{pr}\}$, $\{F_e^{nd}\}$ =*element pressure and nodal force vector.*

3. Structural Analysis

3.1 Analysis Modeling

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 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 elements. The weld of endplate to fuel rod is modelled the same 3-D elastic beams with rigid properties given by much higher Young's modulus than that of endplate material. Fuel bundle elements are modelled as 3-D elastic beams with rods properties included in sheath and meat. The length of each rod 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 elements 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. Fig. 1 shows an overview of the fuel bundle modelling around side-stops.

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[3]. Both the maximum displacements at endplate are founded to agree within 1 mm. Therefore, it is enough to study the structural integrity behavior in details. The structure analysis model consists of 8,450 nodes and 11,085 elements for ANSYS code. The static analysis was calculated first so as to find the forces, displacements, moments and stress behavior on 13 fuel bundles modelled as 3-D beam and truss elements. The present analysis is considered normally only to withstand hydraulic load against double side-stops.

In addition, the endplate of downstream bundle #1 fixed on side-stops conformed to the structural integrity. The static analysis for the endplate model was performed by modelling the endplate into the fine segments and by using the displacement values which had been obtained in previous 3-D beam element analysis. It is predicted that the last endplate has a large effect on the stiffness of fuel bundles. The stress intensity in the endplate is evaluated to verify the mechanical strength, and is the largest of the absolute values of $\sigma_1-\sigma_2,\ \sigma_2-\sigma_3,\ \sigma_3-\sigma_1$ in principle stresses $(\sigma_1, \sigma_2, \sigma_3)$,

$$\sigma_I = \max(\,|\sigma_1-\sigma_2|\,,\ |\sigma_2-\sigma_3|\,,\ |\sigma_3-\sigma_1|\,)$$

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, the drag load distribution through 13 bundles in Fig. 2 shows that the side-stops(ST) endplate outer elements in the downstream bundle #1 carry higher load values, while the intermediate ring and inner rings have low load values, respectivly. 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. 3 show 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 bundle #2, because the drag load given in bundle #1 is much higher than that of bundle #2. Table 1 summarizes the calculated results for the endplate model. The stress intensity is considered to be important factor to conform the structure integrity. Overall stress intensity values on the endplate is reasonable to be compared with the the yielding and ultimate tensile strength. The stress intensity shows that 6 nodes loaction in total 508 nodes is over the yielding strength but the maximum value is lower than ultimate tensile strength of endplate. The local higher stress intensities of only 6 nodes in 508 nodes is not mainly effected on the overall endplate sturcture. It explains to allow the local endplate displacements less than 1 mm in which the structure integrity of fuel bundle endplate is enough to keep its integrity.

Table 1. The Calculated Stress Intensities over $\sigma_{I(yield)}$ of Endplate

Item	Stress intensities(Mpa) at 6 Nodes					
	N345	N471	N414	N402	N405	N320
Stress Intensity (MPa)	372	374	365	421	383	513

5. Conclusion

The structural analysis model for complicated CANFLEX fuel bundles was set up by the comparion between the analysis and strength tests. The calculated results for 13 fuel bundle string and endplate fine model are the forces, displacements and stresses due to hydraulic drag load. The local stress intensities of endplate were higher than the yielding strength, 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 drag load. The structural analysis will be continued for further study to improve and optimize the fuel design.

References

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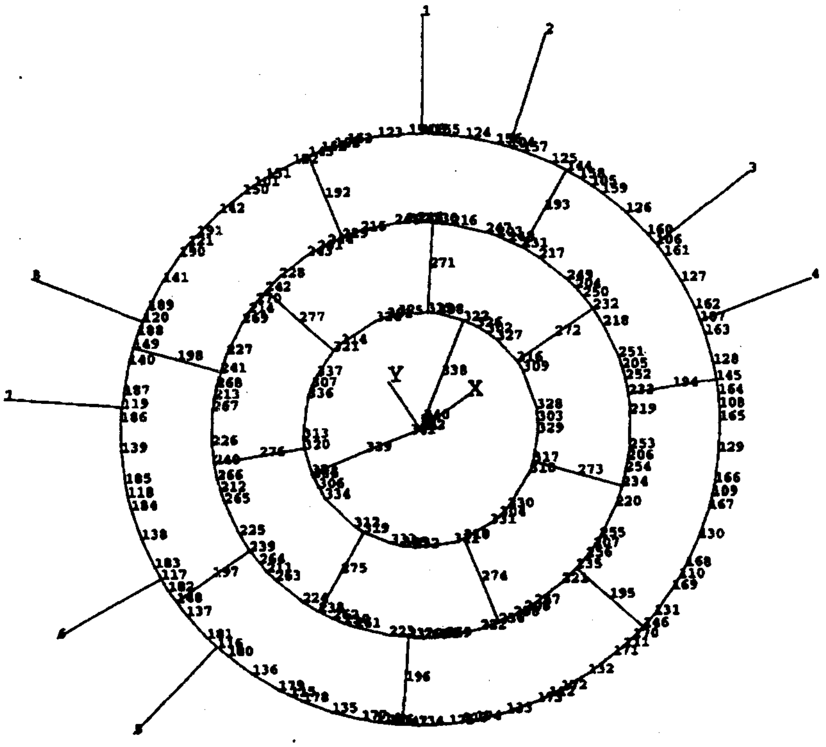

Fig. 1 CANFLEX Fuel Bundle Model at Endplate/Sheath Junction

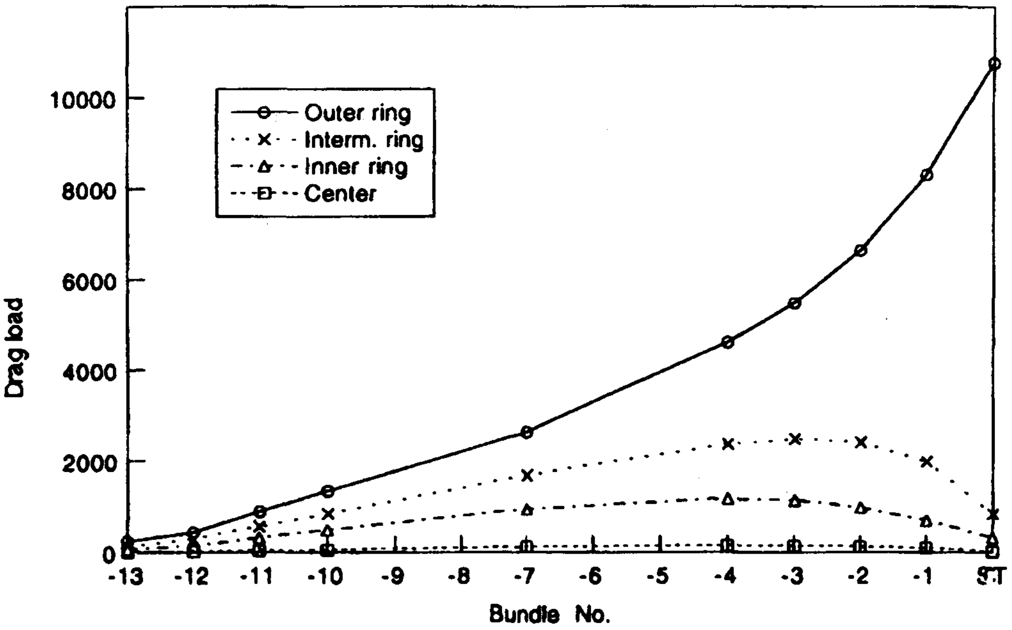

Fig. 2 Drag Load Carried by Outer, Interm. and Inner Ring Elements

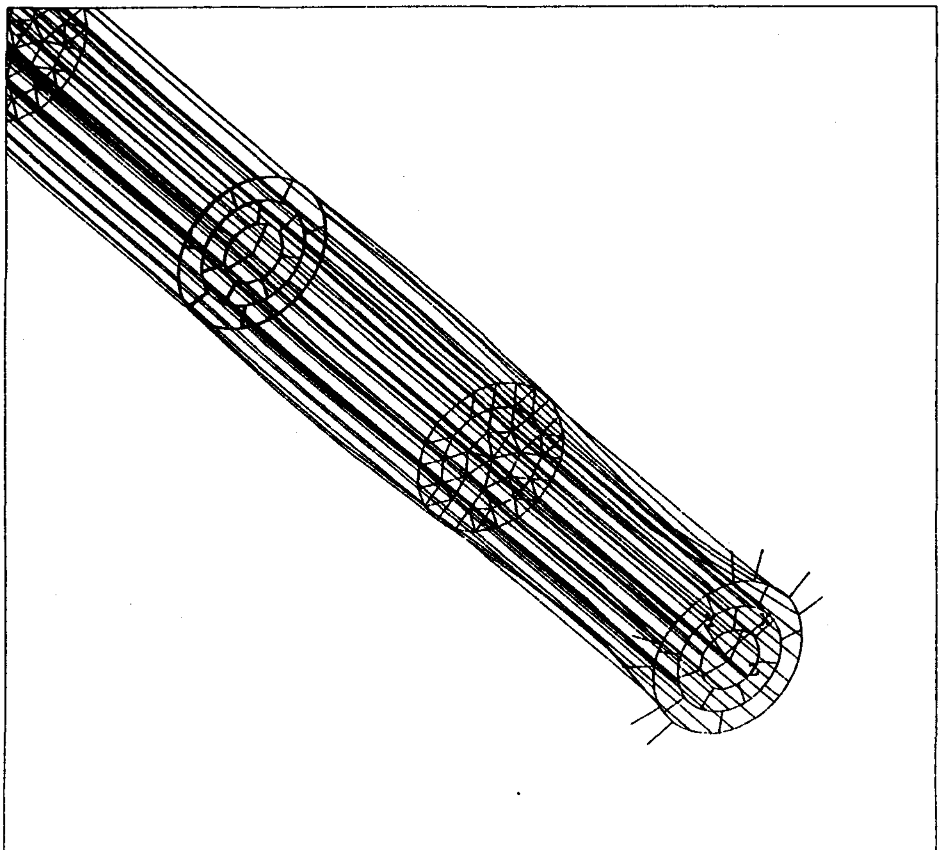

Fig. 3 Deformed Shape of Fuel Bundle String
at Downstream Bundle #1